

REPORT OF UNDERWAY $p\text{CO}_2$ MEASUREMENTS IN SURFACE WATERS
AND THE ATMOSPHERE DURING
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(RVIB Nathaniel B. Palmer Cruise 00/2)

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1. General

1-a) The Cruise:

The data start on julian day 100, at 0600 UTC 9 April 2000, and continue until the system was shut down preparing to enter Chilean EEZ waters, at 0200 UTC 2 May 2000. The ship departed and returned to Punta Arenas, Chile, so this cruise includes parts of TWO crossings of the Drake Passage. The ship operated on the north-west side of the Antarctic Peninsula between latitudes 64°S and 61°S . There was considerable structure in the SST data, implying operating in and out of ice. Further details must await a proper cruise report from the Chief Scientist or other source.

1-b) The $p\text{CO}_2$ data:

The primary source of data are files created by the ships data acquisition system, (RVDAS). A program runs to combined $p\text{CO}_2$ data, TSG data, and several other parameters, such as latitude, longitude, windspeed, water-flow in the uncontaminated seawater line, etc. We used raw $p\text{CO}_2$, TSG temperature and salinity, and position from the ship's GPS data in the merged RVDAS file. These files have the name: NDP0001pco2.dXXX, where XXX is the yearday. They are stored in the rawdata subdirectory, and have been merged into rawdata.txt. We then edit rawdata.txt to remove extra observations after the last set of standards. Further, as the procpco2.prg program runs it identifies places where the number of standards is wrong. This did not find any problems in this file.

Thirty-three seawater and one air observation are made between standard sets. Each observation involves flowing the equilibration gas for 180 seconds. We also flow the air for 180 seconds before stopping for an observation. Details on these and other aspects of the analysis system are explained later.

Standards:

Cylinder	Concentration (ppm)
Nitrogen (UHP)	0.0
CC02231	236.39
CC02218	109.95
CC15551	362.8
CA02205	495.18

A 4th order calibration curve is used with all 5 standards, as described in Section 2.

Standards flow for about 70 seconds before an observation is made.

1-c) AIR data:

There is considerable positive spiking in the air data. This is usually due to contamination by stack gas, and that assumption would certainly apply here. Much more troubling, though, is that the average value (for observations less than 368.0) is 367.61 ± 0.19 . The extrapolation from the Keeling South Pole data, would be 364.91, and if we add 3.0 ppm to the 1998.29 value for 68°S-61°S Tans data band we get 365.81. Both of these are very much below 367.9. Why?

To calculate $\Delta p\text{CO}_2$ we use the Keeling South Pole data, extrapolated to April 2000. The last observations in that file are for year 1997. A longterm trend is fitted to these observations, then extrapolated forward. Naturally, there is some uncertainty in this extrapolation, but it should only be about 1-2 ppm. I further have a simple linear interpolation for latitude north of 90°S which is applied. This value goes into the "air_tans," and "vco2_air" variables in the 0002sfc database.

1-d) Editing:

Generally, several criteria were used to reject data points:

- When the water flow dropped below 48 l/min.
- $T_{eq} > 4.0^\circ\text{C}$.
- Sample air flow > 50 or Sample air flow < 38 .
- $p\text{CO}_2 < 330$. (This is chosen after inspecting the data the first time though).
- TSG Temperature > 3.2
- $T_{eq} - \text{TSG Temperature} > 1.0$ OR < 0.4 .

Then individual observations and groups of observations are rejected. The criteria here is usually spikes in temperature, particularly where the temperature warms sharply. This normally implies some sort of flow problem, beyond what the water flow sensor is reporting. Salinity spikes also show flow and bubble problems, and that variable is used in a decision to reject observations. Of the 17,226 observations of seawater $p\text{CO}_2$ we rejected

1,581. One salinity observation was also rejected after all other editing steps. The program **editpco2.prg** performs this editing operation.

To create a 0002sfc.dbf surface format file, we use only ACCEPTED pCO₂ values, but ALL the data are retained in the pco2data.dbf database in the subdirectory: \NBPALMER\NBP00_2\SURFACE\PCO2DATA. We add Thermosalinograph temperature and salinity from the pco2data file, then the ship's barometric pressure (from JGxxx.dat) files, and estimate the air value from the Keeling South Pole database (as explained under 1-d) AIR data .

1-f) Estimating Temperatures:

There are periods where either the TEQ or TSG temperature was either missing or clearly wrong. Fortunately it seems that neither was out at the same time. In the beginning of the program **editpco2.prg** I use an offset between the two values to estimate one from the other. There is a plot showing that this offset can be described by a couple of constant values and one simple linear relationship against time. The difference is usually near 0.67-0.81°C.

