

# Carbon Dioxide in Surface Waters of the Pacific Ocean

## 1. Measurements of the Distribution<sup>1</sup>

CHARLES D. KEELING, NORRIS W. RAKESTRAW, AND LEE S. WATERMAN

*Scripps Institution of Oceanography  
University of California at San Diego, La Jolla*

**Abstract.** Direct measurements of carbon dioxide in surface waters of the Pacific Ocean from 30°N to 65°S indicate high concentration relative to atmospheric CO<sub>2</sub> in a broad belt near the equator and approaching the coast of South America. Elsewhere the concentration has been generally found to be nearly in equilibrium with the atmosphere or somewhat lower.

### INTRODUCTION

The partial pressure of CO<sub>2</sub> in discrete samples of ocean water has been determined extensively by means of wet-chemical techniques [Krogh, 1904; Wattenberg, 1933; Buch, 1934, 1939a, b, 1942; Deacon, 1940; Eriksson, 1959; and unpublished data from cruises of the *Vityaz*, 1957–1959]. Most of these measurements are so uncertain that they support only very broad generalities [Rankama and Sahama, 1950, p. 545]. Wattenberg's numerous and systematic measurements in the Atlantic Ocean during the Meteor Expedition of 1925–1927 [see Defant, 1961, pp. 80–83], however, reveal consistent patterns both at the ocean's surface and in the deeper waters.

During the International Geophysical Year, 1957–1958, the partial pressure of CO<sub>2</sub> in surface ocean water was for the first time measured continuously by a method of direct equilibration. The observing program was shared by several investigators [see Lill *et al.*, 1958], who monitored CO<sub>2</sub> with infrared gas analyzers on long north-south traverses under a wide range of oceanic conditions. Atmospheric CO<sub>2</sub> was also measured. Takahashi [1961] has published a survey of the Atlantic Ocean during the 14th cruise of the *Vema*. In the present paper we report a survey in the Pacific Ocean on Downwind Expedition from October to December 1957 and Monsoon Expedition from January to April 1961.

### EXPERIMENTAL PROCEDURE

Our survey of CO<sub>2</sub> in the Pacific Ocean followed, in general, the methods employed in the Atlantic Ocean by Takahashi [1961]. To measure atmospheric CO<sub>2</sub> near the ocean surface, we adhered closely to the procedure used at Mauna Loa Observatory, described by Pales and Keeling [1965]. Features specific to the Pacific Ocean survey are described below.

A nondispersive infrared gas analyzer was installed on the research vessel *Horizon* for Downwind Expedition and on the research vessel *Argo* for Monsoon Expedition. The analyzer, described by Smith [1953] was equipped, as at Mauna Loa Observatory, with a strip chart recorder to monitor continuously the concentration of CO<sub>2</sub> in parts per million of dry air (ppm). It was shock mounted to reduce the influence of the ship's vibration; the average amplitude of the recorder noise was kept within 1 ppm, as compared with 0.5 ppm under laboratory conditions on land.

*The air system.* Atmospheric CO<sub>2</sub> was measured directly by drawing in air at mast height (10 to 20 m above sea level) through intake cups protected against sea spray. Normally, the air streams from that pair of air lines, either forward or aft, most nearly upwind from the ship's smoke stack, were sampled alternately. The air was passed rapidly through polyethylene tubing on the weather decks and then through copper tubing inside the ship. Air flow of 1 to 2 l/min was maintained by connecting each line to the suction side of a rubber diaphragm pump and partially venting through a relief valve on the pressure side. To remove

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water vapor the line selected for sampling was shunted with a solenoid valve through a cold trap maintained near  $-50^{\circ}\text{C}$  by a refrigerator. The air was then rewarmed to ambient temperature, passed through the analyzer cell, and vented.

*The equilibrator system.* The  $\text{CO}_2$  in surface water was determined by recording the concentration of  $\text{CO}_2$  in a closed volume of air which was circulated so as to be in nearly continuous equilibrium with a constantly renewed supply of sea water. The water was pumped continuously from an intake in the ship's hull 2 to 3 m below the water surface, through the equilibrator, and then discarded. For Downwind Expedition the equilibrator was constructed after a design of Levine *et al.* [1956]. For Monsoon Expedition a simpler design (Figure 1) similar to that of Takahashi [1961] was adopted. Air was continuously circulated in a closed loop containing a rubber diaphragm pump, flow gage, the equilibrator (a 20-liter glass jar with a shower head water sprayer), and a cold trap. With a network of automatically operated solenoid valves, air in the equilibrator loop could be shunted into a second circuit, which included the measuring cell of the  $\text{CO}_2$  analyzer, without interrupting the flow and with no loss of gas.

The sequence of sampling was controlled electrically by a timer and a plug board selec-

tor. During Downwind Expedition, the sampling cycle consisted of 5 min of reference gas (see below), 5 min of air, and 20 min of equilibrated air. For Monsoon Expedition, because of more rapid response by the equilibrator, a 20-min sequence of 5 min of reference gas, 5 min of air, and 10 min of equilibrated air was used. By recording in sequence the concentration of  $\text{CO}_2$  in atmospheric air, in equilibrated air, and in reference gas, an almost continuous record could be made of the concentration of  $\text{CO}_2$  in the atmosphere and in the surface water through which the ship was passing.

Whenever the equilibrator was not operated, a 30-min sequence was employed which consisted of 10 min from each of two air lines followed by 10 min of reference gas.

