La mer 32: 167–172, 1994
Société franco-japonaise d'océanographie, Tokyo

Some Indications of Excess CO_2 Penetration near Cape Adare off the Ross Sea*

Chen-Tung Arthur CHEN

Abstract: The Antarctic Bottom Water (AABW) is generally believed to be formed in the Weddell Sea. It contains little anthropogenic CO_2. The role of the Ross Sea as a sink for excess CO_2 is perhaps even smaller as it contributes much less to AABW than does the Weddell Sea. On the other hand, I have reported earlier that excess CO_2 is found on the shelf around the Antarctica. Excess CO_2 is also found to penetrate rather deeply off Cape Adare at the northwest corner of the Ross Sea. I report here more detailed analysis using the GEOSECS, International Geophysical Year and the R/V Polar Sea data.

1. Introduction

Thermohaline circulation transports warm water poleward from low latitudes. As surface waters cool, their capacity to absorb CO_2 from the atmosphere increases and they act as a sink for anthropogenic CO_2. The ability of the North Atlantic Deep Water to absorb the excess CO_2 has been demonstrated (CHEN, 1982, 1987) but the situation is somewhat different in the Southern Ocean where the Antarctic Bottom Water (AABW) plays a major role. The AABW is generally believed to be formed in the Weddell Sea. Sea ice, however, blocks the air-sea exchange of gases thus limits the influx of excess CO_2 to the surface water. The upwelled Weddell Sea Deep Water (WSDW) dilutes the anthropogenic CO_2 concentration in the surface water, which then mixes with the Weddell Sea Shelf Water and more WSDW to from AABW. Since the WSDW probably was formed before industrialization and the surface water is also deficient in excess CO_2, the AABW contains little anthropogenic CO_2 (6 ± 5 μmol kg^{-1}) (CHEN and POISSON, 1984, POISSON and CHEN, 1987). As a result, the Weddell Sea is not a major sink for excess CO_2 (CHEN and RODMAN, 1990; CHEN, 1991).

The role of the Ross Sea as a sink for excess CO_2 is perhaps even smaller as it contributes much less to AABW than does the Weddell Sea. Recent data, however, indicates that freons have penetrated throughout the shelf area and have even appeared near the base of the continental slope at depths of 2.5 to 3.0 km. This is a good indication of newly formed AABW (MICHEL *et al.*, 1985; TRUMBORE *et al.*, 1991) which may carry some excess CO_2.

CHEN (1982) reported earlier that excess CO_2 is found on the shelf around the Antarctica. Excess CO_2 is also found to penetrate rather deeply off Cape Adare at the northwest corner of the Ross Sea (CHEN, 1987; 1993a). I report here more detailed analysis using the GEOSECS and International Geophysical Year (IGY) data. The R/V Polar Sea (JACOBS *et al.*, 1989) CO_2 data are spaced too far apart vertically and can not be used to estimate the excess CO_2 signal. The chlorofluorocarbons (CFCs) collected during the R/V Polar Sea cruise are, however, quite usefull for tracing newly formed waters. To my knowledge no other CO_2 or tracer data are available. The station locations are given in Fig. 1.

2. Method

The method of excess CO_2 computation and its limitations have been described in detail elsewhere (CHEN and MILLERO, 1979; CHEN and PYTKOWICZ, 1979; CHEN *et al.*, 1982: CHEN, 1982, 1984: CLINE *et al.*, 1985). The method involves a back-calculation of the CO_2 concentration of a parcel of seawater to its initial concentration at the sea surface by correcting

* Received June 30, 1994
** Institute of Marine Geology, National Sun Yat-Sen University, Kaohsiung, Taiwan, R.O.C.

