First Carbon-14 Observations in the Great Australian Bight

by

J. Ribbe[(*)(1)], J. T. Bye[(1)], G. E Jacobsen[(2)], E. M. Lawson[(2)], A. M. Smith[(**)(2)], M. Tomczak[(1)] & C. Tuniz[(2)]

Paper to be presented at the

7th International Conference on Accelerator Mass Spectrometry
Workshop on Applications of AMS to Global Climate Change, 18 May 1996
Scripps Institution of Oceanography, La Jolla, California, USA

(*) corresponding author
(**) is presenting the paper at the workshop

(1) The Flinders University of South Australia, School of Earth Sciences, GPO Box 2100, Adelaide 5001 SA, Australia

(2) Australian Nuclear Sciences and Technology Organisation, Private Mailbag 1, Menai 2234 NSW, Australia

Abstract

The Great Australian Bight south of Australia is an important link for the flow of surface, intermediate and deep water between the Indian and Pacific Ocean. Carbon-14 is a tracer of this flow and for the first time, water samples for subsequent carbon-14 analysis were collected at several locations within the Bight.

We report and discuss the observed carbon-14 distribution in relation to the general hydrography of the area. For all sample depths, a close correlation of the Bight data with previous measurements from the southeast Indian Ocean was found. Our data represent the first successful Australian Accelerator Mass Spectrometry measurements for ocean water samples, and in the future, we plan to use the observations to validate output from computational experiments with a general ocean circulation model of the Southern Ocean.

1. Introduction

Carbon-14 is a powerful environmental geochemical tracer of both the global carbon cycle and the global thermohaline and wind driven oceanic circulation. The first comprehensive oceanic carbon-14 database was established through an international collaboration within the framework of the Geochemical Ocean Sections Study (GEOSECS) from 1972 to 1978. This database represents the base line study for most research into the manyfold aspects of climatic change predictions.

Most carbon-14 is produced in two ways. Firstly, it is produced naturally by incoming cosmic rays interacting with nitrogen atoms in the upper atmosphere. Secondly, atmospheric nuclear weapon tests represented an artificial source during the 1950s and 1960s. The natural carbon-14 distribution within the interior ocean is considered to be in a steady state, while the anthropogenic component represents a transient signal which on average has penetrated the ocean to an approximate depth of 400 to 500 m.

The atmospheric carbon-14 distribution is considered to be homogeneous, but the exchange with the ocean depends on wind speed and surface temperature. While an increase in wind speed results in an increased oceanic carbon-14 uptake, a rise in surface temperature results in a decreased uptake. Therefore, large horizontal carbon-14 gradients are observed in near surface layers which are acted upon by the wind-driven oceanic surface circulation. In contrast, the interoceanic carbon-14 gradients are only weak within the deep ocean and require an analytical precision of <0.5 %.

Once a water mass is removed from the ocean surface, the carbon-14 content is considered to be a quasi-conservative property characteristic of that water mass. Radioactive decay acts as a clock, allowing the age of the water to be determined. Only a minor fraction of carbon-14 (<10 %) is involved in any other than physical transport mechanisms.

Since GEOSECS, much progress has been made in regard to the analytical requirements on carbon-14 measurements with the required precision of <0.5 % to resolve the weak interoceanic carbon-14 gradients. This includes a reduction of the required water sample size from 250 litres to 0.5-1 litre due to the application of the Accelerator Mass Spectrometry (AMS) method .

The Great Australian Bight (GAB) to the south and the Indonesian Passage to the north of Australia are both important passages for the surface, intermediate and deep water flow between the Indian and Pacific Ocean. Both field observations and ocean models have clearly identified the role of the Indonesian Passage for the global thermohaline circulation. In contrast, the flow pattern south of Australia is less well understood; both in direction as well as in absolute quantities.

We report in this note the first carbon-14 observations from the eastern domain of the GAB. The sample locations close a gap identified within the large scale sample program of the World Ocean Circulation Experiment (WOCE) carried out for the Indian, Pacific and Atlantic Ocean. Our results were evaluated in a comparison with GEOSECS data, and the large scale hydrographic situation and allowed for some preliminary conclusions on the flow pattern within the GAB and on the quality of the data.

2. Sample Collection and Measurement

The water samples were collected during a RV Franklin cruise into the Great Australian Bight in July 1994 (Figure 1). The samples were drawn from a CTD/rosette system equipped with 24 Niskin bottles into glass bottles of volume 0.25 litre. Microbiological activity was terminated adding $HgCl_2$ to each sample. The bottles were sealed with Apiezon grease treated glass stoppers and held in position using masking tape.

