Modelling the relationship between $^{231}\text{Pa} / ^{230}\text{Th}$ distribution in North Atlantic sediment and Atlantic Meridional Overturning Circulation

Mark Siddall$^1$*, Thomas F. Stocker$^1$, Gideon M. Henderson$^2$, Fortunat Joos$^1$, Martin Frank$^3$, Neil R. Edwards$^4$, Stefan Ritz$^1$, Simon A. Müller$^1$.

1. Climate and Environmental Physics, Physics Institute, University of Bern, Bern, Switzerland.
2. Department of Earth Sciences, University of Oxford, Parks Road, Oxford, United Kingdom.
3. IFM-GEOMAR, Leibniz Institute for Marine Sciences, University of Kiel, Wischhofstrasse 1-3, 24148 Kiel, Germany
4. Open University, Milton Keynes, United Kingdom.

*siddall@ldeo.columbia.edu
† Now at Lamont-Doherty Earth Observatory of Columbia University, 61 Route 9W, Pallisades, NY 10964, USA.

Abstract

Down-core variations in North Atlantic $^{231}\text{Pa}_{ss} / ^{230}\text{Th}_{ss}$ have been interpreted as changes in the strength of the Atlantic Meridional Overturning Circulation (AMOC). This modelling study confirms that hypothetical changes in the AMOC would indeed be recorded as changes in the distribution of sedimentary $^{231}\text{Pa}_{ss} / ^{230}\text{Th}_{ss}$. At different sites in the North Atlantic the changes in sedimentary $^{231}\text{Pa} / ^{230}\text{Th}$ that we simulate are diverse and do not reflect a simple tendency for $^{231}\text{Pa}_{ss} / ^{230}\text{Th}_{ss}$ to increase towards the production ratio (0.093) when the AMOC strength reduces but instead are moderated by the particle flux. In its collapsed or reduced state the AMOC does not remove $^{231}\text{Pa}$ from the North Atlantic – instead $^{231}\text{Pa}$ is scavenged to the North Atlantic sediment in areas of high particle flux. In this way the North Atlantic $^{231}\text{Pa}_{ss} / ^{230}\text{Th}_{ss}$ during AMOC shut-down follows the same pattern as $^{231}\text{Pa}_{ss} / ^{230}\text{Th}_{ss}$ in modern ocean basins with reduced rates of meridional overturning (i.e. Pacific or Indian Oceans). We suggest that
mapping the spatial distribution of $^{231}\text{Pa}_{xx} / ^{230}\text{Th}_{xx}$ across several key points in the North Atlantic is an achievable and practical qualitative indicator of the AMOC strength in the short term. Our results indicate that additional North Atlantic sites where down-core observations of $^{231}\text{Pa}_{xx} / ^{230}\text{Th}_{xx}$ would be useful coincide with locations which were maxima in the vertical particle flux during these periods. Reliable estimates of the North Atlantic mean $^{231}\text{Pa}_{xx} / ^{230}\text{Th}_{xx}$ should remain a goal in the longer term. Our results hint at a possible ‘seesaw-like’ behaviour in $^{231}\text{Pa} / ^{230}\text{Th}$ in the South Atlantic.

Keywords:

$^{230}\text{Th}$; $^{231}\text{Pa}$; scavenging; meridional overturning circulation; Younger Dryas

1. Introduction

$^{231}\text{Pa}$ and $^{230}\text{Th}$ are produced in the ocean by the $\alpha$ decay of $^{235}\text{U}$ and $^{234}\text{U}$. The activity of U in the ocean is uniform [Chen et al. 1986] so that $^{231}\text{Pa}$ and $^{230}\text{Th}$ are produced at a constant rate with a production activity ratio ($\beta^{\text{Pa}} / \beta^{\text{Th}}$) of 0.093 throughout the ocean. $^{231}\text{Pa}$ and $^{230}\text{Th}$ are removed from the open ocean by a process of reversible scavenging onto sinking particles [Bacon and Anderson 1982; Nozaki et al. 1987]. $^{231}\text{Pa}$ is scavenged from the water column less effectively than $^{230}\text{Th}$ and is transported over longer distances before deposition in the sediment [Yu et al. 1996]. For this reason the sedimentary $^{231}\text{Pa} / ^{230}\text{Th}$ reflects the combined effects of large-scale advection, diffusion and convection patterns in the ocean alongside vertical transfer linked to particulate fluxes [McManus et al. 2004; Marchal et al. 1999; Siddall et al. 2005; Thomas et al. 2006]. Sedimentary Pa/Th ratios may therefore provide information about the rate of past ocean circulation to complement information about the distribution of water masses recorded by tracers such as $\delta^{13}\text{C}$ and Cd / Ca. Such rate information is crucial to assessment of heat and carbon fluxes in the ocean, making $^{231}\text{Pa} / ^{230}\text{Th}$ a potentially powerful tool to understand past climate change. The development of better understanding of the behaviour of $^{231}\text{Pa}$ and $^{230}\text{Th}$ in the oceans is therefore an important goal.
Sedimentary $^{231}\text{Pa}_{xs} / ^{230}\text{Th}_{xs}$ has been extensively studied in the North Atlantic. The residence time for $^{231}\text{Pa}$ (100-200 years) is similar to the transit time of water masses from the North to the Southern Ocean and thus a considerable amount of $^{231}\text{Pa}$ is exported from the North Atlantic to the Southern Ocean. In contrast, the residence time of $^{230}\text{Th}$ is of the order of several decades so that much less $^{230}\text{Th}$ is removed from the North Atlantic compared with $^{231}\text{Pa}$. Therefore, low $^{231}\text{Pa}_{xs} / ^{230}\text{Th}_{xs}$ in the surface sediment of the North Atlantic is linked to the convection and advection of deep water masses in the North Atlantic (i.e. the AMOC). Yu et al. [1996] considered differences in the mean sedimentary $^{231}\text{Pa}_{xs} / ^{230}\text{Th}_{xs}$ between the present day and the Last Glacial Maximum for the whole Atlantic to suggest that there was little difference in the strength of the AMOC between the two periods. Using the Bern2.5D (zonally-averaged) ocean model Marchal et al. [2000] showed that the mean sedimentary $^{231}\text{Pa}_{xs} / ^{230}\text{Th}_{xs}$ for the North Atlantic was a more accurate measure of the AMOC than the mean sedimentary $^{231}\text{Pa}_{xs} / ^{230}\text{Th}_{xs}$ for the whole Atlantic. The Marchal et al. [2000] study concluded that existing data were consistent with no glacial-to-recent change in AMOC strength, but do not rule out a reduction by up to 30%. The work of Marchal illustrated the usefulness of introducing $^{231}\text{Pa}$ and $^{230}\text{Th}$ into ocean models. Given the pronounced zonal differences in particle flux and ocean circulation across the North Atlantic their introduction into a model with a full three-dimensional configuration is a necessary step in improving our understanding of the dynamics of these nuclides in the ocean [Siddall et al. 2005].