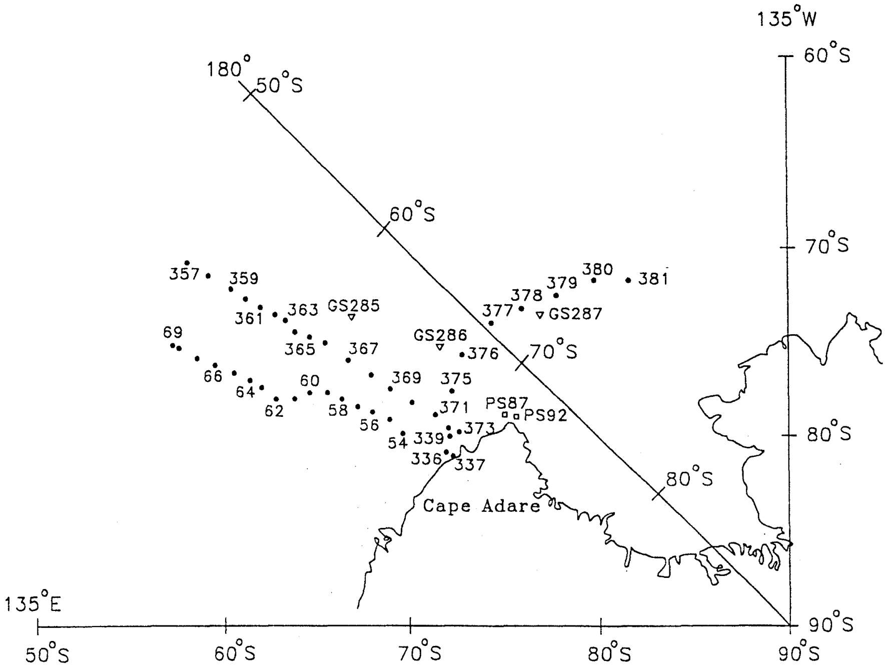

Fig. 1. Station locations in the study area (▽ GEOSECS; ● IGY; □ Polar Sea).

for changes due to the decomposition of organic material and dissolution of carbonate tests.

Specifically, the method assumes that a water parcel maintains a fixed degree of saturation with respect to atomospheric CO_2 at the sea surface. Respiration and carbonate dissolution add carbon dioxide to the water parcel after it sinks. The respiration induced increase in CO_2 can be calculated from the oxygen data using Redfield ratio (REDFIELD *et al.*, 1963) while CO_2 changes due to carbonate dissolution can be calculated from the alkalinity changes. By correcting the CO_2 data for these changes, estimates can be made of the CO_2 concentration of the water parcel when it was last in contact with the atmosphere. These back calculated CO_2 concentrations of waters with various ages are then compared with each other and with the contemporary surface CO_2 concentrations to obtain the oceanic CO_2 increase.

3. Results and Discussion

Fig. 2 shows the north-south cross-section of excess CO_2 centered along 160° E based on IGY data. The lower boundary of penetration is taken as the level where the excess CO_2 signal equals to $5 \pm 10\,\mu$mol/kg. The depth could be up to 100 m to deep or 300 m to shallow because of the vertical sample spacing and because of the uncertainty in the method.

The thin broken line shows the minimum temperature layer which is probably the modified remnant of the isothermal layer produced during the previous winter (FOSTER and CARMACK, 1976: WEISS *et al.*, 1979). The excess CO_2 content falls between 20 and $30\,\mu$mol/kg with an average of $25\,\mu$mol/kg in this layer.

The maximum temperature contour (broken lines) is near the core of the Circumpolar Deep Water (CDW) which is also at approximately the same level as the maximum AOU (apparent oxygen utilization) layer. Excess CO_2 does not appear to penetrate deeply enough to reach the core of the warm, old CDW. Also the deep and bottom waters do not appear to contain significant amounts of anthropogenic CO_2.

Temperature contours indicate that IGY 62 (at 60° S) is north of the Polar Front. Antarctic Intermediate Water (AAIW), formed by strong vertical convection, apparently carries anthropogenic CO_2 with it more deeply north of the Polar Front. The anthropogenic CO_2 penetrates

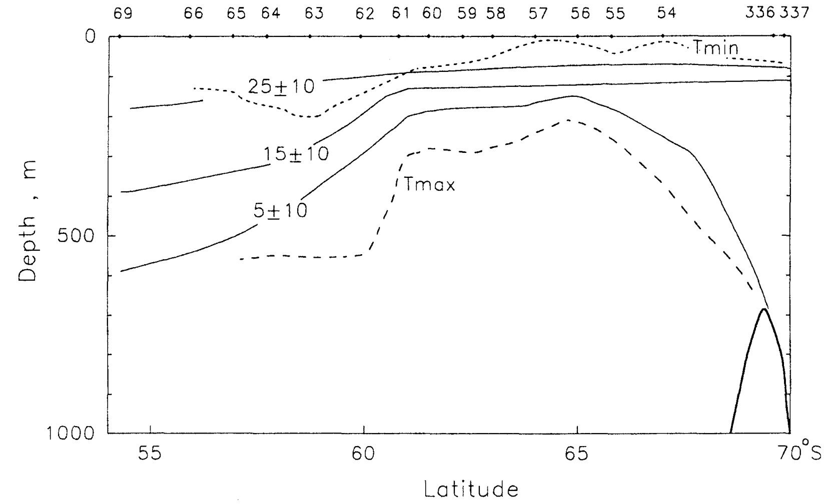

Fig. 2. Excess CO_2 cross-section along 160° E.