1-g) Other Data:

The subdirectory navdata contains the merged jgXXX.dat files. These contain barometric pressure and wind speed as observed by the ship's sensors. We merged these data into the master file using julian date, and using the julian date just BEFORE our pCO₂ data were observed. This formed an offset of about 30 seconds between the barometric pressure and wind speed and the pCO₂ observation. Ship's barometric pressure was 1.8 ± 0.2 mbar higher on average than the equilibrator barometric pressure. This ship's barometric pressure was used with observed sea surface temperature, and salinity to calculate pCO₂ of air from the Keeling South Pole estimated VCO₂ assuming 100% relative humidity. Delta pCO₂ is the difference between our pCO₂ at SST and this pCO₂ of wet air.

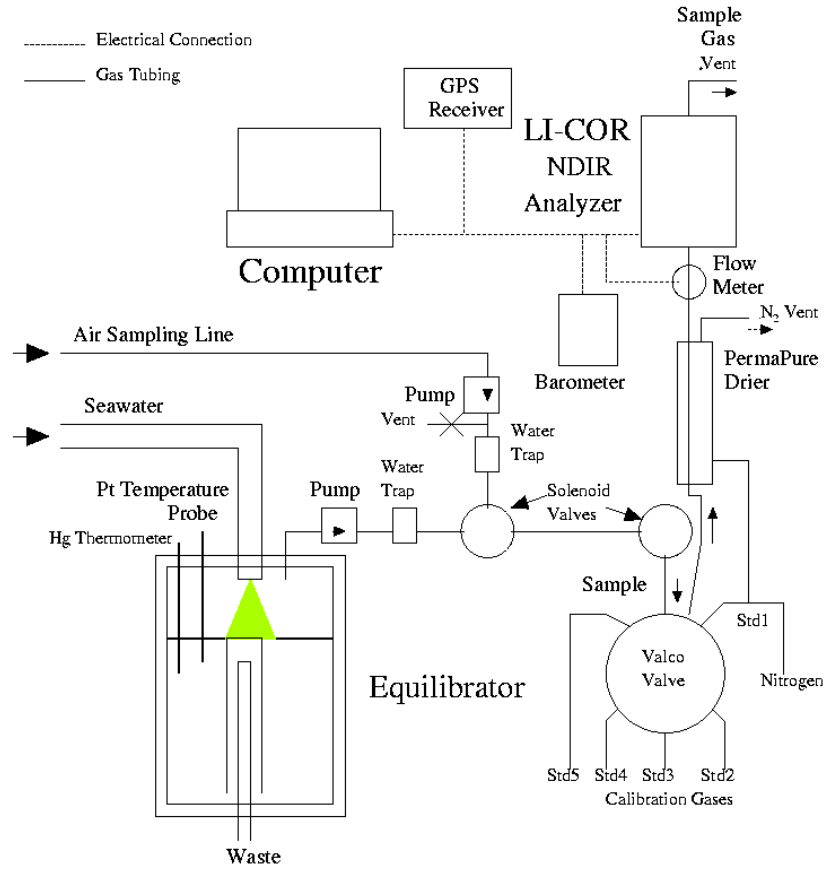
Wind speed units are meters seconds⁻¹.

2. MEASUREMENTS OF pCO₂ IN SURFACE WATERS

2-a) The LDEO Underway System for Surface Water pCO₂ Measurements:

The system for underway measurements of pCO₂ in surface waters consists of a) a water-air equilibrator, b) a non-dispersive infra-red CO₂ gas analyzer and c) a data logging system. The measurement system is schematically shown in Fig. 1, and is similar with the one described in Bates et al. (1998). Each of these units and the data reduction procedures used will be described below.

Figure 1 - The underway pCO₂ system used for the measurements of pCO₂ in surface waters during the Southern Ocean JGOFS (AESOP) Program.