The concentration of  $\text{CO}_2$  in seawater is highly dependent upon temperature [Harvey, 1955; Kanwisher, 1960; Takahashi, 1961], and the design of the apparatus used on Downwind Expedition did not provide as close a temperature control as desirable. Corrections based on the tables of Harvey [1955] generally amounted to 3 to 5 ppm. Consequently the results for the water are not as accurate as those for the atmosphere. On Monsoon Expedition the temperature change from outside the ship to the equilibrator was kept so small (less than  $0.5^{\circ}\text{C}$ ) that little error was introduced. The relative accuracy of the data for the water during Downwind Expedition is about  $\pm 5$  ppm, during Monsoon Expedition,  $\pm 3$  ppm. The relative accuracy of the atmospheric measurements is about  $\pm 1$  ppm. The relative accuracy of the difference between the air and water values is approximately equal to that of the water measurements.

*Reference gas.* For calibration of the analyzer and for comparison with atmospheric and equilibrated air, mixtures of  $\text{CO}_2$  in nitrogen were used as at Mauna Loa Observatory [Pales and Keeling, 1965]. Approximately every three days, measurements were interrupted for several hours and the sensitivity of the apparatus was determined by repeatedly comparing two or more reference gases. The concentrations of all reference gases were determined in the laboratory before and after use on the respective expeditions. The final concentration values are accurate to approximately  $\pm 0.2$  ppm.

*Relationship of concentration to partial pres-*

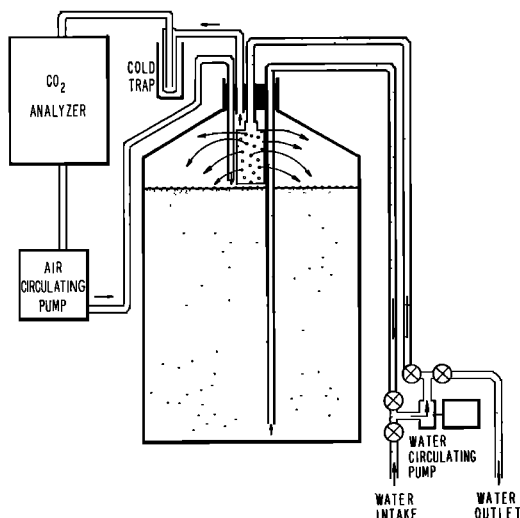


Fig. 1. Air-water flow system to equilibrate sea water as used on Monsoon Expedition.

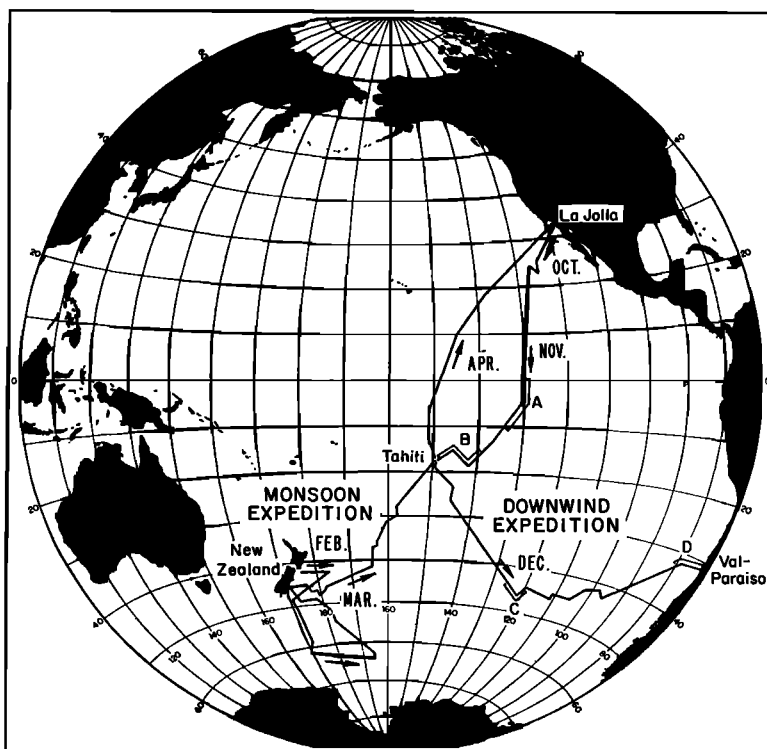


Fig. 2. Ship track for Downwind Expedition of 1957 and for Monsoon Expedition of 1961.

*sure*. The concentration of  $\text{CO}_2$  in the air and sea water, as reported below, is expressed as a volume fraction (mixing ratio) in parts per million. This quantity, denoted by  $\mu_{\text{CO}_2}$ , is related to the partial pressure of  $\text{CO}_2$ ,  $p_{\text{CO}_2}$ , by the relation

