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Meridional circulation across the Antarctic Circumpolar Current serves as a double ^{231}Pa and ^{230}Th trap

Michiel Rutgers van der Loeff[a,*], Celia Venchiarutti[a,b], Ingrid Stimac[a], Jan van Ooijen[c], Oliver Huhn[d], Gerd Rohardt[a], Volker Strass[a]

[a] Alfred Wegener Institut, Helmholz Center for Polar and Marine Research, PO Box 120161, D 27515 Bremerhaven, Germany
[b] European Commission – Joint Research Centre, Institute for Reference Materials and Measurements (IRMM), Retieseweg 111, 2440 Geel, Belgium[1]
[c] Royal Netherlands Institute for Sea Research, PO Box 59, NL 1790 AB Den Burg, Texel, Netherlands
[d] Institute for Environmental Physics, Universität Bremen, Postfach 33 04 40, D-28334 Bremen, Germany

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ABSTRACT

Upwelling of Circumpolar Deep Water in the Weddell Gyre and low scavenging rates south of the Antarctic Circumpolar Current (ACC) cause an accumulation of particle reactive nuclides in the Weddell Gyre. A ventilation/reversible scavenging model that successfully described the accumulation of ^{230}Th in this area was tested with other particle reactive nuclides and failed to adequately describe the depth-distributions of ^{231}Pa and ^{210}Pb. We present here a modified model that includes a nutrient-like accumulation south of the Antarctic Polar Front in an upper meridional circulation cell, as well as transport to a deep circulation cell in the Weddell Gyre by scavenging and subsequent release at depth. The model also explains depletion of ^{231}Pa and ^{230}Th in Weddell Sea Bottom Water (WSBW) by ventilation of newly formed deep water on a timescale of 10 years, but this water mass is too dense to leave the Weddell Gyre.

In order to quantify the processes responsible for the ^{231}Pa- and ^{230}Th-composition of newly formed Antarctic Bottom Water (AABW) we present a mass balance of ^{231}Pa and ^{230}Th in the Atlantic sector of the Southern Ocean based on new data from the GEOTRACES program. The ACC receives $6.0 \pm 1.5 \times 10^6$ dpm s^{-1} of ^{230}Th from the Weddell Sea, similar in magnitude to the net input of $4.2 \pm 3.0 \times 10^6$ dpm s^{-1} from the north. For ^{231}Pa, the relative contribution from the Weddell Sea is much smaller, only $0.3 \pm 0.1 \times 10^6$, compared to $2.7 \pm 1.4 \times 10^6$ dpm s^{-1} from the north. Weddell Sea Deep Water (WSDW) leaving the Weddell Gyre northward to form AABW is exposed in the ACC to resuspended opal-rich sediments that act as efficient scavengers with a Th/Pa fractionation factor $F \leq 1$. Hydrothermal inputs may provide additional removal with low F. Scavenging in the full meridional circulation across the opal-rich ACC thus acts as a double ^{231}Pa and ^{230}Th trap that preconditions newly formed AABW.

1. Introduction

The pair of long-lived radionuclides ^{231}Pa and ^{230}Th is well suited for paleoceanographic interpretations. These nuclides are produced at a constant rate in the water from their respective U parents, ^{235}U and ^{234}U. Both are rapidly removed from the water column by scavenging but differences in their reactivities cause the two to be fractionated by particle flux, particle composition, and ocean circulation with the result that their activity ratio in surface sediments deviates from the production ratio of 0.093 (Anderson et al., 1983). The original interpretation of ^{231}Pa and ^{230}Th accumulation in sediments of the Southern Ocean was based on boundary scavenging. DeMaster (1981) interpreted high ^{231}Pa and ^{230}Th accumulation rates in the opal belt of the South Atlantic as indicative of high productivity, and the ^{231}Pa/^{230}Th ratio in Holocene and LGM sediments was used by Kumar et al. (1995) as indication for glacial–interglacial changes in the zones of high productivity. Yu et al. (1996) demonstrated that ^{231}Pa produced in the Atlantic Ocean was deposited in the opaline sediments of the ACC, paving the way to use the isotope ratio as a proxy for meridional overturning circulation (MOC).