Three sediment core records of $^{231}\text{Pa}_{xs} / ^{230}\text{Th}_{xs}$ covering the last 20 ka have been published recently: McManus et al. [2004] described the $^{231}\text{Pa}_{xs} / ^{230}\text{Th}_{xs}$ record from Atlantic core OCE 326-GGC5 on the western margin of the North Atlantic (33°42´N, 57°35´ W, 4550 m, from here on named SiteW): Gherardi et al. [2005] presented a record from the eastern North Atlantic (Core SU81-18, 37°46´N, 10°11´W, 3135 m, from here on named SiteE); and, Hall et al. [2006]

* the xs subscript is used to indicate that the values represent excess $^{231}\text{Pa}$ and $^{230}\text{Th}$ activities which have been corrected for $^{231}\text{Pa}$ and $^{230}\text{Th}$ originating from U decay within the detrital particles of the sediments and thus only reflect the $^{231}\text{Pa}$ and $^{230}\text{Th}$ adsorbed from the water column.
described the record from a core in the far North Atlantic (DAPC2; 55°58´N, 09°37´W, 1709 m, from here on named SiteN).

Importantly, at SiteW and SiteE, significant increases or changes in the particle fluxes are not apparent in $^{230}$Th-normalized sediment flux records so that changes in the sedimentary $^{231}$Pa$_{xs}$ / $^{230}$Th$_{xs}$ are likely to be entirely due to changes in the AMOC. The $^{231}$Pa$_{xs}$ / $^{230}$Th$_{xs}$ records from SiteW and SiteE are provided in fig. 1 and show broad similarities. There were pronounced increases in $^{231}$Pa$_{xs}$ / $^{230}$Th$_{xs}$ at each site between 17 and 14 ka BP (i.e., broadly during the time of Heinrich event 1, H1) and smaller increases during the Younger Dryas (YD) [McManus et al. 2004; Gherardi et al. 2005]. Gherardi et al. [2005] note that the increase in $^{231}$Pa$_{xs}$ / $^{230}$Th$_{xs}$ during H1 at SiteE lagged the changes in the SiteW record and is of shorter duration. The recovery of $^{231}$Pa$_{xs}$ / $^{230}$Th$_{xs}$ following H1 and the YD was synchronous at both sites. The SiteN record presents a more complicated history of changes in particle flux. During the Holocene the $^{231}$Pa$_{xs}$ / $^{230}$Th$_{xs}$ is at the production ratio. Hall et al. [2006] have suggested that this results from the high opal flux to the sediment at this site during the Holocene. During the glacial termination there are brief increases in $^{231}$Pa$_{xs}$ / $^{230}$Th$_{xs}$ which are suggested to correspond with localised freshwater inputs close to SiteN [Hall et al. 2006].

Because the SiteW record approached the $^{231}$Pa / $^{230}$Th production ratio during H1, it has been suggested that this record indicates a nearly total cessation of the AMOC during this period. The reasoning behind this suggestion is that if $^{231}$Pa is not advected away from the North Atlantic it should be removed where it is produced and the sedimentary $^{231}$Pa$_{xs}$ / $^{230}$Th$_{xs}$ should approach the $^{231}$Pa / $^{230}$Th production ratio. However, this suggestion does not take into account the effects of horizontal-eddy diffusion on the sedimentary $^{231}$Pa$_{xs}$ / $^{230}$Th$_{xs}$, as will become clear in this paper.

Diffusive processes drive a down-gradient transport of $^{231}$Pa into areas of high particle flux, where the $^{231}$Pa is removed. This leads to peaks in $^{231}$Pa / $^{230}$Th in areas of high particle flux [Lao et al. 1992; Kumar et al, 1993], a process which has been described as the ‘particle-flux effect’ [Siddall et al. 2005]. In addition, different particle types scavenge varying proportions of the two
isotopes – the ‘particle-type effect’ [e.g. Chase et al. 2002]. ‘Boundary scavenging’ is the combined effect of this ‘particle-type effect’ and the ‘particle-flux effect’ at ocean boundaries. Thus the distribution of particles plays an important role in the fractionation of $^{231}\text{Pa} / ^{230}\text{Th}$ in the ocean [Anderson et al. 1983; Walter et al., 1997; Chase et al. 2002; Henderson & Anderson 2005; Siddall et al. 2005; Heinze et al. 2006] (Note that Siddall et al. [2005] show that no ‘particle flux effect’ is associated with the maximum in dust flux beneath the Saharan dust plume, indicating that dust is not a significant scavenger of $^{231}\text{Pa}$). Indeed Marchal et al. [2000] found that surface sedimentary $^{231}\text{Pa} / ^{230}\text{Th}$ ratios increase to levels well above the production ratio in areas with high particle flux during slow-downs or shut-downs of the AMOC in a zonally-averaged model. Given the zonal differences in particle flux and ocean circulation across the North Atlantic these effects may be even more pronounced in a 3-dimensional model.

In this paper we attempt to improve our understanding of the effect of variations in the Atlantic Meridional Overturning Circulation (AMOC) on the fractionation of $^{231}\text{Pa}$ and $^{230}\text{Th}$ in the North Atlantic using the Bern3D model [Müller et al. in press].

2. Method

2.1 The Bern3D model

The Bern3D model used in this work has been discussed in detail by Müller et al. [in press] and Siddall et al. [2005]. It transports tracers such as $^{231}\text{Pa}$ and $^{230}\text{Th}$ via advection, diffusion and convection processes within the Bern3D model [Müller et al. in press]. The Bern3D model is a computationally efficient ocean model of intermediate complexity based on the planetary geostrophic equations complemented by a linear drag term [Edwards and Marsh 2005]. The model resolution is 36 by 36 grid squares of equal area across the globe in the horizontal plane with 32 depth levels. The Bern3D model simulates the large-scale circulation on seasonal and longer time scales reasonably well. The AMOC in the model has a strength of 14 Sv, which is slightly weak compared to some other estimates, but within the range of observations ($16 \pm 3$ Sv...
[Ganachaud 2003] to 18.2 ± 2.5 Sv [Talley et al. 2003]). We note especially that the previous work on this subject used a model with an unusually high AMOC of 24 Sv [Marchal et al. 2000].

