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Comment on "Glacial-interglacial circulation changes inferred from ^{231}Pa/^{230}Th sedimentary record in the North Atlantic region" by J.-M. Gherardi et al.

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1. Introduction

[1] The excess ^{231}Pa/^{230}Th activity ratio of North Atlantic sediments (^{231}Pa/^{230}Th hereafter) varies with water depth, geographical location and time [*Yu et al.*, 1996; *Siddall et al.*, 2007]. ^{231}Pa and ^{230}Th are produced at a constant rate in seawater from the decay of dissolved ^{235}U and ^{234}U, respectively. Both ^{231}Pa and ^{230}Th are removed from seawater via (reversible) scavenging onto sinking particles, with ^{231}Pa being removed less effectively than ^{230}Th. ^{231}Pa has an oceanic residence time with respect to scavenging of 50–200 years in the North Atlantic, and its rain rate to the seafloor is usually lower than its production rate in the overlying water column. By contrast, ^{230}Th has a much shorter residence time (10–40 years), and its rain rate to the seafloor is thought to be largely independent of particulate flux, and approximately equal to its rate of production [*Anderson et al.*, 1983].

[2] It has been estimated that roughly half of the ^{231}Pa produced in the present-day North Atlantic is transported to the Southern Ocean, while most of the ^{230}Th is buried locally [*Yu et al.*, 1996]. As a consequence, the ^{231}Pa/^{230}Th ratio in deep modern North Atlantic sediments falls somewhat below the seawater production ratio. If ocean circulation were to stagnate, the sedimentary ^{231}Pa/^{230}Th ratio would be expected to approach the production ratio in seawater. The rationale for using sedimentary ^{231}Pa/^{230}Th ratios to estimate past rates of the Atlantic meridional overturning circulation (AMOC) is that lower rates of advection would result in lower export of ^{231}Pa from the North Atlantic, and hence a higher local sedimentary ^{231}Pa/^{230}Th ratio.

[3] However, ocean circulation is just one of several factors contributing to variability in the sedimentary ^{231}Pa/^{230}Th ratio. There also appears to be strong sensitivity of the sedimentary ^{231}Pa/^{230}Th ratio to both particulate flux, and to the composition of particles in the water column.

[4] The chemical composition of particles in the water column has been shown by a number of authors to have an impact on sedimentary ^{231}Pa/^{230}Th ratio [*Chase et al.*, 2002; *Scholten et al.*, 2005; *Gil et al.*, 2009; *Lippold et al.*, 2009]. *Scholten et al.* [2008] argue that, in certain locations, spatial variability in fractionation between ^{231}Pa and ^{230}Th is more important in determining local sedimentary ^{231}Pa/^{230}Th ratios than ocean circulation. They caution that before sedimentary ^{231}Pa/^{230}Th is interpreted as reflecting changing circulation, it is necessary to show that fractionation between ^{231}Pa and ^{230}Th has not changed through time (note that a way to estimate the amount of fractionation in times past has not yet been developed). Clearly, sedimentary ^{231}Pa/^{230}Th can be influenced by changes in number and type of particulates, or by changes in ocean circulation. This comment focuses solely on a recent interpretation of variations in North Atlantic sedimentary ^{231}Pa/^{230}Th in terms of changing ocean circulation.

[5] *Gherardi et al.* [2009, hereafter G09] present a compilation of new and existing records of ^{231}Pa/^{230}Th ratios in cores from across the North Atlantic Ocean at water depths between 1710 m and 4550 m (Figure 1, black dots). After discounting the possible impact of particle flux and chemical composition on sedimentary ^{231}Pa/^{230}Th, G09 directly interpret these records as a kinematic proxy for deep water circulation. Comparing mean Holocene and Last Glacial Maximum (LGM) ^{231}Pa/^{230}Th ratios from different core locations and depths led them to conclude that the overturning circulation in the North Atlantic during the LGM was shallower than today, and that the overturning at intermediate depths was more vigorous than at the present day.

[6] In this comment, two lines of reasoning are presented to suggest that the main conclusions drawn by G09 should be reexamined. First, it is argued that the G09 description of the modern-day AMOC is incorrect. Second, it is argued that the G09 method of making composite vertical profiles of sedimentary ^{231}Pa/^{230}Th for various time slices using cores widely separated in space does not work in the modern-day ocean.

2. Modern-Day AMOC

2.1. Description of the Modern-Day AMOC

[7] G09 (p. 1) state in their abstract, and reiterate in their conclusions that "The ^{231}Pa/^{230}Th ratio measured in upper Holocene sediments indicates slow water renewal above

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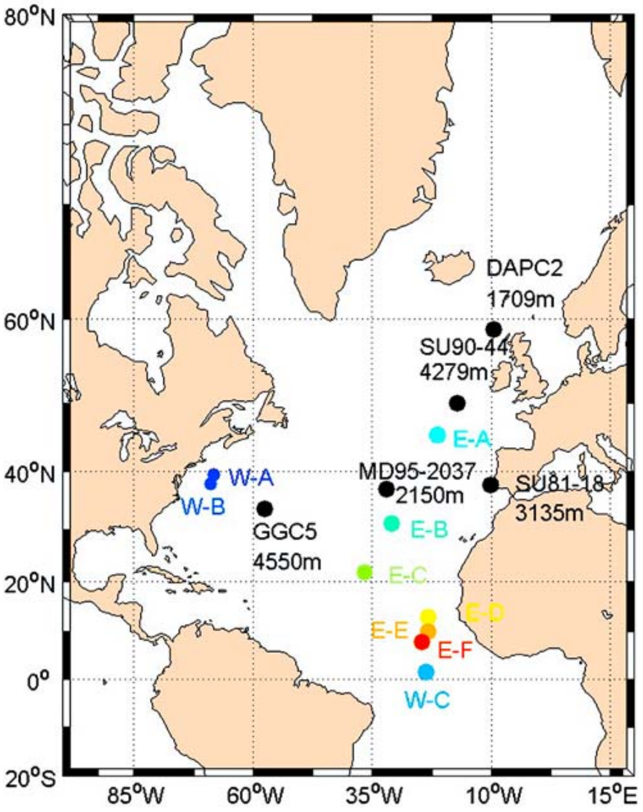

Figure 1. Map of the North Atlantic showing core locations used by G09 (black dots) and those used in the calculation of ^{231}Pa and ^{230}Th residence times in Figure 2 (color dots).