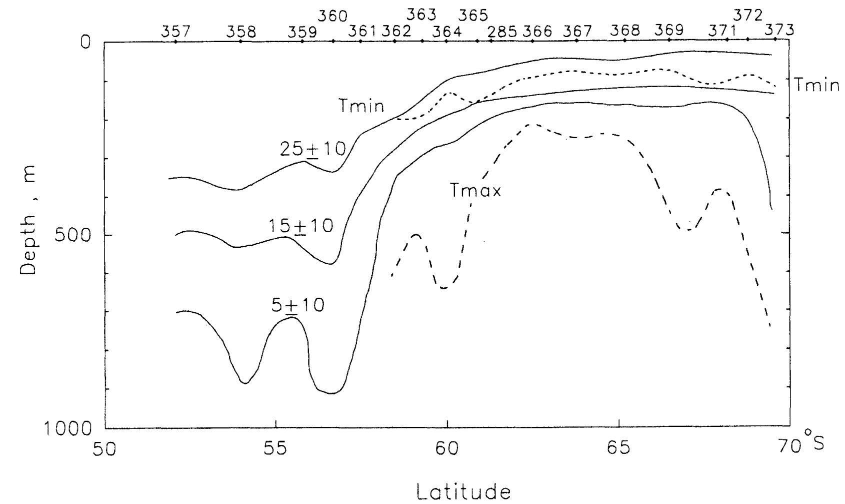

Fig. 3. Excess CO_2 cross-section along 166° E.

less deeply at the more southerly stations due to the upwelling of the old CDW, evidenced by the upwardly concaved structure of the maximum temperature contour. The CDW pushes upward on and disperses the younger Antarctic Surface Water (GORDON *et al.*, 1977, 1984). As a result, the excess CO_2 penetrates less than 300 m between 61 and 66 °S.

South of IGY 54, however, the maximum temperature contour deepens again and intersects the bottom at IGY 336 and 337 near Cape Adare. This is an indication of some downwelling of the fresher, newly cooled seawater. Excess CO_2 also penetrates to near the bottom at these stations which are located on the upper continental slope.

Figure 3 shows the excess CO_2 values at roughly 166° E based on IGY and GEOSECS data. Excess CO_2 penetrates deeper north of the Polar Front near IGY 365. South of the Polar Front the contour concaves upward due to upwelling of CDW but deepens at the southernmost sation, IGY 373. No excess CO_2 is evident in the bottom layer.

Figure 4 shows the west-east cross-section of

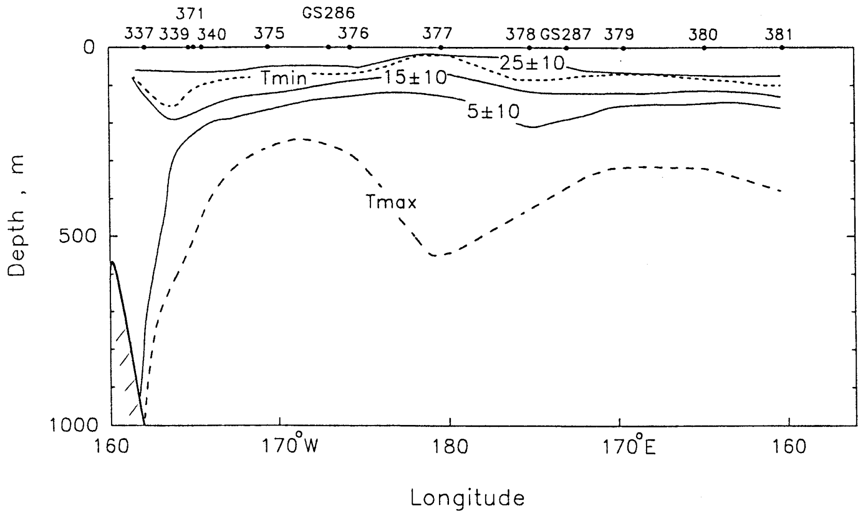

Fig. 4. Excess CO_2 cross-section along 69 °S.