Particle fields are prescribed using satellite-derived export productivity fields and appropriate dissolution profiles for each particle type. Particle dissolution in the model is discussed in detail by Siddall et al. [2005] and so here we provide a brief description: dissolution of CaCO₃ with respect to depth is described by an exponential penetration profile; dissolution of Particulate Organic Carbon (POC) with respect to depth is described by a power law; and dissolution of biogenic opal is described a temperature (rather than depth) dependent dissolution scheme, which gives near vertical profiles at high latitude. Particles are subject to a uniform settling rate across all particle types - no distinction is made for particles of different size classes. Siddall et al. [2005] found that scavenging of $^{231}$Pa and $^{230}$Th by dust was not significant in controlling the broad pattern of $^{231}$Pa and $^{230}$Th distribution in the ocean so the dust flux is neglected for the purpose of the present study. Particle fields are shown in fig.2. This approach has somewhat under-represented the flux of opal in the northern North Atlantic and equatorial Pacific. This is not a significant problem because in these areas high particle fluxes compensates for the poorly represented ‘particle-type effect’, explaining why the model adequately represents the modern sedimentary $^{231}$Pa / $^{230}$Th distribution [Siddall et al. 2005].

2.2 $^{231}$Pa and $^{230}$Th partition coefficients

A reversible scavenging model is applied to $^{231}$Pa and $^{230}$Th so that the process of adsorption onto falling particles and subsequent desorption at depth leads to an accumulation of $^{231}$Pa and $^{230}$Th with depth [Bacon and Anderson 1982; Roy-Barman et al. 1996]. Within such a scheme adsorption / desorption take place due to the sinking of particles to depths with different $^{231}$Pa and $^{230}$Th concentrations and due to particle dissolution. Nuclide adsorption / desorption processes linked to particle aggregation and disaggregation are not considered explicitly. As in Siddall et al. [2005] an equilibrium-scavenging coefficient is used to describe the relationship between adsorbed and desorbed isotopes. This model assumes that $^{231}$Pa and $^{230}$Th in the water column are at equilibrium with falling particles.
Such equilibrium-scavenging coefficients have often been used to describe the relationship between adsorbed and desorbed $^{231}$Pa and $^{230}$Th [Henderson et al. 1999; Chase et al. 2002; Luo and Ku 1999; 2004a;b; Li 2005]. The dimensionless equilibrium-scavenging coefficient, $K$, is defined as the ratio between dissolved, $A_d$, and particle-associated, $A_p$, activity:

$$K_p = \frac{A_p}{A_d C_p},$$

where $C_p$ is the dimensionless ratio of the particle mass per cubic meter to the density of the fluid and the activities are in units of dpm m$^{-3}$. The superscript $i$ represents $^{231}$Pa or $^{230}$Th and the subscript $p$ represents the particle type (POC, dust, CaCO$_3$ or opal). $K$ values for separate particle types have proved difficult to observe directly [Honeyman et al. 1988] and it is uncertain how readily laboratory assessment of their values [Geibert and Usbeck 2004] can be extrapolated to the field. Modelling work has confirmed the observational assertion [Chase et al. 2002] that the global $^{231}$Pa/$^{230}$Th distribution in the ocean is largely controlled by the global distribution of the biogenic opal compared to CaCO$_3$ flux to the ocean sediments [Marchal et al. 1999; Siddall et al. 2005], the magnitude of the particle flux [Bacon et al. 1976; Anderson et al. 1983; Anderson et al. 1990] and deep ocean advection [Marchal et al. 1999; Siddall et al. 2005].

Values for equilibrium partition coefficients used in this study are given relative to a reference value which is approximately equivalent to the partition coefficient of $^{230}$Th with respect to CaCO$_3$ ($K_{ref} = 1 \times 10^7$) [Chase et al. 2002]. Values for equilibrium partition coefficients used in this paper are summarised in table 1 and are identical to those used in Siddall et al. [2005].

Boundary scavenging is the range of processes by which particle-reactive elements are preferentially removed to the sediment at ocean margins, including both high productivity and particle type effects [Bacon et al. 1976; Anderson et al. 1983; Anderson et al. 1990] - high
lithogenic flux from rivers/coastal erosion provide a primary source of additional particulate flux for scavenging and the supply of nutrients from rivers increases primary productivity, in turn also increasing the particulate flux available for scavenging close to the coasts. High productivity upwelling zones near the coast are represented by the model but there is no representation of the input of lithogenic material at the coast. Boundary scavenging is effectively represented in the model only by the effect of higher productivity related to upwelling areas in grid boxes close to the coast. The potential effect of nepheloid layers on the $^{231}$Pa and $^{230}$Th is also not explicitly considered here other than that the sedimentary $^{231}$Pa / $^{230}$Th is equilibrated with the water immediately above the sediment-water interface. In this way this work is directly parallel to that presented by Thomas et al. [2006] who considered a 1D model of $^{231}$Pa / $^{230}$Th in the ocean for which equilibrium scavenging occurred at the sediment-water interface. Redissolution of $^{231}$Pa and $^{230}$Th from the surface sediment is not considered and is not thought to be significant [François et al., submitted]. There has been some suggestion that particle size classes may scavenge differentially and that particles in smaller size classes cannot sink without undergoing aggregation. We do not account for this process explicitly here but we note that these particles may effectively be considered as part of the dissolved phase in our model. Taking these limitations into account we are attempting here to understand the broad spatial pattern of changes in $^{231}$Pa / $^{230}$Th fractionation as a result of severe changes to the AMOC – we anticipate that our simplified model will be useful as a first step in understanding these changes. We note that the model we present is capable of representing the modern sedimentary $^{231}$Pa / $^{230}$Th distribution [Siddall et al. 2005] and so we feel justified in these assumptions.