2-b) Water-air Equilibrator:

The equilibrator has a total volume of about 30 liters and is equipped with a specially designed drain which maintains automatically the level of water in the equilibrator at a constant level at about half the height of the equilibrator leaving about 15 liters of headspace. Seawater from the ship's uncontaminated water line is continuously pumped into the equilibrator at a rate of about 10 liters/min, giving a mean residence time of water in the equilibrator of about 1.5 minutes. The headspace above the water serves as an equilibration chamber. A carrier gas (commonly marine air) is drawn into the chamber by a diaphragm pump, and exchanges CO₂ with a continuous flow of seawater sprayed into the chamber through a shower head. Because of large gas-water contact areas created by fine water droplets as well as gas bubbles in the pool of water, CO₂ equilibration between the carrier gas and seawater is achieved rapidly with a e-folding time of 2 to 3 minutes. Under normal operating conditions, the carrier gas in the equilibration chamber is pumped into the infra-red gas analyzer at a rate of about 50 ml/min. At this rate, the residence time of the carrier gas in the equilibration chamber is about 300 minutes, that is about 100 times as long as the equilibration time. Therefore, the carrier gas in the head space is always in equilibrium with water. The over all response time of the equilibrator system has been estimated to be of an order of several minutes. The large volume of water in the equilibrator is chosen in order to have a large thermal inertia of the equilibrator, so that the effects of room temperature changes on the equilibration temperature may be minimized. The temperature of water in the equilibrator is monitored continuously using a Guildline platinum resistance thermometer (readable to 0.05 °C) and recorded on the data logging computer. A calibrated mercury thermometer is also inserted in the equilibrator for testing the performance of the platinum thermometer.

At the gas intake end of the equilibrator, a flow indicator based on U-tube manometer is attached. This gives a visual confirmation for the fact that marine air is taken into the equilibration chamber at a desired flow rate. Since we operate the system with the equilibration chamber at the same pressure as the ambient room pressure, the total pressure, at which the gas was equilibrated, is measured using a precision electronic barometer (Setra Model 270, Action, MA) outside the equilibrator. This equilibration pressure is also logged on the computer.

The temperature and salinity of seawater at the in situ conditions were measured using a SeaBird Model SBE-21 thermosalinograph aboard the N. B. Palmer and a SIO/ODF thermosalinograph unit based on Neil Brown sensors aboard the R. Revelle. The precision of the report temperature data has been estimated to be about 0.005 °C.

2-c) Infra-red CO₂ Gas Analyzer:

The equilibrated gas was passed through a water trap (to collect aerosols and condensates), mass flow controller and a reverse flow naphion dryer (PermaPure flushed with pure nitrogen gas) to remove water vapor (to a level of -20°C), and was introduced into the IR sample cell at a rate of about 50 ml/min for CO₂ determinations. A LI-COR infra-red gas analyzer (Model 6251, Lincoln, NB) was used. After about 3 minutes of

purging period, the gas flow was stopped and readings were recorded on the computer. Although an electronic circuit was provided by the manufacturer in order to linearize the CO₂ response, it exhibited a few inflexions that deviated from linearity by a few ppm. Therefore, we chose not to use the outputs from the linearization circuit supplied by the manufacturer. Instead, we used five standard gas mixtures (one pure nitrogen and four CO₂-air mixtures) during the expeditions, and established response curves using the raw output from the analyzer. The CO₂ concentrations in the gas mixtures were calibrated using the SIO standards determined by C. D. Keeling's group using the manometric method. The concentrations of CO₂ in the standard gas mixtures were summarized above.

During normal operations, each of the standard gas mixtures was passed through the analyzer for 70 to 90 seconds at a rate of about 60 ml/min. This replaced the IR analyzer cell completely with the new gas. The flow was stopped for 5 seconds and then a millivolt reading from the analyzer was taken and recorded. Samples of equilibrated air and marine air were pumped through the analyzer for 180 seconds (3 minutes) at a rate of about 50 ml/min to purge the previous sample in the IR cell. The flow was stopped for 5 seconds and a reading for the analyzer output was recorded. This procedure was intended to eliminate errors due to fluctuations of the dynamic pressure within the IR cell by irregular gas flow rates. The slow flow rates used for samples were required for the removal of water vapor using the PermaPure membrane dryer. Between two sets of calibration runs using the five standard gases, 6 to 20 samples were analyzed depending upon the stability of the IR analyzer.

2-d) Data Logging System:

The following values were recorded on a laptop computer. The sample locations were derived from a GPS positioning unit that is a part of our surface water pCO₂ system. The CO₂ readings for samples were recorded once every 3 minutes (180 seconds), and those for the standard gas mixtures once every 1.5 minutes.

Date,

Time (GMT),

Latitude,

Longitude,

Sample ID (standard gas cylinder numbers, seawater CO₂, atmospheric CO₂)

Barometric pressure in the laboratory (to 0.1 mb)

IR cell temperature,

Gas flow rate in the IR cell (to 0.1 ml/min),

Temperature of equilibration (to 0.01 °C),

Analyzer output (millivolts to 0.1 mv)

CO₂ concentration in dry gas sample (preliminary based on the last response curve), and pCO₂ (preliminary value based on the last response curve).