$$\mu_{\text{CO}_2} = p_{\text{CO}_2}/P$$

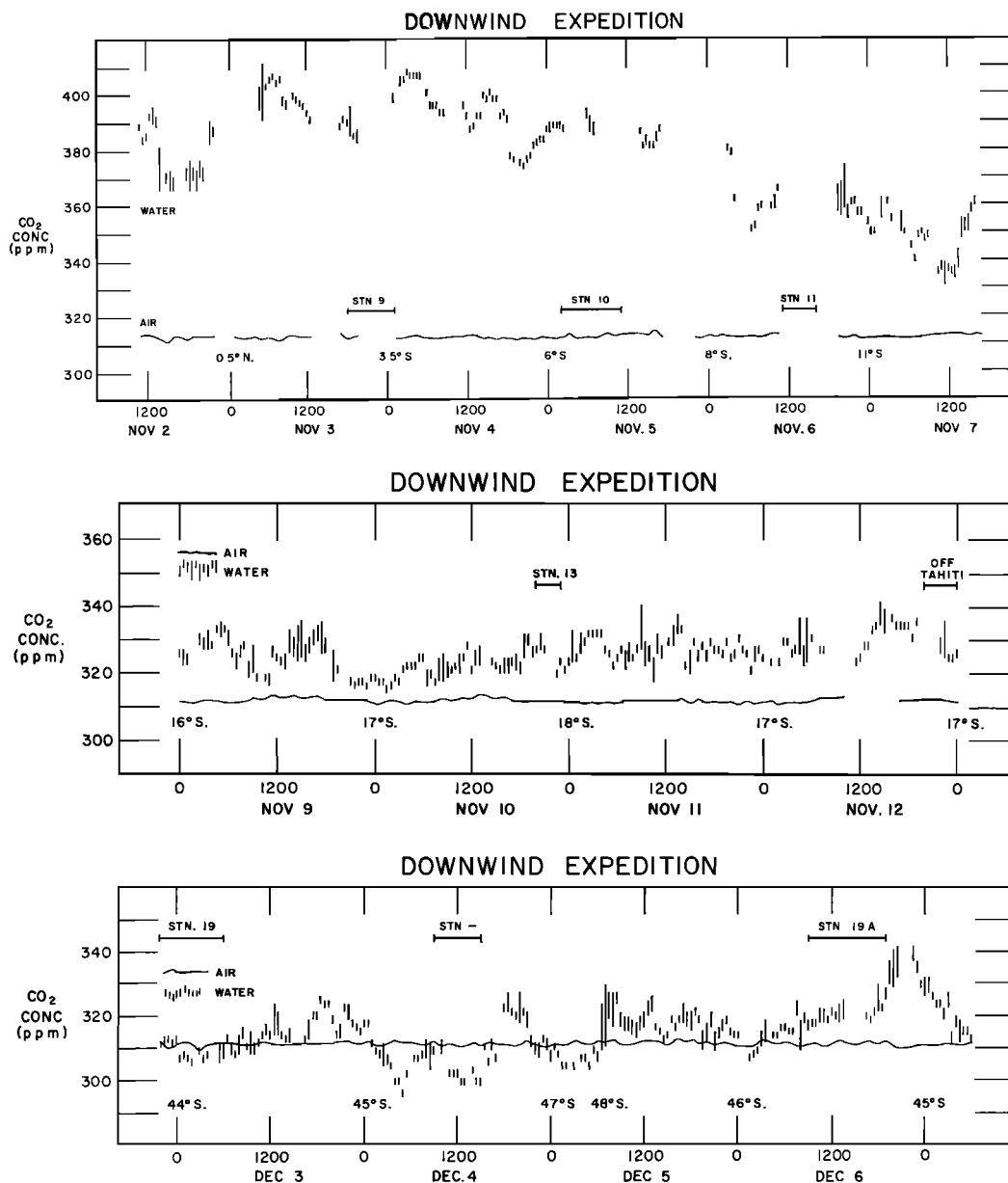
where  $P$  is the total pressure exerted in the atmosphere or sea water by the gases which pass through the infrared gas analyzer.

In our experiments each gas stream (air, air equilibrated with sea water, or reference gas) before infrared analysis was passed through a water vapor trap and was brought to ambient pressure. Since the vapor pressure of water as a contributor to the ambient pressure always remained approximately constant during any 30-min sequence of sampling, variations in water vapor pressure could have no influence on  $\mu_{\text{CO}_2}$  as determined directly from the strip chart records of the analyzer.

In computing  $p_{\text{CO}_2}$  for atmospheric air, the total gas pressure should be equated to the pres-

sure of the dry air column as determined by the barometric pressure and the absolute humidity. On both expeditions these quantities were monitored at frequent intervals (the humidity by the wet bulb-dry bulb technique) but the data are not reported here because, to an approximation sufficiently accurate for most purposes, the barometric pressure can be assumed to be 1 atm and the humidity can be calculated on the assumption that the air was saturated at the average air temperature, as reported in Tables 1 and 2.

To compute  $p_{\text{CO}_2}$  for sea water it is necessary to measure, or predict, the pressure exerted in the equilibrator by all the noncondensable gases dissolved in the water. Two factors must be considered: (1) Whether these gases were close to equilibrium with the atmosphere at the ocean surface. (2) Whether, with respect to these gases, equilibrium was achieved. In reference to the first factor, we made no precise concentration measurements of dissolved gases other than  $\text{CO}_2$ . Determination of dissolved oxygen by the Winkler method [Barnes, 1959,



Figs. 3 to 5. The concentration of CO<sub>2</sub> near the sea surface, in the atmosphere, and in sea-water, plotted versus local time, for selected portions of Downwind Expedition. The roughly horizontal line is the atmospheric concentration versus time; the vertical lines indicate the observed range in the corrected concentration in the equilibrated air (very nearly proportional to the partial pressure of CO<sub>2</sub> in the water) during a single measuring period of 10 to 20 minutes. The ship's latitude is shown for 0000 hours each day above the time axis. Time intervals when the ship was on station are shown by horizontal lines above the air trace and are referenced to the original expedition station numbers. Data were taken along A for Figure 3, along B for Figure 4, and along C for Figure 5 (see Figure 2).

p. 178] indicate that equilibrium with respect to atmospheric oxygen existed within experimental accuracy (about  $\pm 5\%$ ) during both expeditions. The limited available evidence suggests that nitrogen and argon are usually close to equilibrium at the ocean surface [Rakestraw and Emmel, 1938; Benson and Parker, 1961]. In reference to the second factor, equilibrium of  $\text{CO}_2$  in water is relatively slow because  $\text{CO}_2$  chemically reacts with the water [Hood, 1963 p. 132]. The atmospheric gases which measurably affect the total pressure in the equilibrator do not react with water and should equilibrate faster than  $\text{CO}_2$ . This prediction is supported by our observation that values of  $\mu_{\text{CO}_2}$  in sea water showed no relation to whether we began the equilibration with air (78%  $\text{N}_2$ ) or with reference gas ( $>99\%$   $\text{N}_2$ ). To an approximation, again sufficiently accurate for most purposes,  $p_{\text{CO}_2}$  can be computed for the water by equating the total gas pressure,  $P$ , to the value used to compute  $p_{\text{CO}_2}$  for air.