This proxy builds on the idea that the ^{231}Pa/^{230}Th ratio in deep waters increases with water mass age and that it is reflected in

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* Corresponding author.
E-mail address: mloeff@awi.de (M. Rutgers van der Loeff).

[1] Present address.

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the ^{231}Pa/^{230}Th ratio in deposited sediments. Glacial–Interglacial changes in ^{231}Pa/^{230}Th ratios in North Atlantic sediments have been interpreted to show changes in North Atlantic Deep Water (NADW) flow (McManus et al., 2004). Cores recovered from the South Atlantic at 2440 and 3213 m, now bathed in NADW, were covered by Southern Component Water (SCW) during the Last Glacial Period (LGP) and their LGP ^{231}Pa/^{230}Th ratios have been interpreted in terms of northward flow (Jonkers et al., 2015; Negre et al., 2010). Similarly, south Atlantic cores from greater depth are expected to record the history of AABW flow (Lippold et al., 2016). Interpretations in terms of northward flow of SCW or AABW depend on assumptions on the scavenging history and resulting preformed ^{231}Pa/^{230}Th ratio in these southern source waters (Jonkers et al., 2015; Lippold et al., 2016; Negre et al., 2010). Considering that the ^{231}Pa/^{230}Th ratio in newly deposited particles is largely determined by the lower 1000 m of the water column (Thomas et al., 2006) and that wide areas of the abyssal sediments are bathed in AABW, it is important to know what controls the ^{231}Pa and ^{230}Th activities in freshly produced AABW. A large part of AABW enters the ACC from the Weddell Gyre as Weddell Sea Deep Water (WSDW), whether it is produced in the Gyre (according to a traditional estimate 60–70% of AABW, Orsi et al., 1999, 2002) or advected in the coastal current from the Indian Ocean (Hoppema et al., 2001; Jullion et al., 2014; Meredith et al., 2000). The processes controlling the ^{231}Pa/^{230}Th ratio in the WSDW are therefore important for the interpretation of the ratio in deep water sediments at lower latitudes as proxy for MOC (Anderson et al., manuscript in preparation).

According to the classical reversible scavenging model, the activities of dissolved and particulate ^{230}Th$_{xs}$ and ^{231}Pa$_{xs}$ increase linearly with depth (Bacon and Anderson, 1982; Nozaki et al., 1981), where the subscript xs means excess activities, i.e. the activities of nuclides produced by U decay in seawater. Although all activities presented here are excess activities, we will, following Deng et al. (2014), leave out the subscript in this paper. Rutgers van der Loeff and Berger (1993) reported ^{230}Th and ^{231}Pa profiles from the Weddell Gyre that reached maximum concentrations at mid-depth, and showed how the distribution of these isotopes was controlled by upwelling of CDW and low scavenging rates in these waters south of the ACC characterized by low particle flux (Fischer et al., 1988).

The scavenging of Pa depends strongly on the opal flux. The F ratio (scavenging preference of Th over Pa) changes dramatically through the ACC. North of the ACC the F ratio is 10 or higher, whereas in the opal belt and south of it Pa is much more strongly scavenged than further north, giving an F ratio < 1 (Chase et al., 2002; Walter et al., 1997). The change in F ratio across the ACC is a circumpolar phenomenon. Chase et al. (2003) gave a detailed description of the change in the south Pacific based on water, surface sediment and sediment trap data. They showed that, in this area of the Pacific with little deep water formation, the activities of ^{230}Th and ^{231}Pa show no significant gradients on isopycnal surfaces implying that the upwelling and isopycnal ventilation are too rapid to allow changes in nuclide activities in the upwelled water masses. In the Atlantic sector, upwelled deep waters have a long residence time in the Weddell Gyre under a low-scavenging regime, and although we know that ^{230}Th accumulates under these circumstances (Rutgers van der Loeff and Berger, 1993), it has not yet been clearly shown whether the low scavenging regime with a low F ratio also allows ^{231}Pa to accumulate.