2-e) Data Deduction Procedures:

The concentration of CO₂ in the sample was computed by the following way based on the millivolt reading and time of the reading. The millivolt reading taken for each of the five standard gases at the time of sample measurement was computed by linearly interpolating as a function of time using the readings taken before and after the respective standard gases were analyzed. This yields millivolt reading for each of the five standard gases at the time when the sample was analyzed. These five values were fit to a fourth-order polynomial equation (with five constants to be determined). This serves as the response curve. The CO₂ concentration in the sample was computed using the response curve that was established at the time of each sample analysis. This method has been demonstrated to yield more reliable CO₂ values compared with those computed, for example, using a least-squares fit of a quadratic or cubic functions to the five calibration points. The method described above yields atmospheric CO₂ values that are consistent with those reported for the South Pole and the Cape Grim by the Climate Monitoring and Diagnostics Laboratory/NOAA in Boulder, CO.

The partial pressure of CO₂ in seawater, (pCO₂)_{sw}, at the temperature of equilibration, T_{eq}, in the unit of microatmospheres (µatm) was computed using the expression:

$$(pCO_2)_{sw} @ T_{eq} = (V_{CO_2})_{eq} \times (P_b - P_w), \dots \dots \dots [1]$$

- (V_{CO₂})_{eq} = the mole fraction concentration (ppm) of CO₂ in the dried equilibrated carrier gas;
 P_b = the barometric pressure (that is equal to the total pressure of equilibration) in atmospheres; and
 P_w = the equilibrium water vapor pressure at T_{eq} (°C) and salinity.

The water vapor pressure was computed using the following formulation;

$$P_w \text{ (atm)} = (1/760) \times (1 - 5.368 \times 10^{-4} \times \text{Sal}) \times \text{EXP} \{ [0.0039476 - (1/TK)] / 1.8752 \times 10^{-4} \}, \dots \dots [2]$$

where Sal is salinity in PSU measured using the ship's thermosalinograph, and TK is the temperature of equilibration in °K.

The (pCO₂)_{sw} at the in situ temperature, T_{in situ}, was computed using a constant value of 0.0423 % per °C for the effect of temperature (Takahashi et al., 1993):

$$(pCO_2)_{sw} @ T_{in \text{ situ}} = (pCO_2)_{sw} @ T_{eq} \times \text{EXP}[0.0423 \times (T_{in \text{ situ}} - T_{eq})].$$

The value for T_{in situ} is taken to be the seawater temperature measured by the ship's thermosalinograph at the time of pCO₂ measurements. T_{eq} is generally warmer than T_{in situ} by 0.5 ~ 0.8 °C. Hence the temperature correction is normally less than 3% of pCO₂ values.

The over all precision of the reported $p\text{CO}_2$ sw values has been estimated to be about ± 1.5 uatm.

3. MEASUREMENTS OF $p\text{CO}_2$ IN THE ATMOSPHERE

3-a) Measurements:

The air measurement system is shown schematically in Fig. 1. Uncontaminated marine air samples were collected about 10 m above the sea surface using a DEKORON tubing (1/4" i.d., Calco Inc., PA), a thin-wall aluminum tubing protected by plastic casing. The intake was located at the middle of the foremast about 10 m above the sea surface. A KNF Neuberger air pump that was located near the IR analyzer was used to pump air through the tubing and into the IR analyzer. Even when air samples were not analyzed, the pump was on all the time to keep the air flowing through the sampling line. For the analysis, the air sample was passed through a water trap and a drying column to remove water vapor (the same PermaPure column as used for the equilibrated gas) and introduced into the IR cell for CO_2 analysis at a rate of about 50 ml/min. After 3 minutes of purging the cell, the flow was stopped for 5 seconds and the IR millivolt output reading was recorded.

3-b) Data Processing:

The partial pressure of CO_2 in the air, $(p\text{CO}_2)_{\text{air}}$, was computed in the unit of microatmospheres (μatm) in the same way as that for seawater using Eq. [3] below:

$$(p\text{CO}_2)_{\text{air}} = (V_{\text{CO}_2})_{\text{air}} \times (P_b - P_w), \dots \dots \dots [3]$$

$(V_{\text{CO}_2})_{\text{air}}$ = the mole fraction concentration (ppm) of CO_2 in the dried air sample;
 P_b = the barometric pressure at sea surface in atmospheres; and
 P_w = the equilibrium water vapor pressure at $T_{\text{in situ}}$ ($^{\circ}\text{C}$) and salinity given by Eq. [2].

The precision of the atmospheric $p\text{CO}_2$ values have been estimated to be about ± 1 μatm .

4. REFERENCES CITED

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