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Oxygen isotope distribution at shallow to intermediate depths across different fronts of the Southern Ocean: Signatures of a warm-core eddy

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ABSTRACT

Southern Ocean, an important component of the earth's climate system, is changing in response to the anthropogenic climate change. To understand better the dynamics of the Southern Ocean, we documented oxygen isotopic variability and its relation to salinity, especially at intermediate depths (to 1000 m) across different fronts, at six stations in the Southern Ocean. Signatures of a warm-core eddy extended from 40 to 44 °S and 56 to 59.5 °E. It consisted of Subtropical Surface Water (STSW). Other water masses identified were the Antarctic Surface Water (AASW), Antarctic Intermediate Water (AAIW), and Upper Circumpolar Deep Water (UCDW) based on the salinity, temperature and oxygen isotopic ratios. The slope of the oxygen isotope-salinity relationship indicates that the water in the warm-core eddy was derived from a region dominated by evaporation/precipitation while the water surrounding the eddy came from a region dominated by melting/freezing. The shoaling of AAIW up to water depth of 500 m was observed along the transect. These new oxygen isotope data, especially from the intermediate depths, will also help fill existing gaps in the global seawater oxygen isotope dataset.

1. Introduction

The Southern Ocean (SO) plays a very important role in the global climate as it connects the circulation of different ocean basins through the eastward flowing Antarctic Circumpolar Current (ACC). The ACC connects the surface layers with deep ocean water and supplies the major intermediate and deep water masses of the world's oceans (Rintoul et al., 2001; Cunningham, 2005; Rintoul and Garabato, 2013). It is characterized by a well-defined frontal structure, which facilitates the zonal transport of water across which the physical properties change radically. Eddies have also been recognized as an important mode of meridional water transport in the SO along with the northward Ekman flux driven by strong westerlies (Rintoul and Garabato, 2013). The Subtropical front (STF) has been identified as a major region of eddy formation (Saraceno et al., 2004; Jullion et al., 2010). Eddy fluxes have been found to be much more important in the SO compared to other basins (Rintoul et al., 2001). Eddies are the significant mode of poleward heat transport in the SO (deSzoeke and Levine, 1981; Bryden and Heath, 1985; Boebel et al., 1999; Sun and Watts, 2002). In fact, the importance of eddies in affecting the climate is now being realized. Recently, using satellite data Frenger et al. (2013) observed 600,000 individual eddies in the SO. They also reported that the mesoscale eddies can affect the wind, clouds and rainfall. They further observed that the southern hemispheric warm-core anticyclone eddies can modify the turbulence in the atmospheric boundary layer through associated sea surface temperature (SST) anomalies, resulting in strengthened near-surface winds, enhanced cloud fraction and increased rainfall (Frenger et al., 2013). Eddies have also been reported to affect the air-sea CO_2 exchange (Dufour et al., 2013) and productivity in the SO (Ito et al., 2005). A modeling study by Ito et al. (2005) has shown that the productivity in the SO is significantly influenced by the eddy-induced circulation.

In view of the significance of eddies in the SO, it is important to make concerted efforts to understand their dynamics vis-à-vis the frontal structure. One of the essential tools to study the water masses is the oxygen isotopic ratio ($\delta^{18}O$) of seawater (Bigg and Rohling, 2000; Meredith et al., 2008; Tiwari et al., 2013). It acts as a conservative tracer unless and until the water comes in contact with processes in hydrological cycle, such as evaporation, precipitation, advection, melting, and freezing (Clark and Fritz, 1997). During such processes, the $\delta^{18}O$ values and salinity are affected simultaneously as fresh water has no salinity and low $\delta^{18}O$ values. During evaporation, the equilibrium as well as the kinetic fractionation prefer lighter isotope of the oxygen (^{16}O), which along with other processes like 'amount-effect' result in lower $\delta^{18}O$ values of the subsequent precipitation. In this study, we explore the frontal structure including the role of eddies on the intermediate water

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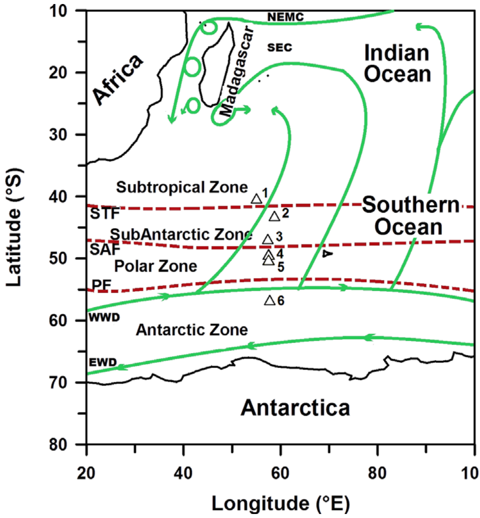

Fig. 1. Sampling locations: Locations of sampling (Station no. 1–6) depicted by triangles along a meridional section (along ~57.5 °E). Schematic positions of different fronts are shown by dashed lines; STF, SAF, and PF refer to the Subtropical Front, Subantarctic Front, and the Polar Front, respectively. Oceanic circulation features are also shown; SEC, NEMC, EWD, and WWD refer to the South Equatorial Current, Northeast Madagascar Current, East Wind Drift, and West Wind Drift, respectively.