#### DESCRIPTION OF THE CONTINUOUS DATA

For the Downwind Expedition of 1957 the data are continuous throughout the track shown in Figure 2 except for short periods when the instrument was being repaired or calibrated.

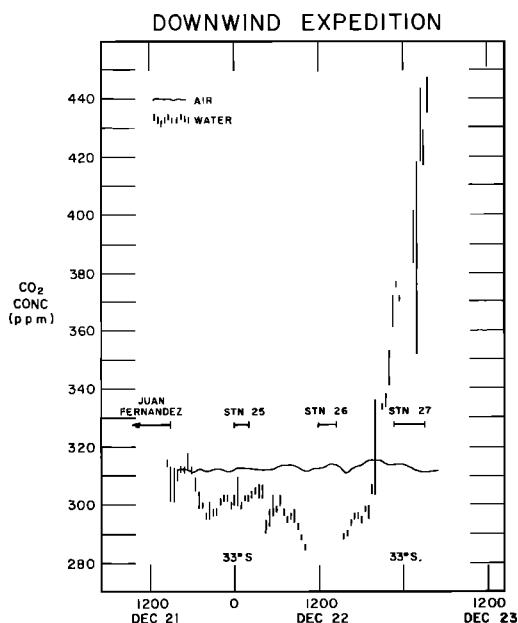


Fig. 6. See legend of Figures 3-5. Data taken along *D* in Figure 2.

Segments marked *A*, *B*, *C*, *D* are sections from which detailed plots of the data have been prepared. For Monsoon Expedition the atmospheric data are nearly continuous, but the equilibrator was operated only about 30% of the time during each 24-hour period (see Figure 2). No detailed plots are shown for these periods.

In section *A* (Figure 3) the water was markedly supersaturated (saturation is with respect to the contemporary atmosphere at the sea surface) throughout the section, peak values occurring close to the equator. The range in observed concentration in water during a single 20-min period was often considerable. Sometimes this was clearly due to actual differences in the water during measurement; at other times it may have been due to experimental error. The ship's course was predominantly north to south. Section *B* (Figure 4) continues the record after a lapse of  $1\frac{1}{2}$  days. The ship's course was predominantly westward, toward Tahiti. The supersaturation had fallen to a low average value with minor oscillations and no long-term trend. Section *C* (Figure 5), which covers the southernmost position of the ship, is similar to section *B*, but the minor oscillations are more distinct. Some of the water was slightly undersaturated. In section *D* (Figure 6) the ship was proceeding eastward toward Valparaiso, Chile. At first the  $\text{CO}_2$  in the water and atmosphere was close to equilibrium, but on approaching the South American coast the ship got into the Peru current, where the concentration in the water rose rapidly to a level 50% higher than in the atmosphere, strong evidence for the upwelling of deep water.

Some measurements of  $\text{CO}_2$  in subsurface water were made, to a maximum depth of about 125 m. The concentration increased with depth, sometimes very considerably. The data were too few to evaluate and are not further discussed here.

No regular diurnal changes were discovered, but when the results from both expeditions are surveyed a very clear influence of latitude is observed. The results are assembled in Table 1 and illustrated in Figure 7 for Downwind Expedition and in Table 2 and Figure 8 for Monsoon Expedition. The values for  $\text{CO}_2$  in the air and water have been averaged for every  $2\frac{1}{2}^\circ$  of latitude. The atmospheric values appear as

an almost straight horizontal line. Several features show clearly on first inspection: (1) the reproducibility on each individual expedition of the traces in the southern latitudes (on Downwind Expedition, between 30° and 40°, two sections of the ship's track diverged by several thousand kilometers); (2) the lack of symmetry between the two hemispheres; (3) the very sharp increase in the tropical latitudes.

## DISCUSSION

*Rankama and Sahama* [1950, p. 544] assert that the atmosphere and the ocean with respect to CO<sub>2</sub> tend to 'regulate each other.' This paradoxical conclusion results from an appraisal of the measurements of *Buch* [1934, 1939a, b, 1942], which indicate a range of CO<sub>2</sub> concentrations in the atmosphere as large as that observed in surface ocean waters (up to 100 ppm).