2.3 The control run

Here we consider the effect of a shut-down of the AMOC to a value of 2 Sv from the steady state value of 14 Sv (fig. 3). We maintain the same control spin up as in Siddall et al. [2005] for purposes of comparison. Details of the equilibrium scavenging coefficients used for the control run and spin up can be found in Table 1. Fig. 4a compares surface sedimentary $^{231}$Pa and $^{230}$Th from the control run of Siddall et al. [2005] with observations. The sources for the observations shown in all of the figures in this paper are listed in Siddall et al. [2005].
A shut-down of the AMOC to a value of 2 Sv from the steady state value of 14 Sv (fig. 3) is achieved by adding freshwater to the North Atlantic between 45 N and 70 North. The zone of freshwater addition is shown between the black lines in fig. 2. The freshwater flux is increased linearly over 500 model years to a peak of 0.8 Sv and reduced again to 0 Sv over 500 years, provoking the collapse of the AMOC. The effect of shutdown on the AMOC is shown in fig. 5a. There is an almost total cessation of the AMOC throughout the water column. An identical but negative freshwater flux is used to restart the AMOC following the shutdown (fig. 5a).

As discussed above, the Bern3D model does not fully resolve processes adjacent to lateral boundaries. Diffusive processes and boundary scavenging may be somewhat exaggerated at these boundaries. We therefore consider it unwise to compare observations with our model within one grid square of the coast. Unfortunately SiteE and SiteN are within one grid space of the coast in our model and therefore we opt to compare SiteE and SiteN data with equivalent sites one grid space closer to the open ocean and away from spurious effects of the coast in our model. The alternative sites give similar results to the grid squares around them, except to the grid squares adjacent to the coast. In other words our results are not sensitive to our precise choice of site unless it is adjacent to the coast. The data comparison site depths are always equivalent to the depths of the observations.

3. Freshwater forcing experiments

3.1 Changes in $^{231}\text{Pa} / ^{230}\text{Th}$ during a collapse of the AMOC

The effect of AMOC shutdown on sedimentary $^{231}\text{Pa} / ^{230}\text{Th}$ is shown as a time-series for the three sites in Figure 5, and for the whole North Atlantic during complete shut down in Fig. 4b. In this principal experiment the particle fluxes were kept constant at our estimated modern values, as shown in Figure 2 and described above. The equilibrium scavenging coefficients are as in the control experiments of Siddall et al. [2005] (table 2). The ratios follow a similar pattern of variation at SiteW and SiteE, with a range comparable with those in the observations. This result
lends support to the idea that variations in $^{231}\text{Pa} / ^{230}\text{Th}$ at both sites are controlled largely by changes in the AMOC.

The limitations of the model are apparent by comparison with data – the observed lead of changes in $^{231}\text{Pa}_{\text{xs}} / ^{230}\text{Th}_{\text{xs}}$ at SiteW versus SiteE is not simulated. The exact reasons for the difference between the model result and the data are difficult to understand precisely. For now we put these differences down to the relative simplicity of the model and the limitations of our current approach. For example SiteE is very close to the Portuguese coast and may be subject to effects not resolved by the model. Both Gherardi et al. [2005] and Hall et al. [2006] point out the possible effect of variations in the precise location and timing of freshwater input in the ocean during such events and these effects are not well resolved in this model. It is also possible that the precise depth at which the two cores are placed plays a role in that the deep water masses which bathe the two core sites may vary (SiteW is approximately 1400 m deeper than SiteE) and that the representation of water mass movement in the model is not adequate to resolve this effect [Müller et al. in press]. This may also explain the offset values for the simulation of modern conditions at SiteE. A more detailed study of this phasing relationship and the relationship of changes in the $^{231}\text{Pa} / ^{230}\text{Th}$ with respect to depth is beyond the scope of this paper but should be addressed in a future work.

The observed variation in $^{231}\text{Pa}_{\text{xs}} / ^{230}\text{Th}_{\text{xs}}$ at SiteN is not well reproduced; there is little change in $^{231}\text{Pa} / ^{230}\text{Th}$ at the site in the simulations. We note that our simulations are initiated from present-day conditions and not LGM conditions. Differences in atmospheric boundary conditions and/or particle flux between the LGM and modern day may explain the discrepancies between the SiteN record and our simulations. Indeed, Hall et al. [2006] suggest that the production-ratio $^{231}\text{Pa} / ^{230}\text{Th}$ found in their core during the Holocene is linked to the high level of opal in this core during the Holocene. The effects of changing particle flux during freshwater events are considered in a later subsection.
The most striking feature of the simulations is a pronounced maximum in the sedimentary $^{231}$Pa / $^{230}$Th ratios in the northern North Atlantic during AMOC shutdown. Shutting down the AMOC forces the North Atlantic $^{231}$Pa / $^{230}$Th system into a state similar to the North Pacific or North Indian Ocean, which is governed primarily by horizontal-eddy diffusion towards areas of high particle flux. Comparing fig. 2 and figs. 4b,c reveals that indeed the maximum in surface sedimentary $^{231}$Pa / $^{230}$Th in the northern North Atlantic during an AMOC shutdown coincides with the maximum in particle flux.

Our results agree with the modelling study of Asmus et al. [1999] which shows that $^{231}$Pa / $^{230}$Th in the Southern Ocean is likely insensitive to changes in the AMOC. However there is an interesting hint at a seesaw-like response [e.g. Stocker and Johnsen 2003] in the reduced $^{231}$Pa / $^{230}$Th ratios off the Atlantic coast of South America during the period of freshwater forcing. This is due to an increase in the deep western boundary current in this location as a result of the reduced circulation in the North Atlantic.