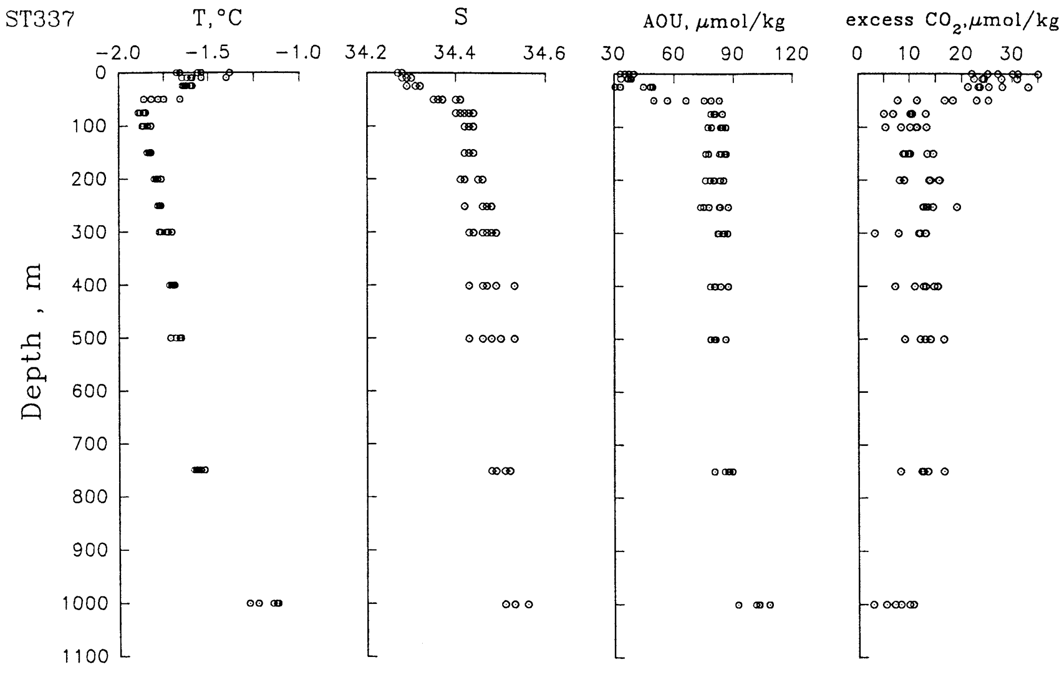

Fig. 5. Temperature, salinity, AOU and excess CO_2 at IGY 337.

excess CO_2 concentration along roughly 69° S based on IGY and GEOSECS data. All stations are south of the Polar Front, and all stations, except for IGY 337, have a water depth deeper than 1000 m. As mentioned earlier, the excess CO_2 penetrates to near the bottom at IGY 337 on the upper continental slope.

IGY 339 sits on the lower continental slope with a water depth of 3350 m. No excess CO_2 could be detected below 250 m at this station (Fig. 4). In fact, all stations except IGY 337 in the cross-section show rather shallow excess CO_2 penetration.