TABLE 1. Summary of the Analyses of Air and Water on Downwind Expedition

Latitude Interval	Time Interval, month, day, hour (local time)	CO <sub>2</sub> in Air		CO <sub>2</sub> in Water		Water Temperature	
		No. of Measur.	Av. Conc., ppm	No. of Measur.	Av. Conc., ppm	No. of Measur.	Av. Temp., °C
°N	1957						
27.5-30.0	10/21/1900-10/23/1000	90	311.5	35	346.2	15	20.3
25.0-27.5	10/23/1100-10/24/1700	63	310.8	50	337.8	24	21.5
22.5-25.0	10/24/1800-10/25/1100	10	311.5	8	330.8	7	22.8
20.0-22.5	10/25/1200-10/26/0000	40	311.0	21	331.0	12	22.9
17.5-20.0	10/26/0100-10/27/1400	92	310.5	52	333.6	32	25.0
15.0-17.5	10/27/1500-10/28/0300	28	310.8	17	332.1	9	25.8
12.5-15.0	10/28/0400-10/29/0500	19	310.2	11	335.3	6	27.0
10.0-12.5	10/29/0600-10/30/0500	45	310.9	27	335.9	19	27.3
7.5-10.0	10/30/0600-10/31/0000	19	311.8	25	321.1	12	27.5
5.0-7.5	10/31/0100-11/ 1/0900	145	312.2	33	328.7	11	27.9
2.5-5.0	11/ 1/1000-11/ 2/1000	41	312.3	5	384.6	2	26.3
0-2.5	11/ 2/1100-11/ 3/0300	28	312.7	12	379.0	7	26.7
°S							
0-2.5	11/ 3/0400-11/ 3/1300	25	312.2	12	400.3	8	26.2
2.5-5.0	11/ 3/1400-11/ 4/1300	37	312.6	19	397.2	13	26.2
5.0-7.5	11/ 4/1400-11/ 5/1800	62	312.2	25	389.9	14	26.7
7.5-10.0	11/ 5/1900-11/ 6/1700	23	312.7	10	364.8	5	26.9
10.0-12.5	11/ 6/1800-11/ 7/0600	19	312.1	7	358.2	6	27.1
12.5-15.0	11/ 7/0700-11/ 8/0700	32	312.8	18	345.4	10	27.3
15.0-17.5	11/ 8/0800-11/ 9/0000						
	11/11/2300-11/13/0000	58	312.2	32	330.5	29	27.2
17.5-20.0	11/ 9/0100-11/11/2200						
	11/19/1000-11/20/1100	243	312.0	127	325.2	71	26.6
20.0-22.5	11/20/1200-11/21/1400	63	311.7	39	313.7	19	25.9
22.5-25.0	11/21/1500-11/23/0500	43	311.2	35	306.4	12	24.5
25.0-27.5	11/23/0600-11/24/1900	6	311.8	33	312.6	2	23.1
27.5-30.0	11/24/2000-11/26/1300	37	311.7	48	306.8	8	21.1
30.0-32.5	11/26/1400-11/27/0400	48	311.8	23	306.2	13	20.3
32.5-35.0	11/27/0500-11/28/1700	110	311.8	44	310.6	20	17.7
35.0-37.5	11/28/1800-11/29/1200	21	312.2	23	319.3	7	16.2
37.5-40.0	11/29/1300-11/30/0500	29	311.3	26	323.0	10	14.4
40.0-42.5	11/30/0600-12/ 1/1500	48	311.7	42	317.5	15	13.0
42.5-45.0	12/ 1/1600-12/ 3/1400	92	311.7	77	313.5	41	10.6
45.0-47.5	12/ 3/1500-12/ 5/0200	57	311.4	60	311.1	32	8.6
47.5-50.0	12/ 5/0300-12/ 5/1200	17	311.7	18	314.8	10	7.8
45.0-47.5	12/ 5/1300-12/10/0600	174	311.4	192	318.6	92	8.9
47.5-45.0	12/10/0700-12/13/0000						
	12/14/0100-12/16/0000	157	311.6	151	317.0	72	10.8
40.0-42.5	12/13/0100-12/14/0000						
	12/16/0100-12/18/1300	98	312.4	99	319.2	50	12.7
37.5-40.0	12/18/1400-12/19/1300	34	313.4	33	328.3	18	16.4
35.0-37.5	12/19/1400-12/20/1000	30	313.2	21	328.2	9	18.3
32.5-35.0	12/20/1100-12/23/0600	97	313.0	59	307.9	25	17.7