3.2 Sensitivity to scavenging of $^{231}$Pa by POC and the $^{231}$Pa residence time

An important uncertainty in the modelling of $^{231}$Pa / $^{230}$Th is the significance of POC for $^{231}$Pa / $^{230}$Th scavenging [Dutay et al. 2006]. Here we consider the effect of varying $K^\text{P}_{\text{POC}}$ to assess the robustness of our conclusions to uncertainty in the role of POC scavenging. In the control simulation the scavenging of $^{231}$Pa was set to the reference value ($1 \times 10^7$). Here we consider uncertainty in the scavenging of $^{231}$Pa by POC by varying the respective equilibrium-scavenging coefficient by a factor of 2 around the control reference equilibrium distribution coefficient. This allows us to consider the full range of published estimates for the residence times of $^{231}$Pa (Table 2). The residence time of $^{230}$Th in the model low enough such that $^{230}$Th is removed to the sediment before lateral transport in the ocean can have a strong effect. In this range changes by a factor of 2 to $K^\text{T}_{\text{POC}}$ do not alter the sedimentary $^{231}$Pa / $^{230}$Th ratios substantially because the residence time of $^{230}$Th remains considerably less than the time needed to achieve lateral transport of $^{230}$Th by the ocean. Experiments varying $K^\text{T}_{\text{POC}}$ are not included here for reasons of brevity and for the fact that there is little to learn from them in this context.
Figures 4, 5 and 6 show that the qualitative behaviour of the model runs is very similar in all three cases ($K_{\text{Pa}}^{\text{POC}} = K_{\text{ref}}$, $K_{\text{Pa}}^{\text{POC}} = K_{\text{ref}} / 2$, $K_{\text{Pa}}^{\text{POC}} = K_{\text{ref}} \times 2$), giving us confidence that we are describing robust features of the $^{231}\text{Pa} / ^{230}\text{Th}$ system. Quantitatively there are variations of the order of 10 to 20% in the $^{231}\text{Pa} / ^{230}\text{Th}$ ratio as a result of uncertainty in the scavenging of $^{231}\text{Pa}$ by POC (fig. 5). During the period of collapse the most dramatic changes to the $^{231}\text{Pa} / ^{230}\text{Th}$ ratios occur for the weakest POC scavenging (fig. 5). This is because the residence time of $^{231}\text{Pa}$ in the water column is greatest for runs with weak POC scavenging, facilitating both the strongest advection of $^{231}\text{Pa}$ when the AMOC is on and diffusion of $^{231}\text{Pa}$ into areas of high particle flux when the AMOC is off. Importantly the most striking feature of the simulations - a pronounced maximum in the sedimentary $^{231}\text{Pa} / ^{230}\text{Th}$ ratios in the North Atlantic – is common to all three simulations (compare simulations in fig. 6 and fig. 4).

3.3 Sensitivity to changes in particle flux during a collapse of the AMOC

We have established that by keeping the particle flux constant during the experiments we observe the development of a pronounced $^{231}\text{Pa} / ^{230}\text{Th}$ peak in the northern North Atlantic. Because this effect is due to the higher particle fluxes in the northern part of the North Atlantic compared to the southern part of the North Atlantic (fig. 2) it is important to take into account the possible effect of changes in particle flux during a collapse of the AMOC. Schmittner [2005] shows the results of ensemble-simulations of a coupled climate-ecosystem model of intermediate complexity on the effect on biological productivity of a collapse of the AMOC resulting from surface freshwater forcing. This study found that the biological productivity in the northern North Atlantic is approximately halved during periods of freshwater forcing because of the nutrient limitation induced by the additional stratification which was caused by the imposition of a ‘freshwater lid’ on the northern North Atlantic. Based on the results of Schmittner [2005] we consider the effect of halving the particle fluxes of CaCO$_3$, opal and POC in the zone of freshwater forcing (i.e. a scenario consistent with our experiments). Such a simple ‘cartoon’ of changes in productivity neglects increases in particle flux in the equatorial Atlantic [e.g. Hughen et al. 1996], decreases in the equatorial Pacific [e.g. Bradtmiller et al. 2006] or in the subantarctic ocean [e.g. Sachs and Anderson 2005]. We are not trying to generate an accurate map of $^{231}\text{Pa} /$
During a shut down of the AMOC, rather this exercise is a means to begin to understand how our results might be sensitive to the covariation of particle fluxes with the AMOC strength. Changes to the particle flux are implemented during the period of freshwater forcing. As an additional case of a possible extreme reduction in the particle flux beneath the freshwater forcing area we consider a simulation where CaCO₃, opal and POC fluxes are fixed to typical gyre values in order to consider particle fluxes from a region where present-day biological productivity is nutrient-limited because of intense stratification.

These model runs demonstrate that there is little difference from the control run as a result of halving the particle flux in the North Atlantic (compare figs. 4 and 8), which Schmittner et al. [2005] is the more realistic of the two scenarios during a freshwater forcing event. However, setting the particle flux to typical ocean-gyre values leads to a minimum in $^{231}\text{Pa} / ^{230}\text{Th}$ in the North Atlantic (figs. 7 and 8). Setting the particle flux to typical ocean-gyre values leads to an improved representation of the observed $^{231}\text{Pa}_{\text{ss}} / ^{230}\text{Th}_{\text{ss}}$ at SiteN. Although such an extreme case may be unrealistic across much of the North Atlantic we speculate that this simulation may indicate the significance of reduced opal flux during the LGM and glacial termination as compared to the Holocene for the sedimentary $^{231}\text{Pa}_{\text{ss}} / ^{230}\text{Th}_{\text{ss}}$ ratios – the relatively low opal flux during this period might sensitise SiteN to changes in circulation. Indeed Hall et al. [2006] find coincident variation of $^{231}\text{Pa}_{\text{ss}} / ^{230}\text{Th}_{\text{ss}}$ with the opal flux during the onset of the Holocene, supporting the idea that changes in particle flux have played an important role in setting sedimentary $^{231}\text{Pa} / ^{230}\text{Th}$ in this region during the Holocene but that circulation effects play an important role during the LGM and the glacial termination. Given the limitations of the approach we take to the particle fluxes we do not want to overemphasise this interpretation but simply note that it is within the bounds of our sensitivity experiments.

### 3.4 Slow-down vs. shut-down during H1 and the Younger-Dryas

Here we address whether or not the available downcore $^{231}\text{Pa}_{\text{ss}} / ^{230}\text{Th}_{\text{ss}}$ data may be explained by a slow-down of the AMOC during H1 and the Younger Dryas or whether a complete shut down is required. The definition of slow-down vs. shut-down remains model-dependent. The Bern3D
model does not support a stable AMOC strength between 12 Sv and 2 Sv (i.e. the AMOC strength switches rapidly from 12 Sv to 2 Sv). Here we define a slow down as a reduction from 14 Sv to 12 Sv and a shut down as a collapse of the AMOC from 12 to 2 Sv. The Bern3D model has an AMOC which is relatively slow and we would also like to consider the effect of increasing the AMOC on the sedimentary $^{231}$Pa / $^{230}$Th in the model.