The radiocarbon content of the water samples were measured at the Australian National Tandem Accelerator for Applied Research (ANTARES) based at the Australian Nuclear Science and Technology Organisation (ANSTO) in Sydney, Australia. Total inorganic carbon was extracted from the water samples in the form of carbon dioxide and the AMS targets were prepared by catalytic reduction of the gas into graphite. The AMS facility and the procedure used for high precision measurements is described in Smith et al. (1994). We report our data as $\Delta^{14}C$ and follow the guidelines laid out for ocean water samples by Stuiver & Polach (1977). The precision of the percent modern carbon (pMC) contents of each sample listed in Table (1) is in the order of <0.5 %. Our data are only of preliminary nature, and the complete data base for the GAB is to be established within the next 12 months.

3. Results and Discussion

In the following, a brief review of the general hydrographic situation for the GAB precedes a comparison of our data with those made during the international GEOSECS expedition into the southeast Indian Ocean. Of particular interest for the interpretation of our data is the concept of the global thermohaline circulation and the flow of the main water masses within the deeper layers of the GAB between the Indian and Pacific Ocean. Carbon-14 is a tracer of this flow.

Our sample positions were located to the north of the Subtropical Front (STF) which is found between approximately 38º S to 41º S (Figure 1) in the west and 43º S to 44º S in the east. The front separates the surface waters of the subtropical and subantarctic domain, the latter bounded by the Subantarctic Front (SAF) found between approximately 46º and 48º S (eg. Belkin & Gordon, 1996). The Polar Front (PF) is located further to the south of the SAF and both fronts are associated with strongly eastward directed zonal mass transports confining the flow of the Antarctic Circumpolar Current (ACC). The transitional zone to the north of the SAF and south of the STF is known as the Subantarctic Zone (SAZ).

The wind driven surface circulation within the GAB manifests itself in form of a large anti-cyclonic gyre to the north of the STF. The southern branch of this gyre is part of the ACC while its most eastern branch flowing in a northwest direction is known as the Flinders Current (Bye, 1972). To the north and following the Australian continental shelf edge, the eastward directed Leeuwin Current is the dominant feature within the surface layer. The current is maintained to the north of Western Australia by steric height differences between the Pacific and Indian Ocean, and advects Indonesian Throughflow water into the GAB (Tomczak & Godfrey, 1994).

Below the wind driven surface layer, the intermediate, deep and bottom water flow is primarily sustained by thermohaline processes. A region between approximately 100º E and 120º E within the SAZ was identified by Ribbe & Tomczak (1996a, 1996b) as a formation site for Subantarctic Mode Water (SAMW) in a ocean general circulation model (Figure 1). The formation process is driven by convection and SAMW is being advected within the depths range of 300 to 500 m into the GAB, Tasman Sea, northern Indian Ocean and western Pacific Ocean in agreement with observations made by McCartney (1982).

Other observational evidence suggested that within the intermediate water level between approximately 800 m to 1100 m, the flow through the GAB is directed from the Pacific into the Indian Ocean (Reid, 1965; Fine, 1993). Similar results have been inferred by Rintoul (1996; pers. comm.) for the flow within the deeper and bottom layers from data recently recorded along transects between Australia and Antarctica.

In addition to local air to sea exchange mechanisms for naturally and bomb produced carbon-14, the hydrographic situation and large scale circulation establishes a pattern of possible carbon-14 sources for the GAB. Within the surface layers, these are the Leeuwin Current in the north and the ACC in the south of the Bight. In subsurface layers, the formation of SAMW in the southeast Indian Ocean for the depths range of 300 m to 500 m depths, and the exchange of intermediate, deep and bottom water between the Pacific and Indian Ocean constitute possible carbon-14 sources.

In comparing our data with those collected during GEOSECS, the time variability of the atmospheric carbon-14 signal is to be accounted for, hence, making a quantitative analysis difficult. The input of bomb produced carbon-14 into the ocean peaked in the early 1970s and atmospheric values declined sharply since then. Newly formed water masses would dilute any previously established carbon-14 values.

It was not possible to separate our individual water samples into two smaller ones to allow a duplicate measurement for comparison. Therefore, the evaluation of these first carbon-14 data from the GAB is only possible in a comparison with GEOSECS samples collected from the Indian Ocean in 1978.

It is possible to estimate the approximate penetration depth D of a tracer using the empirical relationship $D \sim (T^2 \cdot K_v)^{1/2}$ where T is time and K_v is the vertical mixing coefficient usually set to 10^{-4} m^2/s. An atmospheric tracer signal would have been mixed down to an average depth of approximately 200 to 300 m within the 15 to 20 years since GEOSECS. Down-welling, up-welling and other oceanic removal processes for surface water influence this depth, and it is most likely that a depth of 200 m is on average an upper limit for the penetration of newly introduced tracer quantities. We therefore argue that our comparison with GEOSECS data allows us to infer information on the quality of the GAB data and the oceanic circulation for all but the top 200 m of the water column.