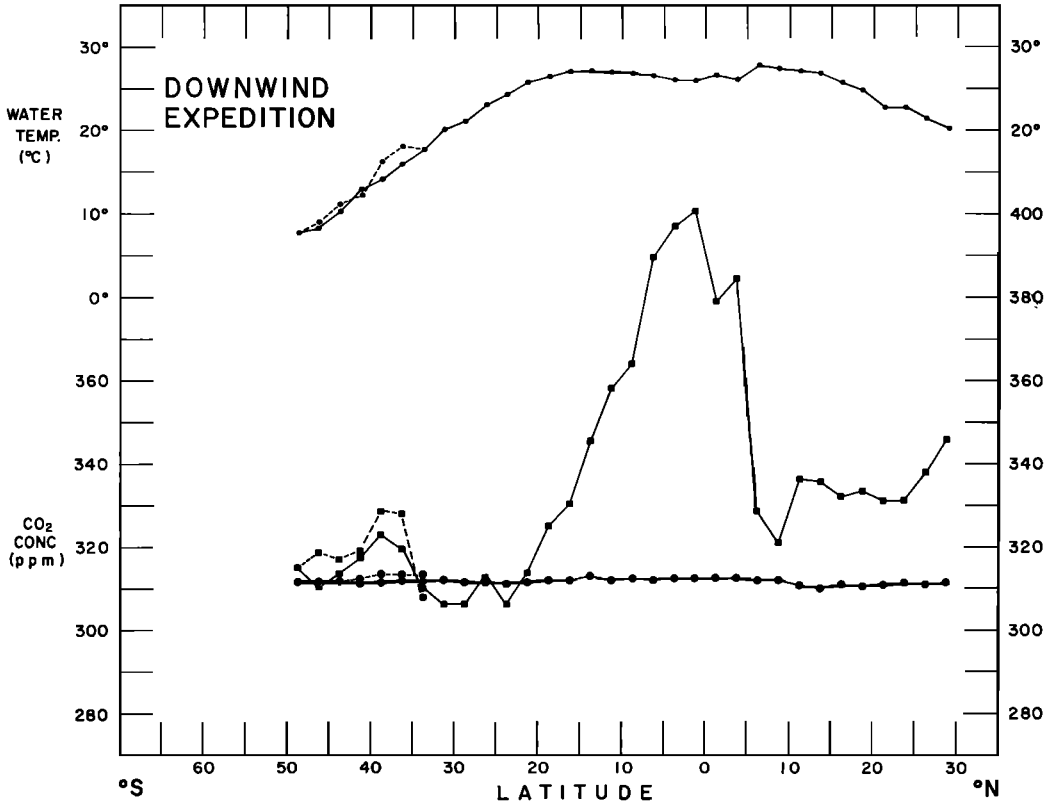


Fig. 7. The concentration of  $\text{CO}_2$  near the ocean surface in the atmosphere ( $\circ$ ), and in sea water ( $\blacksquare$ ), as a function of latitude for Downwind Expedition. The dashed line pertains to the northward part of the voyage (see Figure 2).

Buch's range in atmospheric values is not substantiated by recent measurements, summarized in Figure 9. Near the equator, for example, the concentration of  $\text{CO}_2$  in the atmosphere is about 1 ppm above the average atmospheric concentration. This compares with a supersaturation of nearly 100 ppm in the water (Figures 7 and 8). Supersaturation here can only be a result of processes which occur in the water, essentially independent of the small atmospheric variation. Recent data for other regions, though less complete, clearly support a similar conclusion.

To establish *how* the observed  $\text{CO}_2$  distribution in the water is produced is less simple. For the equatorial Pacific Ocean the observed hydrographic data and ocean currents have been discussed by *Knauss* [1960]. The distribution of

oxygen gas in a vertical section at  $140^\circ\text{W}$  (a longitude approximately midway between the Downwind and Monsoon equatorial crossings) is shown in Figure 10. The displacement of lines of constant oxygen concentration between  $2^\circ\text{N}$  and  $2^\circ\text{S}$  relative to higher latitudes can be explained either by vertical turbulence associated with the eastward undercurrent (shown by dashed lines) or by downward flow below, and upward flow above, a level near 100 meters, or a combination of both processes.

Data on the subsurface distribution of  $\text{CO}_2$  in the Pacific Ocean are meager. The only reliable fact is that the concentration tends to increase markedly with depth in the first few hundred meters largely because of the decomposition of dead organisms which have sunk from the overlying surface water [*Defant*, 1961, pp. 79–

TABLE 2. Summary of the Analyses of Air and Water on Monsoon Expedition

Latitude Interval	Time Interval, month, day, hour (local time)	CO <sub>2</sub> in Air		CO <sub>2</sub> in Water		Water Temperature	
		No. of Measur.	Av. Conc., ppm	No. of Measur.	Av. Conc., ppm	No. of Measur.	Av. Temp., °C
°S	1961						
42.5-45.0	1/31/1900- 2/ 2/0900	75	314.3	22	271.6	13	14.3
45.0-47.5							
47.5-50.0	2/ 4/1100- 2/ 4/1600			10	286.7	5	11.2
50.0-52.5	2/ 4/1700- 2/ 5/1700			17	296.4	10	10.3
52.5-55.0	2/ 5/1800- 2/ 6/0500			11	290.5	5	9.1
55.0-57.5	2/ 6/0600- 2/ 6/1900			15	306.6	8	6.3
57.5-60.0	2/ 6/2000- 2/ 9/0700	70	312.8	15	306.2	9	6.5
60.0-62.5	2/ 9/0800- 2/10/0300	61	313.0	9	316.3	6	4.4
62.5-65.0	2/10/0400- 2/14/1200	162	314.2	32	329.6	15	1.8
60.0-62.5	2/14/1300- 2/15/1100	55	314.3	29	313.8	10	2.7
57.5-60.0	2/15/1200- 2/10/1600	65	314.2	22	313.2	10	6.0
55.0-57.5	2/16/1700- 2/17/1600	52	313.9	40	318.1	15	8.0
52.5-55.0	2/17/1700- 2/19/1100	122	313.4	32	300.8	10	9.1
50.0-52.5	2/19/1200- 2/20/1200	91	313.1	20	302.2	9	8.7
47.5-50.0	2/20/1300- 2/22/0000	70	313.0	15	286.4	6	10.4
45.0-47.5	2/22/0100- 2/22/1800						
	2/26/0800- 3/ 1/0700	286	311.4	76	276.5	29	13.0
42.5-45.0	3/ 1/0800- 3/ 2/0700	68	312.0	13	281.9	6	16.5
40.0-42.5	3/ 2/0800- 3/ 4/0500	136	313.0	37	303.6	14	17.4
37.5-40.0	3/ 4/0600- 3/ 5/0700	80	312.4	8	315.7	3	18.1
35.0-37.5	3/ 5/0800- 3/ 7/0200	120	312.4	35	329.0	11	20.3
32.5-35.0	3/ 7/0300- 3/ 8/1800	112	313.7	35	327.2	12	21.3
30.0-32.5	3/ 8/1900- 3/ 9/1600	59	314.0	23	335.5	9	23.3
27.5-30.0	3/ 9/1700- 3/10/1600	67	313.3	28	324.8	11	25.5
25.0-27.5	3/10/1700- 3/13/0000	104	313.1	44	312.2	17	26.9
22.5-25.0	3/13/0100- 3/13/1600	33	314.5	19	312.3	7	27.0
20.0-22.5	3/13/1700- 3/14/1300	35	315.0	20	312.6	7	27.6
17.5-20.0	3/14/1400- 3/15/0800	27	314.8	25	307.3	10	27.4
15.0-17.5	3/23/1400- 3/24/0400	36	316.7	13	310.7	5	28.1
12.5-15.0	3/24/0500- 3/25/0300	68	316.1	21	315.3	8	28.3
10.0-12.5	3/25/0400- 3/25/1900	46	315.6	19	326.8	7	28.9
7.5-10.0	3/25/2000- 3/26/2000	66	315.7	25	332.2	10	28.6
5.0- 7.5	3/26/2100- 3/28/0200	84	316.0	25	363.3	10	28.3
2.5- 5.0	3/28/0300- 3/29/1300	88	315.6	55	387.2	20	28.1
0- 2.5	3/29/1400- 3/30/1700	75	316.0	44	385.9	15	27.2
Equator	3/30/1800- 4/ 1/0100	43	315.1	17	398.0	7	26.2
°N							
0- 2.5	4/ 1/0200- 4/ 2/0000	47	316.3	27	377.7	10	26.3
2.5- 5.0	4/ 2/0100- 4/ 2/1600	46	316.1	43	338.2	13	27.0
5.0- 7.5	4/ 2/1700- 4/ 4/0100	56	316.4	31	338.6	13	26.7
7.5-10.0	4/ 4/0200- 4/ 5/1900	36	316.6	35	317.6	13	25.9
10.0-12.5	4/ 5/2000- 4/ 7/2300	95	316.6	79	310.1	29	25.2
12.5-15.0	4/ 8/0000- 4/ 9/1100	31	316.4	32	304.7	12	24.2
15.0-17.5	4/ 9/1200- 4/11/1100	132	316.8	57	296.3	22	22.9
17.5-20.0	4/11/1200- 4/12/2100	66	317.2	65	280.8	24	21.3
20.0-22.5	4/12/2200- 4/13/1600	33	317.2	36	286.3	13	20.2
22.5-25.0	4/13/1700- 4/14/2000	36	317.1	35	298.5	13	18.9
25.0-27.5	4/14/2100- 4/15/1900	49	317.7	50	305.1	18	17.9
27.5-30.0	4/15/2000- 4/16/1900	36	318.4	24	308.6	9	16.4
30.0-32.5	4/16/2000- 4/17/1300	42	317.3	31	304.9	12	15.2