Table 1
Sampling locations.

Station no.	Latitude	Longitude	Sampling date
1	40 °26.70′ S	55 °03.386′ E	28-01-2013
2	42 °44.00′ S	58 °29.00′ E	30-01-2013
3	46 °58.87′ S	57 °30.75′ E	01-02-2013
4	49 °36.01′ S	57 °31.83′ E	02-02-2013
5	50 °29.40′ S	57 °30.91′ E	02-02-2013
6	56 °34.70′ S	57 °39.23′ E	05-02-2013

formation in the SO using the δ^{18}O values of seawater. We also present here slopes of oxygen isotope-salinity relationship from different regions along the cruise track so as to determine whether the source of the water is from a region dominated by evaporation/precipitation or melting/freezing. These δ^{18}O values will also add to the existing global gridded δ^{18}O dataset, and will address the deficiency of values for the deeper waters (Schmidt et al., 1999).

2. Material and methods

During the 7th Indian expedition to the Southern Ocean in the austral summer (January–February) of 2013, water samples were collected for oxygen isotope analysis from 11 depths (surface, 10, 30, 50, 75, 100, 120, 200, 500, 750 and 1000 m) at six CTD stations along a meridional section (along ~57.5 °E; see Fig. 1 and Table 1 for sampling locations). Earlier studies from this region (Srivastava et al., 2007; Tiwari et al., 2013) have looked at the variability of the oxygen isotopes in the surface waters. In, the present study, the deeper depths were chosen to obtain information from surface to intermediate waters and the processes occurring therein. In the upper layers, the sampling depths were selected at close range so as to get higher resolution data because the near surface region is more affected by the processes like evaporation/precipitation, melting/freezing etc. Water samples were filled up to the brim of 30 ml HDPE bottles with tight fitting caps, wrapped tightly by parafilm and kept frozen during transport to prevent evaporation. Water samples for salinity measurements were also collected at the same stations and depths. The conductivity ratios were determined onboard using a Guildline Autosal 8400B (accuracy of <0.0001 and a range of 2–42 in salinity), which was calibrated using IAPSO standard sea water having the conductivity ratio of 0.99990. These conductivity ratios were then converted to salinity (UNESCO, 1981). The accuracy of salinity measurements was better than 0.002. The temperature of the surface water was measured using a bucket thermometer (make: Theodor Friedrichs & Co. Meteorologische Gerate und Systeme GmbH, precision of ± 0.5 °C). The temperature of the remaining 10 discrete depths was taken from the CTD data with a precision of 0.001 °C. The oxygen isotopic ratios were measured in the Marine Stable Isotope Lab at National Centre for Antarctic & Ocean Research, Goa, India using an “Isoprime Dual Inlet – Stable Isotope Ratio Mass Spectrometer” using the well established CO_2 equilibration method (Epstein and Mayeda, 1953). The isotopic values are expressed as delta notation (δ), which is the relative difference of isotopic ratios in the sample from an international standard: $\delta^{18}O=\{(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{standard}\}-1$; where, $(^{18}O/^{16}O)_{sample}$ and $(^{18}O/^{16}O)_{standard}$ are the abundance ratios of ^{18}O to ^{16}O in the sample and standard of Vienna Standard Mean Ocean Water (VSMOW), respectively. For the ease of comprehension, δ-values are multiplied by 10^3 and are then expressed in per mil (‰) (Coplen, 2011). The reproducibility of δ^{18}O measurement is ± 0.12‰ (1σ standard deviation), determined by repeat measurement ($n=40$) of the lab standard with δ^{18}O value of -1.22 ± 0.09 with respect to VSMOW (Vienna Standard Mean Ocean Water).

The δ^{18}O-SSS relationship was obtained by ‘Linear Regression’ using the ‘Least Squares’ method (Topping, 1962). The uncertainties on the slope (m) and intercept (c) were calculated according to Topping (1962) as follows: when $y=m\,x+c$; ‘y’ is the δ^{18}O values, ‘x’ is the sea surface salinity, ‘n’ is the number of data points, and the ‘residual’ i.e., $d=m\,x+c-y_{observed}$; then error on the slope is $\sigma_m=[\{n/n-2\}\{\Sigma d^2/(n\Sigma x^2)-(\Sigma x)^2\}]^{1/2}$ while that on the intercept is $\sigma_c=\sigma_m(\Sigma x^2/n)^{1/2}$.

In situ current data from the ship-borne Acoustic Doppler Current Profiler (ADCP) of 38 KHz frequency were used to understand the vertical distribution of horizontal currents along 57.5 °E longitude. The ADCP, which was calibrated just before the cruise was switched on throughout the cruise. The sampling bin size was set at 8 m while the shallowest possible sampling depth was set at 16 m. In addition to this, the near-realtime ocean surface currents at 15 m derived from satellite altimeter and scatterometer data with a spatial resolution of 1/3° X 1/3° and temporal resolution of