Circulation and hydrography in the vicinity of

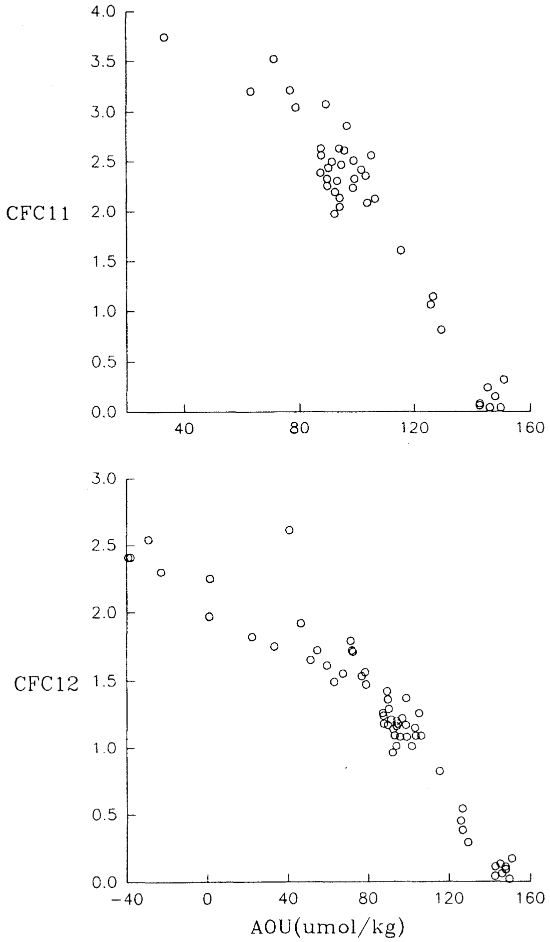

Fig. 6. CFC 11 and CFC 12 concentrations plotted vs. AOU based on the Polar Sea data (JACOBS *et al.*, 1989).

the Ross Sea continental shelf have been reviewed by JACOBS *et al.* (1985). Water on the continental shelf is ultimately derived from CDW, which has upwelled over the continental slope north and east of the Ross Sea, and has been modified by mixing with surface and slope waters. Subsequent interactions with the atmosphere, sea ice and glacial ice cool and reduce the salinities of the shelf waters. These waters eventually become cold and dense enough to move back into and under the CDW to ventilate the deep ocean much like the situation in the Weddell Sea (WEISS *et al.*, 1979; CHEN, 1984). Partial equilibration with atmospheric CO_2 can also occur through gas exchange and mixing with surface and other shelf waters. Direct gas exchange with the atmosphere, however, is limited in winter to breaks and polynyas in the sea ice canopy (TRUMBORE *et al.*, 1991) as sea ice is not entirely permeable to gases (CHEN, 1988). Aa a result, only limited amount of excess CO_2 moves into the winter-formed deep waters on the shelf. The partially ventilated deep water mixes with the surrounding waters as it flows out near the bottom, further diluting the excess CO_2. Finally, the excess CO_2 becomes undetectable excpet in shallow waters or near an area where vertical mixing of the water column occurs quickly.

IGY 337 is an example where vertical mixing occurrs quickly as evidenced by its uniformly low temperature throughout the water column, all between −1.2 and −1.8°C. The salinity varies only between 34.4 and 34.5 below 100 m. AOU varies between 80 and 105 μmol/kg below 100 m (Fig. 5). The relatively low temperature and AOU are indications of rapid turnover.

Earlier work elsewhere has shown a correlation between CFC-11 and excess CO_2 (CLINE *et al.*, 1985; CHEN, 1993b). The Polar Sea stations 87 and 92 sit on the continental slope (Fig. 1). CFCs 11 and 12 are found throughout the water column (to 339 m for PS 92 and to 2058 m for PS 87). Excess CO_2 probably also exists where CFCs are found. The combined Polar Sea CFCs show a decreasing trend when plotted vs. AOU (Fig. 6), reaching zero at an AOU of only about 150 μmol/kg. The IGY and GEOSECS excess CO_2 signals disappear at an AOU of only about 120 μmol/kg. Because of the poor precision of the excess CO_2 signal, it can not be judged whether the difference is because the excess CO_2 (and CFCs) has penetrated deeper during the Polar Sea expedition, reaching older, higher AOU waters.

4. Conclusion

The excess CO_2 does not penetrate more than a few hundred meters south of the Polar Front near the Ross Sea except for a small area near Cape Adare. As a result, the Ross Sea probably has not been a significant excess CO_2 sink.

Acknowledgements

This research was supported by the National

Science Council (NSC 83-0209-M110-002K). I thank S.S. JACOBS for providing the Polar Sea data.

References

CHEN, C.T. (1982): On the distribution of anthropogenic CO_2 in The Atlantic and the Southern Oceans, Deep-Sea Res., **29**, 563–580.

CHEN, C.T. (1984): Carbonate chemistry of the Weddell Sea, Department of Energy DOE/EV/10611-4, 118pp.

CHEN, C.T. (1987): On the depth of anthropogenic CO_2 penetration in the Atlantic and Pacific Oceans. Oceanologica Acta, sp., 97–102.

CHEN, C.T. (1988): Summer-winter comparisons of oxygen, nutrients and carbonates in the polar seas, La mer, **26**: 1–11.