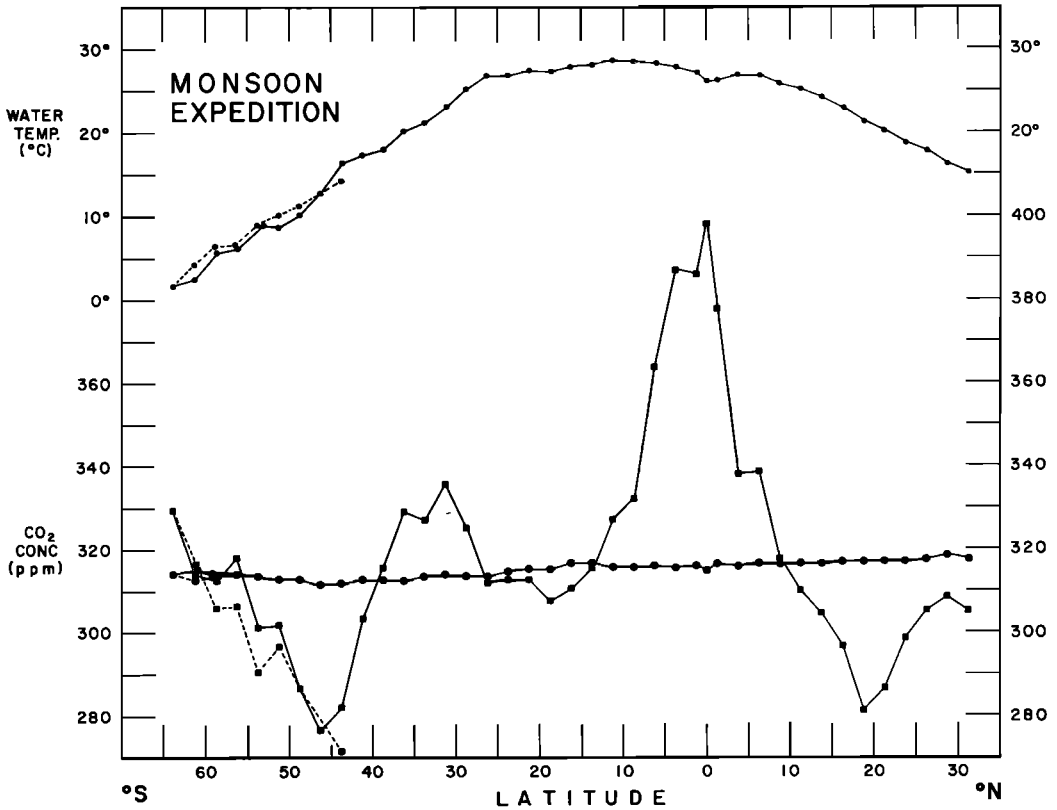


Fig. 8. The concentration of  $\text{CO}_2$  near the ocean surface in the atmosphere ( $\circ$ ), and in sea water ( $\blacksquare$ ), as a function of latitude for Monsoon Expedition. The dashed line pertains to the southward part of the voyage (see Figure 2).