Recently, new data on the distribution of ^{230}Th, ^{231}Pa and ^{232}Th have become available in the GEOTRACES program. Venchiarutti et al. (2011a) described the distribution of these nuclides in Drake Passage and so constrained the composition of Pacific waters transported in the ACC. Deng et al. (2014) quantified the transport of ^{231}Pa and ^{230}Th with NADW into the Southern Ocean. Venchiarutti et al. (2011b) gave new data from Weddell Gyre and Zero Meridian. With this widely improved dataset we now have a firm basis to address the following questions:

- What controls the accumulation of ^{230}Th and ^{231}Pa in the Weddell Gyre and especially in WSDW?
- What controls the composition of ^{230}Th and ^{231}Pa in AABW exported from the Weddell Gyre and across the ACC to the abyssal ocean?
- What is the fate of the ^{230}Th and ^{231}Pa imported in the SO with NADW (Deng et al., 2014) and what is the mass balance of ^{230}Th and ^{231}Pa in the Atlantic sector of the Southern Ocean?

In this paper, we present a model to explain the observed distributions of ^{230}Th and ^{231}Pa in the Weddell Gyre, check the model by applying it to another particle reactive nuclide (^{210}Pb) and give a mass balance of ^{230}Th and ^{231}Pa in the Atlantic sector of the Southern Ocean. We argue that the ACC functions as a double trap for ^{230}Th and ^{231}Pa, once in the surface water and once again in the outflowing deep water.

2. Hydrography of the Weddell Gyre and adjacent ACC

In the Southern Ocean, shoaling Circumpolar Deep Water (CDW) feeds into a shallow meridional overturning cell, upwelling into surface waters and leading to the formation of intermediate waters, and into a deep cell transforming CDW and forming Antarctic Bottom Water (Chase et al., 2003; Fahrbach et al., 2011, Fig. 2). The transport is overwhelmed by the zonal transport in the ACC.

In the Weddell Gyre, CDW enters from the east and circulates as what is locally known as Warm Deep Water (WDW) at depths of 200–1500 m. WDW with at its core a neutral density anomaly of 27.88 $\text{kg}\,\text{m}^{-3}$ is primarily of Lower Circumpolar Deep Water (LCDW) density. Dense waters are produced by ice formation on the continental shelf (high salinity shelf water, HSSW) and under the ice shelf (Ice Shelf Water, ISW). WDW mixes with these salinified and cooled shelf waters to form Weddell Sea Bottom Water (WSBW) and the somewhat less dense WSDW. When these newly formed deep waters leave the Weddell Gyre they are the source of the circumpolar AABW that fills the abyssal ocean.

The Weddell–Enderby basin has a cyclonic circulation with a strong recirculation in the western part (Fahrbach et al., 2011). The basin is confined by a ridge system in the north, and deep and bottom waters can only leave the basin through gaps in these ridges. Outflows of WSDW to the ACC and beneath the ACC to the Argentine Basin are observed over the south Scotia Sea and Georgia Basin, and over the Enderby Basin toward the Crozet-Kerguelen Gap (Haine et al., 1998; Orsi et al., 1999, 1993) (Fig. 1). About half of the export of WSDW occurs through the gaps in the Scotia Ridge (Jullion et al., 2014; Naveira Garabato et al., 2002). This deep water, that exits through the Georgia Passage and Georgia Basin into the Argentine Basin, is more ventilated, cooler and fresher, with origins rather on the slope of the Antarctic Peninsula, whereas the WSDW leaving further east is derived from the Filchner-Ronne Ice Shelf (Gordon et al., 2001; Naveira Garabato et al., 2002).

3. Upwelling, circulation and scavenging: the behavior of particle-reactive nuclides in the Weddell Gyre

The distribution of ^{230}Th in the Weddell Gyre has been measured during Polarstern expedition ANT-VIII/3 in 1991 by Rutgers van der Loeff and Berger (1993) and more recently during Po-