We consider this question for a realistic range of the AMOC strength by gradual varying the freshwater input to the North Atlantic up to the point where the AMOC collapses (at an overturning strength of 12 Sv). We then increase the AMOC strength up to 18 Sv by gradually applying a negative freshwater forcing over the North Atlantic. Such a negative freshwater forcing may represent an increased moisture flux from the Atlantic to the Pacific than is allowed for in the model. By varying the freshwater forcing slowly over thousands of years the model is always at quasi-equilibrium with the freshwater forcing and we can investigate the properties of the model during a slow-down, rather than a full collapse of the AMOC. The resulting plot of the AMOC strength versus modelled sedimentary $^{231}$Pa / $^{230}$Th is shown in fig. 9. The plots show the data as broad bands, expressing the inter-annual variability in the AMOC in the Bern3D model with mixed boundary conditions.

From fig. 9 it is clear that in our model a slow-down in the AMOC can explain the magnitude of the observed YD variability in $^{231}$Pa$_{ss}$ / $^{230}$Th$_{ss}$. The available data are not conclusive on whether the AMOC shut-down or slowed down during the YD but we consider the fact that observed sedimentary $^{231}$Pa$_{ss}$ / $^{230}$Th$_{ss}$ always remain below the $^{231}$Pa / $^{230}$Th production ratio is more consistent with a slow-down than a shut-down.

We may also use the model to assess any ambiguity in whether the observed sedimentary $^{231}$Pa$_{ss}$ / $^{230}$Th$_{ss}$ ratios support a shut-down in the AMOC during H1 as has been suggested by several authors [McManus et al. 2004; Gherardi et al 2005]. There is little ambiguity in the data or the model that H1 consisted of a more severe slow-down of longer duration than that during the YD. However, with the available $^{231}$Pa$_{ss}$ / $^{230}$Th$_{ss}$ a shut-down of the AMOC cannot be confirmed -
comparing fig. 4 and fig. 10 reveals that there is no difference between the slow-down and shut-down scenarios which is discernable at the core sites. The model results indicate that data from core sites in the high particle flux zone to the north of SiteW and to the north west of SiteE (fig. 2) would help resolve this ambiguity in interpretation. If we consider that a halving of the particle flux is the most likely scenario during a freshwater event [Schmittner 2005] then the model presented here suggests that $^{231}\text{Pa}_{\text{xs}} / ^{230}\text{Th}_{\text{xs}}$ at these sites would show a pronounced peak during AMOC shut-down events while slow down events may only cause a slight increase in $^{231}\text{Pa}_{\text{xs}} / ^{230}\text{Th}_{\text{xs}}$ (compare fig. 10 and fig. 4). One caveat to this suggestion is that this precise result depends on the exact location of the maximum particle flux. If the results of Schmittner et al. [2005] are in error then our finding that the maximum in $^{231}\text{Pa}_{\text{xs}} / ^{230}\text{Th}_{\text{xs}}$ would correspond with the maximum particle flux likely remains robust but the location of the maximum particle flux may differ. During AMOC shut-down North Atlantic $^{231}\text{Pa} / ^{230}\text{Th}$ in the model shows similar characteristics to other ocean basins with reduced overturning circulation (Pacific, Indian Ocean) and this increases our confidence in this prediction (for the control simulation fig. 4a and fig. 4b).

We note that the model appears to capture some asymmetry between East and West in the North Atlantic – the variation of $^{231}\text{Pa} / ^{230}\text{Th}$ with respect to the AMOC is greater in the West than the East, in agreement with observations (fig. 1).

4. Further discussion

Here we have included experiments varying separately the particle flux and the scavenging of $^{231}\text{Pa}$ by POC. We have also carried out experiments covarying these parameters but no substantial new insight was gained beyond what is discussed here and so these experiments are not included here.

Under present-day conditions, $^{231}\text{Pa}$ is removed from the North Atlantic by advection and there is little variation in $^{231}\text{Pa}_{\text{xs}} / ^{230}\text{Th}_{\text{xs}}$ across the basin (unlike other basins where deep advection is lower). During a shut down of the AMOC, however, $^{231}\text{Pa}$ is not removed by advection and the particle-flux effect effectively concentrates $^{231}\text{Pa}$ in areas of high particle flux. The spatial
distribution of $^{231}\text{Pa} / ^{230}\text{Th}$ in the North Atlantic may therefore give a convincing fingerprint of changes in the strength of the AMOC. In order to identify this fingerprint cores should be taken from the northern North Atlantic. In this area the model predicts a spatial maximum in sedimentary $^{231}\text{Pa} / ^{230}\text{Th}$ during a slow down or a shut down. This spatial maximum in sedimentary $^{231}\text{Pa} / ^{230}\text{Th}$ coincides with the particle-flux maximum in the northern North Atlantic (Fig. 2). Cores taken from this region should show a more marked change during a shut down than during a slow down. An advantage of this approach is that we should be able to increase our confidence in the link between changes in the AMOC and H1 with a relatively small number of extra cores. Our method is limited by our assumed changes in the particle fluxes during changes to the AMOC. Should the particle fluxes vary during AMOC slow downs or shut downs in a fashion which is different to any of our scenarios the main conclusion that the maximum in $^{231}\text{Pa} / ^{230}\text{Th}$ would coincide with the particle flux maximum is likely robust.

Our results demonstrate that the spatial variation of sedimentary $^{231}\text{Pa}_{\text{ss}} / ^{230}\text{Th}_{\text{ss}}$ in the North Atlantic is likely to increase during a slow down or shut down of the AMOC. Even under present day conditions (with relatively little basin-wide variability) the mean North Atlantic $^{231}\text{Pa}_{\text{ss}} / ^{230}\text{Th}_{\text{ss}}$ ratio is sensitive to the effects of boundary scavenging, undersampling and the particle-flux effect. It would take a substantial number of extra cores in order to generate an accurate value for the mean $^{231}\text{Pa}_{\text{ss}} / ^{230}\text{Th}_{\text{ss}}$ during the glacial termination, LGM and Holocene. Our results indicate that an increased understanding of the spatial distribution of $^{231}\text{Pa}_{\text{ss}} / ^{230}\text{Th}_{\text{ss}}$ in the North Atlantic sediment combined with studies of changes in particle flux in those cores might be a good way to proceed in the shorter term as adequate data to generate basin-wide mean values is generated. The northern sectors of the modern Pacific or Indian oceans may be the best analogies for understanding the sedimentary $^{231}\text{Pa} / ^{230}\text{Th}$ system for the Atlantic during a period of slow-down or shut-down of the AMOC.