CHEN, C.T.A.(1991): Descriptive chemical oceanography of the Weddell Sea , Proceedings, National Science Council, **15**, 2, 133–142.

CHEN, C.T.A. (1993a): The oceanic anthropogenic CO_2 sink, Chemosphere, **27**, 1041–1064.

CHEN, C.T.A. (1993b): Anthropogenic CO_2 distribution in the North Pacific Ocean, J. Oceanogr. **49**, 257–270.

CHEN, C.T. and F.J. MILLERO (1979): Gradual increase of oceanic carbon dioxide, Nature, **277**, 205–206.

CHEN, C.T. and R.M. PYTKOWICZ (1979): On the total, CO_2-titration alkalinity–oxygen system in the Pacific Ocean, Nature, **281**, 362–365.

CHEN, C.T., F.J. MILLERO and R.M. PYTKOWICZ (1982): Comment on "calculating the oceanic CO_2 increase: a need for caution", by A.M. SHILLER, J. Geophys. Res., **87**, 2083–2085.

CHEN, C.T. and A. POISSON (1984): Excess carbon dioxide in the Weddell Sea, U.S. Antarctic J., Review, 74–75.

CHEN, C.T.A. and M.R. RODMEN (1990): The inhomogeneous distribution of tritium and radiocarbon in the abyssal Southern Ocean, Terrestrial Atmospheric and Oceanic Sciences, **1**, 91–109.

CLINE, J.D., R.A. FEELY, K. KELLY-HANSEN, J.F. GENDRON, D.P. WISEGARVER and C.T. CHEN (1985): Current inventory of anthropogenic carbon dioxide in the North Pacific gyre. NOAA Technical Memorandum, ERL PMEL-60, 46pp.

FOSTER T.D. and E.C. CARMACK (1976): Frontal zone mixing and Antarctic Bottom Water formation in the Southern Weddell Sea. Deep-Sea Res., **23**, 301–317.

GORDON A.L., D.T. GEORGI and H.W. TAYLOR (1977): Antarctic polar front zone in the Western Scotia Sea - summer 1975, J. Phys. Oceanogr., **7**, 309–328.

GORDON A.L., C.T. CHEN and W.G. METCALF (1984): Winter mixed layer entrainment of the Weddell deep water, J.Geophys. Res., **89**, 637–640.

JACOBS S.S., R.G. FAIRBANKS and Y. HORIBE (1985): Origin and evolution of the water masses near the Antarctic Continental Margin: evidence from $H_2^{18}O/H_2^{16}O$ ratios. *In*: Oceanol. Ant. Cont. Shelf, Ant. Res. Ser. 43, AGU, 59–85.

JACOBS S., W. HAINES, J.L. ARDAI Jr and P. MELE (1989): Ross Sea Oceanographic Data, 1983–1987, LDGO 89-4, Lamont-Doherty Geological Observatory of Columbia University, Palisades, NY.

MICHEL, R.L., R.S. KEIR. and A. SCHROEDER (1985): Chemical Oceanography during the 1985 Wilkes Land Expedition. Antarctic Journal of the United States, **20**, 105–106.

POISSON, A. and C.T.A. CHEN (1987): Why is there little anthropogenic CO_2 in the Antarctic bottom water? Deep-Sea Res., **34**, 7, 1255–1275.

TRUMBORE, S.E, S.S. JACOBS and W.M. SMETHIE, Jr (1991): Chlorofluorocarbon evidence for rapid ventilation of the Ross Sea, Deep-Sea Res., **38**, 845–870.

WEISS R.F., H.G. OSTLUND and H. CRAIG (1979): Geochemical studies of the Weddell Sea. Deep Sea Res., **26**, 1093–1120.

ロス海アデーレ岬沖における過剰 CO_2 透入の徴候

Chen-Tung Arthur CHEN

要旨：南極底層水（AABW）は一般にウェッデル海で形成されると考えられており，人為起源の CO_2 をわずかに含んでいる。ウェッデル海に比べ，ロス海は過剰 CO_2 の沈降の場としての役割は小さいと考えられるが，GEOSECS, IGY および R/V Polar Sea のデータのより詳細な解析により，ロス海北西かどのアデーレ岬沖において，過剰の CO_2 がより深い層へ透入している事実が明かとなった。