The closest GEOSECS sample positions (Stuiver & Ostlund, 1983) in the southeast Indian Ocean are G431, G432, G433, G435 and G436 (Figure 1). The latter two are the only positions sampled in proximity or north of the STF in the eastern Indian Ocean, all other positions are located to the south. The GAB sample positions A8 and A22 are also located to the north of the STF.

Most difficult to interpret are the surface values of the carbon-14 distribution in the GAB as these are significantly effected by any variability in the bomb carbon-14 entry function. Above 1000 m our data overlap well with data from G435 and exhibit values characteristic for upper Indian Ocean thermocline water. A surface value is available only for A8 where we measured 95.5 ppt. The subsurface values from A22 at 200 and 400 m with 90.1 and 70.8 ppt respectively indicate a surface value of around 100 to 110 ppt (Figure 2).

North of the STF, newly formed SAMW is most likely to be identified as a maximum in the carbon-14 concentration within the depth range of 200 to 600 m. It contains the surface characteristics of water from the SAZ which are subducted into the upper layers of the permanent thermocline. The formation of SAMW by convection results in a much faster removal of carbon-14 from the ocean surface compared to other vertical transport mechanisms such as mixing and down-welling. Newly formed SAMW is advected out of the formation region into areas in which carbon-14 is removed from the ocean surface by mixing and down-welling only. Therefore, it may be possible to identify SAMW in those regions as a subsurface maximum within the depth range of 200 to 600.

There is some indication that we were able to observe the existence of newly formed SAMW in the GAB at sample location A8. A subsurface maximum of 108 ppt was observed in 450 m. G435 exhibits a similar but much weaker maximum at approximately 200 m. At A22 no indication of a subsurface maximum below 200 m depth was found and we may be able to conclude that SAMW is not advected as far north into the GAB as position A22. Temperature and salinity profiles recorded at A8 and A22 will be discussed elsewhere, and should provide some more evidence about the extent of SAMW within the GAB (Exelby & Hammat, 1995)

Within the deeper layers, ie. below 1000 m, values are close to the assumed equilibrium distribution of natural carbon-14 and are less effected by any variability in the atmospheric bomb carbon-14 signal. There were nearly identical values found for the intermediate and deep water level. The good correlation found in this depth is particularly encouraging as due to the lack of duplicate measurements from the same sample depth it is our only proof for the reliability of the data, and hence, of the method itself.

We have not been able to derive any conclusions about the direction of flow in the deeper layers from our carbon-14 observations in the GAB as yet. As known from GEOSECS observations, the interbasin gradient are only weak. Any temporal changes in the carbon-14 entry functions would have quite a significant impact on this weak gradients which are already affected by the bomb carbon-14 signal. We require further quasi-synoptic GAB data to establish any existing horizontal carbon-14 gradients within the GAB.

4. Conclusions

The observed vertical distribution of carbon-14 in the GAB was similar to that observed for the southeast Indian Ocean during GEOSECS. We obtained average $\Delta^{14}C$ values for surface, intermediate and deep water with 90 ppt, -100 ppt and -150 ppt respectively. The observation of a subsurface maximum at A8 is a possible indicator for the local presence of newly formed SAMW.

Although good correlation between the Indian Ocean GEOSECS and GAB data was observed, we cannot clearly identify the direction of exchange between the Indian and Pacific Ocean from these data. A similar correlation with GEOSECS Pacific data is not easy as all Pacific Ocean data were collected to far to the eastern and mid-Pacific Ocean regions.

To resolve any possible existing horizontal carbon-14 gradients, we need to obtain further carbon-14 profiles from areas of the western GAB.

We presented the first Australian Accelerator Mass Spectrometry measurements carried out for ocean water samples with the required precision of < 0.5 %. The comparison with GEOSECS data provides us with confidence that the methodology was applied successfully. In the future, the data will be applied to validate output from an ocean general circulation model.

5. References

Bye, J. A. T. (1972). Oceanic circulation south of Australia. In: Antarctic Research Series. Vol 19. Antarctic Oceanology II: The Australian-New Zealand Sector. Editor: D. E Hayes. American Geophysical Union. 95-100.

Belkin, I. and A. Gordon (1996). Southern Ocean Fronts from Greenwich Meridian to Tasmania. J. Geophys. Res. J. Geophys. Res. 101(C2). 3675-3696.

Exelby, J. and J. Hammat (1995). A comparison of observations of the thermohaline structure of the Flinders Current made in 1969-1970 and in 1994. In: Conference Proceedings Ocean and Atmosphere International Conference. 23-27 October 1995. Adelaide. Australia.

Fine, R. A. (1993). Circulation of Antarctic Intermediate Water in the South Indian Ocean. Deep-Sea Res. 40(10. 2021-2042.