Although it has not been a focus of the present study our results hint at a seesaw-like response during the period of freshwater forcing in the North Atlantic. The simulated reduction in $^{231}\text{Pa} / ^{230}\text{Th}$ off the Atlantic coast of South America is due to the enhancement of bottom currents in this area during the period of reduced circulation in the North Atlantic.
There are important limitations to our approach and fully quantitative interpretation of down-core changes in $^{231}\text{Pa}_{\text{ex}} / ^{230}\text{Th}_{\text{ex}}$ remains elusive – there are significant gaps in our understanding of this proxy. Moreover these gaps in our understanding are non-trivial. Here we list a few: the interaction of the $^{231}\text{Pa} / ^{230}\text{Th}$ system with processes of particle aggregation and disaggregation with subsequent variations in settling rate; the effect of particle size; and the effect of seasonal ‘snow falls’ during periods of higher particle production [Scholten et al. 2005] are all unknown and will need to be considered in future modelling and observational studies. Future work will need to consider changes in particle fluxes which are themselves generated by the model (as oppose to the imposed particle fields we apply here). Such model estimates will need to be well constrained by proxy-estimates of these changes to the particle flux.

Acknowledgements

Thanks to Roger François, Alex Thomas, and Nick McCave who provided unpublished $^{231}\text{Pa}$ and $^{230}\text{Th}$ data. Discussion with Ian Hall was useful in preparing this work. Jan Scholten provided very useful comments. Funding was made available from the STOPFEN European Network research project.

References


**Table 1**

List of equilibrium-scavenging coefficients ($K$ values) used in the text as adapted from Chase et al. [2002] following Siddall et al. [2005].

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Experiments</th>
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</thead>
<tbody>
<tr>
<td>$^{230}$Th scavenging by CaCO$_3$</td>
<td>$K_{\text{Th}}^{\text{car}}$</td>
<td>$K_{\text{ref}}$</td>
</tr>
<tr>
<td>$^{230}$Th scavenging by opal</td>
<td>$K_{\text{Th}}^{\text{opal}}$</td>
<td>$K_{\text{ref}}$</td>
</tr>
<tr>
<td>$^{230}$Th scavenging by POC</td>
<td>$K_{\text{Th}}^{\text{POC}}$</td>
<td>$K_{\text{ref}}$</td>
</tr>
<tr>
<td>$^{230}$Th scavenging by dust</td>
<td>$K_{\text{Th}}^{\text{dust}}$</td>
<td>0</td>
</tr>
<tr>
<td>$^{231}$Pa scavenging by CaCO$_3$</td>
<td>$K_{\text{Pa}}^{\text{car}}$</td>
<td>$K_{\text{ref}} / 40$</td>
</tr>
<tr>
<td>$^{231}$Pa scavenging by opal</td>
<td>$K_{\text{Pa}}^{\text{opal}}$</td>
<td>$K_{\text{ref}} / 6$</td>
</tr>
<tr>
<td>$^{231}$Pa scavenging by POC</td>
<td>$K_{\text{Pa}}^{\text{POC}}$</td>
<td>$K_{\text{ref}}$, $2 \times K_{\text{ref}}$, $K_{\text{ref}} / 2$</td>
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<tr>
<td>$^{231}$Pa scavenging by dust</td>
<td>$K_{\text{Pa}}^{\text{dust}}$</td>
<td>0</td>
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### Table 2

A compilation of published residence time estimates for $^{231}$Pa and $^{230}$Th from observations and models.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Observations/model</th>
<th>$^{231}$Pa residence time (yr)</th>
<th>$^{230}$Th residence time (yr)</th>
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<td>116</td>
<td>43</td>
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<tr>
<td>This paper – $K_{Pa_{POC}} = K_{ref} / 2$</td>
<td>model</td>
<td>212</td>
<td>43</td>
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<tr>
<td>This paper – $K_{Pa_{POC}} = K_{ref} \times 2$</td>
<td>model</td>
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<td>43</td>
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<tr>
<td>Henderson &amp; Anderson 2003</td>
<td>observations</td>
<td>130</td>
<td>20</td>
</tr>
<tr>
<td>Yu et al. 1996</td>
<td>observations</td>
<td>200</td>
<td>30</td>
</tr>
<tr>
<td>Anderson et al. 1983</td>
<td>observations</td>
<td>50-100</td>
<td>10-50</td>
</tr>
</tbody>
</table>
Down-core time series of $^{231}\text{Pa}$/$^{230}\text{Th}$ in cores from SiteW ($33^\circ42\text{'}N, 57^\circ35\text{'}W, 4550\text{ m}$ [McManus et al. 2004]) (red), SiteE ($37^\circ46\text{'}N, 10^\circ11\text{'}W, 3135\text{ m}$ [Gherardi et al. 2005]) (blue) and SiteN ($55^\circ58\text{'}N, 09^\circ36\text{'}W, 1709\text{ m}$ [Hall et al. 2006]) (green). The core from SiteW was sampled twice using slightly different methods see McManus et al. [2004] for details - the two records are demarcated using filled and empty red markers. The black dashed line represents the production ratio (0.093).
Figure 2

Particle fluxes used for the Control run and most other runs. The freshwater forcing area used in the experiments as described in the text is between the thick black lines in the North Atlantic. This is also the area over which changes in the particle fluxes were applied (see section 3.3).
Figure 3

The annual mean streamfunction for the AMOC in the Bern3D ocean model for: A, the modern (AMOC on) state ~14 Sv; and B the off state (~2 Sv).
Figure 4

Model simulation of surface sedimentary $^{231}\text{Pa}_{ss} / ^{230}\text{Th}_{ss}$ for: A. the control simulation of the present-day surface sedimentary $^{231}\text{Pa}_{ss} / ^{230}\text{Th}_{ss}$ (AMOC on, 14 Sv), as in Siddall et al. [2005]. Observations are shown as coloured circles; B. Modelled surface sedimentary $^{231}\text{Pa}_{ss} / ^{230}\text{Th}_{ss}$ for the AMOC off state (2 Sv); C. The difference in modelled surface sedimentary $^{231}\text{Pa}_{ss} / ^{230}\text{Th}_{ss}$ between the AMOC on and off states. Diamond = SiteW, Triangle = SiteE, Square = SiteN – actual sites are shown in the upper plot and comparison sites are shown in the lower plots. A complete list of the observational data shown in this plot is given in Siddall et al. [2005].
A: control (AMOC = 14 Sv)

B: control (AMOC = 2 Sv)

C: difference (B-A)