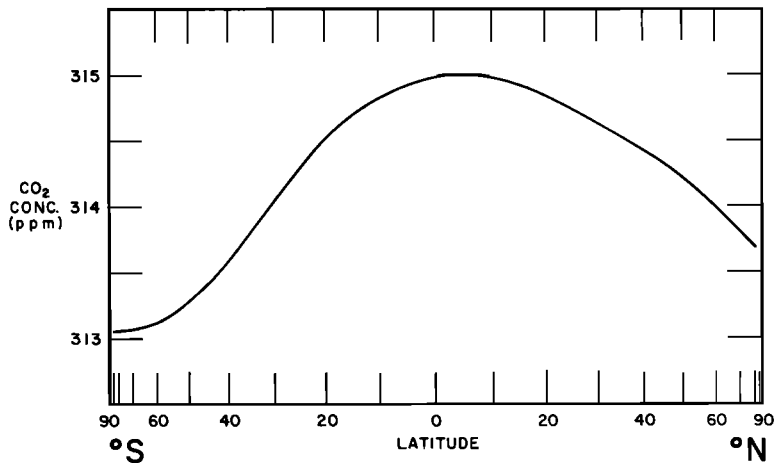


Fig. 9. Smoothed plot of the time-average concentration of atmospheric  $\text{CO}_2$  over the Pacific Ocean as a function of latitude [after Bolin and Keeling, 1963, p. 3913].

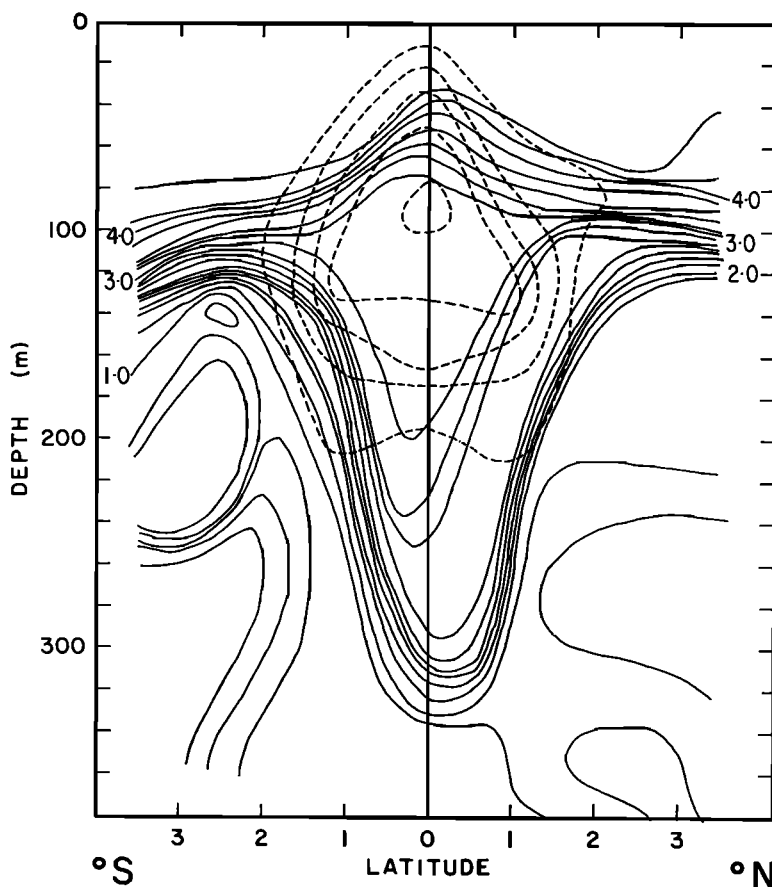


Fig. 10. Velocity cross section (dashed lines) superimposed on oxygen cross section for 140°W [after Knauss, 1960, p. 279]. Velocity contours are 25 to 125 cm/sec.

80]. For example, the variation with depth near 175°W is shown in Figure 11.<sup>2</sup> If a roughly similar variation with depth extends eastward, whatever transport process produces the distribution of temperature and oxygen shown in Figure 10 will also transport CO<sub>2</sub> upward and promote supersaturation in the surface water.

If the atmosphere and ocean are in dynamic equilibrium [Sverdrup *et al.*, 1942, p. 160], which is plausible to assume for a feature as large as that under discussion, the continual loss of CO<sub>2</sub> from the ocean to the atmosphere near the equator must be balanced by a gain elsewhere. The local cycle of CO<sub>2</sub> produced by

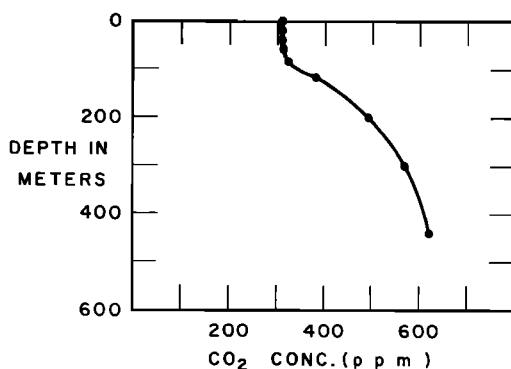


Fig. 11. The average concentration of CO<sub>2</sub> in sea water as a function of depth between 7°N and 7°S near 175°W. Data from Cruise 26 of the *Vityaz* in 1958. The individual data scatter too much to establish a vertical cross section.

<sup>2</sup> From original values submitted to the U. S. Oceanographic Data Center, Washington, D. C.

sinking organisms and vertical motion of the water will promote a steady loss of  $\text{CO}_2$  at the surface only as long as  $\text{CO}_2$  is transported into the regions from the outside. But, since the region of surface supersaturation, according to Figures 7 and 8, is very broad (15 to 20° wide), the source of atmospheric  $\text{CO}_2$  to replenish the equatorial water must be at considerable distance. Its location and the transport path are certainly of interest but cannot be determined without adding greatly to the present data.

For other regions of the Pacific Ocean our information is too incomplete to justify any discussion.

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