McCartney, M. S. (1982). The subtropical recirculation of Mode Waters. J. Mar. Res. 40. Suppl. 427-464.

Reid, J. L., Jr. (1965). Intermediate waters of the Pacific Ocean. Oceanogr. Stud. 2. Johns Hopkins University. Baltimore. Md. 85pp.

Ribbe, J. & M. Tomczak (1996a). On Convection, Subduction and the Formation of Subantarctic Mode Water in the Fine Resolution Antarctic Model (FRAM). Submitted to J. Mar. Systems. January 1996.

Ribbe, J. & M. Tomczak (1996b). On the Formation of Subantarctic Mode Water in the Southeast Indian Ocean. Submitted to J. Geophys. Res. February 1996.

Smith, A. M., D. Fink, M. A. C. Hotchkis, G. E. Jacobson, E. M. Lawson, M. Shyig, C. Tuniz, G. C. Watt, J. Fallon and P. J. Ellis (1994). Equipment and methodology for high precision, high throughput ^{14}C AMS analyses at ANTARES. Nuclear Instruments and Methods in Physics Research B92. 122-128.

Stuiver, M. & H. G. Ostlund (1983). GEOSECS Indian Ocean and Mediterranean Radiocarbon. Radiocarbon. 25(1). 1-29.

Stuiver, M. & H. A Polach (1977). Discussion: Reporting of C14 Data. Radiocarbon. 19(3). 355-363.

Tomczak, M. & J. S. Godfrey (1994). Regional Oceanography: An Introduction. Pergamon. 422pp.

6. List of Figures

Figure 1: Representation of the Great Australian Bight. Indicated are the Bight and GEOSECS sample locations described in this paper and some of the relevant hydrographic characteristics of the surface layer which were taken from a recent publication by Belkin & Gordon (1996). (SAMW = Subantarctic Mode Water, STF = Subtropical Front, NSTF = northern STF, SSTF = southern STF, SAF = Subantarctic Front, PF = Polar Front).

Figure 2: $\Delta^{14}C$ measurements form the Great Australian Bight (A8 and A22) in a comparison with Indian Ocean GEOSECS data.

Profile A22 Location: 35.5º S 134º E			Profile A8 Location: 38º S 136º E		
Depth [m]	$\Delta^{14}C$ [ppt]	Error [ppt]	Depth [m]	$\Delta^{14}C$ [ppt]	Error [ppt]
Surface	-	-	Surface	95.5	8.4
200	90.1	4.3	-	-	-
400	70.8	4.3	400	108.0	5.2
800	-43.6	5.5	-	-	-
1100	-103.1	3.7	1100	-98.6	5.0
1750	-145.2	3.3	1750	-149.5	4.3
			2750	-162.2	4.1

Table 1: $\Delta^{14}C$ [ppt] in the Great Australian Bight

interoceanic = from ocean to ocean

CTD rosette = Conductivity, Temperature, Depth (vi pressure) sample system

Niskin bottles = it is the name for the sample bottle developed by Mr. Niskin

front = equal to boundary, it seperates water of eg. polar and tropical regions, there a plenty of definitions for fronts, based on temperature/salinity/density and others. the fronts only have a limited vertical extension.

cyclonic gyre = low pressure system, however, rotates in the northern hemisphere anti-clockwise, in the southern hemisphere clockwise (because of this, I always mix them up as I did in the early draft of the paper. the GAB gyre is anti-cyclonic).

anti-cyclonic gyre = high pressure system, however, rotates in the northern hemisphere clockwise, in the southern hemisphere anti-clockwise.

advected, advection = is the horizontal movement of water.

SAMW = is a type of water which has a certain temperature and salinity. it's formation is density driven, ie. surface water cools which increases density. it is gaining 'weight' and is heavier than subsurface water. the resulting density instability is adjusted through the process of convection. surface water is plunging down until it comes to rest in a density level of its on density. SAMW is formed by this process. the formation process homogenises the water column over a depth of 200 to 600 m. this process occurs only in some very limited regions of the world ocean, one of those is found in the southeast Indian Ocean.

newly formed water mass = a water mass is characterised by a typical temperature and salinity. they are formed at the ocean surface because it is here were the ocean is heated and changes salinity due to evaporation and precipition. if a newly formed watermass is removed from the ocean surface, its temperature and salinity can only be changed by mixing with a second watermass. therefore, all water below the surface can be explained as the end product of several watermasses which have been produced at the ocean surface.

up-weeling = in this context it means the rise of deep water toward the surface. this is a very dominant process in the southern ocean. the wind is moving surface water northward and this water has to be replaced by water from below. in the southern ocean it results in up-welling of North Atlantic Deep Water.

steric height = is a measure for the elevation of the ocean surface from a reference level. its dimension is [m]. it can be calculated from water density as a function of temperature, salinity and pressure (or depth).