\( \frac{(^{231} \text{Pa}/^{230} \text{Th})}{0.093} \)
Figure 5

The evolution of overturning and sedimentary $^{231}$Pa / $^{230}$Th for three sites during the reduced AMOC run. A. Freshwater forcing (up to 8 Sv over 1000 years, left axis) was applied to the North Atlantic in the region shown in fig. 2. An identical, but negative, freshwater forcing was applied to force the recovery of the AMOC. The overturning collapses from 14 Sv to 2 Sv (right axis). Three cases were considered: the control (thick line); scavenging of $^{231}$Pa by POC halved (thin lines) and; scavenging of $^{231}$Pa by POC doubled (thin dashed lines). The lower three plots show these cases at three sites: B. SiteW (33°42′N, 57°35′ W, 4550 m [McManus et al. 2004]); C. SiteE (37°46′N, 10°11′W, 3135 m [Gherardi et al. 2005]) and; D SiteN (55°58.1′N, 09°36.75′W, 1709 m [Hall et al. 2006]). Black bars represent the H1 to Holocene observed range in $^{231}$Pa / $^{230}$Th and grey bars represent the YD to Holocene observed range in $^{231}$Pa / $^{230}$Th. The thick dashed line represents the $^{231}$Pa / $^{230}$Th production ratio (0.093).
A: FW (Sv)

B: SiteW

C: SiteE

D: SiteN

Max. AMOC (Sv)

Time [year]
Figure 6

Model simulation of surface sedimentary $^{231}$Pa$_{xs}$ / $^{230}$Th$_{xs}$ for the AMOC-on (14 Sv, upper plot) and AMOC off states (2 Sv, middle plot). Also shown is the difference in modelled surface sedimentary $^{231}$Pa$_{xs}$ / $^{230}$Th$_{xs}$ between the AMOC on and off states (lower plot). Diamond = SiteW, Triangle = SiteE, Square = SiteN. A. The scavenging of $^{231}$Pa by POC is halved ($K_{POC}^{Pa} = K_{ref} / 2$). B. The scavenging of $^{231}$Pa by POC is doubled ($K_{POC}^{Pa} = K_{ref} \times 2$).
A: low $^{231}\text{Pa}$ scavenging by POC (AMOC on, 14 Sv)

B: high $^{231}\text{Pa}$ scavenging by POC (AMOC on, 14 Sv)

Middle - Top

$(^{231}\text{Pa}/^{230}\text{Th}) / 0.093$
Figure 7

The evolution of overturning and sedimentary Pa/Th for three sites during the run with both reduced AMOC and altered particle fluxes. Three cases were considered: the control (thick line); particle flux over the freshwater area halved (thin lines) and; particle flux over the freshwater area set to a typical gyre value (thin dashed lines). A. Freshwater forcing is identical to that in the reduced AMOC run (fig. 5). Particle fluxes were altered during the freshwater-forcing period illustrated by the grey box. The lower three plots show these cases at three sites: B. SiteW (33°42′N, 57°35′ W, 4550 m [McManus et al. 2004]) ; C. SiteE (37°46′ N, 10°11′W, 3135 m [Gherardi et al. 2005]) and; D SiteN (55°58.1′N, 09°36.75′W, 1709 m [Hall et al. 2006]). Black bars represent the H1 to Holocene observed range in $^{231}$Pa / $^{230}$Th and grey bars represent the YD to Holocene observed range in $^{231}$Pa / $^{230}$Th. The thick dashed line represents the $^{231}$Pa / $^{230}$Th production ratio (0.093).
Figure 8

Model simulation of surface sedimentary $^{231}$Pa$_{ss}$ / $^{230}$Th$_{ss}$ for the AMOC-on (14 Sv, upper plot) and AMOC off states (2 Sv, middle plot). Also shown is the difference in modelled surface sedimentary $^{231}$Pa$_{ss}$ / $^{230}$Th$_{ss}$ between the AMOC on and off states (lower plot). Diamond = SiteW, Triangle = SiteE, Square = SiteN. A. Particle fluxes (opal, POC, CaCO$_3$) halved. B. Particle fluxes fixed to a value typical of ocean gyres.
A: particle flux in FW zone halved (AMOC on, 14 Sv)

B: particle flux in FW zone minimised (AMOC on, 14 Sv)

(Middle - Top)

(231Pa/230Th) / 0.093

(Middle - Top)

(231Pa/230Th) / 0.093
Figure 9

Plot of mean annual AMOC strength vs. $^{231}\text{Pa} / ^{230}\text{Th}$ at the three sites for three values of the scavenging of $^{231}\text{Pa}$ by POC. The control ($K_{\text{POC}} = K_{\text{ref}}$) is shown as darker areas. The plots show the data as broad bands, expressing the inter-annual variability in the AMOC in the Bern3D model. A. SiteW (33°42´N, 57°35´ W, 4550 m [McManus et al. 2004]) ; B. SiteE (37°46´N, 10°11´W, 3135 m [Gherardi et al. 2005]) and; C. SiteN (55°58.1´N, 09°36.75´W, 1709 m [Hall et al. 2006]). Black bars represent the H1 to Holocene observed range in $^{231}\text{Pa} / ^{230}\text{Th}$ and grey bars represent the YD to Holocene observed range in $^{231}\text{Pa} / ^{230}\text{Th}$. The thin dashed line represents the $^{231}\text{Pa} / ^{230}\text{Th}$ production ratio (0.093). The thick black line is the North Atlantic mean (0 to 70°N) $^{231}\text{Pa} / ^{230}\text{Th}$ ratio in the surface sediment for the control run. Coloured crosses show modelled sedimentary $^{231}\text{Pa} / ^{230}\text{Th}$ at each site during a shut down. Black crosses show the North Atlantic mean $^{231}\text{Pa} / ^{230}\text{Th}$ during a shut down.
A: SiteW

B: SiteE

C: SiteN

\begin{align*}
231\text{Pa} / 230\text{Th} & \\
\text{AMOC (Sv.)} & 
\end{align*}
Figure 10

Model simulation of surface sedimentary $^{231}\text{Pa}_{xs} / ^{230}\text{Th}_{xs}$ for the AMOC-on (14 Sv, upper plot) and AMOC slow-down states (12 Sv, middle plot) for the control simulation. Also shown is the difference in modelled surface sedimentary $^{231}\text{Pa}_{xs} / ^{230}\text{Th}_{xs}$ between the AMOC on and slow-down states (lower plot). Diamond = SiteW, Triangle = SiteE, Square = SiteN.