~2500 m and rapid flushing below, consistent with our understanding of modern circulation."

[8] This statement is incorrect. Ample evidence from present-day direct observations of Atlantic's Deep Western Boundary Current (DWBC) indicates that the southward flow is anything but slow above 2500 m. *Lee et al.* [1996] present a 5.8 year time series of moored current meter observations from east of the Bahamas, at roughly 26.5°N, and show that the core of the DWBC flows at about 2500 m depth [*Lee et al.*, 1996, Figure 3] with mean speeds of around 20 cm s^{-1}. *Schott et al.* [2004] analyze currents from two moored arrays east of the Grand Banks at roughly 42°N (both of which record nearly 2 years of data), and a number of hydrographic sections. From these they construct a "mean transport section" [*Schott et al.*, 2004, Figure 8] which shows 4.2 Sv southward transport by the DWBC above roughly 2000 m depth (their analysis is in isopycnal space), and 8.5 Sv southward transport above roughly 3000 m depth. *Smethie and Fine* [2001] estimate formation rates of various water masses in the North Atlantic based on CFC-11 inventories. They compute inventories of 4.2×10^6 moles for Upper Labrador Sea Water (ULSW) (the least dense of waters formed by open ocean convection in the Labrador Sea), 14.7×10^6 moles for Classic Labrador Sea Water (CLSW) (a water mass which ranges between 500 and 2000 m in depth [*Smethie et al.*, 2000]), and 10.9×10^6 moles for the denser Overflow Waters (Iceland-Scotland Overflow Water (ISOW) and Denmark Strait Overflow Water (DSOW)). From these CFC-11 inventories, they infer formation rates of 9.6 Sv for upper NADW (ULSW plus CLSW), 2.4 Sv for pure ISOW, and 2.4 Sv for DSOW. The above studies are supported by results from the ECCO consortium, a project combining state-of-the-art ocean general circulation models with global ocean data seta via data assimilation. Results show that the zonally integrated flow in the North Atlantic is southward between 1000 m and 4500 m depth, with a maximum close to 2500 m depth [*Wunsch and Heimbach*, 2006].

2.2. Is the Present-Day AMOC Consistent With the G09 Reconstructed Holocene Sedimentary ^{231}Pa/^{230}Th profile?

[9] In order for the conclusions of G09 regarding past changes in the AMOC to hold, it is first essential to demonstrate that their Holocene sedimentary ^{231}Pa/^{230}Th profile is in fact consistent with the modern Atlantic overturning circulation. The two shallowest cores used by G09 in their AMOC reconstructions were from 1709 m and 2159 m depth. Both these cores recorded sedimentary ^{231}Pa/^{230}Th ratios close to the production ratio (0.093) during the Holocene. G09 (p. 2) state "Past decreases in the rate of the Atlantic overturning would translate into higher Atlantic sediment Pa/Th, which would reach the production rate ratio for a total shutdown." But could this statement only hold for deeper waters, with a different set of rules governing sedimentary ^{231}Pa/^{230}Th at shallower depths?

[10] It has been shown by *Anderson et al.* [1983] that in surface waters, scavenging rates are sufficiently high that the average ^{231}Pa/^{230}Th ratio in settling particles must be close to 0.093. Is it possible that the strength of overturning circulation recorded by sedimentary ^{231}Pa/^{230}Th in the Atlantic Ocean is a strong function of depth, such that values of around 0.093 could be consistent with vigorous (modern-day) circulation at depths < 2500 m, but that much lower values (0.05–0.07) reflect a strong overturning circulation at greater depths?

[11] The rationale for using sedimentary ^{231}Pa/^{230}Th as a proxy for the rate of ocean circulation is the very different residence time (τ) of ^{231}Pa and ^{230}Th in the water column. It is widely accepted that nearly all ^{230}Th is scavenged locally, while a significant amount of ^{231}Pa is exported out of the North Atlantic basin [*Yu et al.*, 1996; *Moran et al.*, 2002; *Scholten et al.*, 2008]. By computing averaged dissolved ^{231}Pa and ^{230}Th in the North Atlantic, *Yu et al.* [1996] calculated mean residence times of 26 years for ^{230}Th and 111 years for ^{231}Pa. However, the residence times ^{231}Pa and ^{230}Th might be expected to show significant spatial variability. Following *Yu et al.* [1996] and defining residence times as follows:

$$\tau_{\mathrm{Th}} = (1/\lambda_{\mathrm{Th}})[\mathrm{A}_{230\mathrm{Th}}/\mathrm{A}_{234\mathrm{U}}] \mathrm{and} \tau_{\mathrm{Pa}} = (1/\lambda_{\mathrm{Pa}})[\mathrm{A}_{231\mathrm{Pa}}/\mathrm{A}_{235\mathrm{U}}], \quad (1)$$

(where A is the activity and λ is the decay constant), it follows that residence times of both ^{231}Pa and ^{230}Th will show a close resemblance to the activity of dissolved ^{231}Pa and ^{230}Th in the water column, both of which tend to exhibit

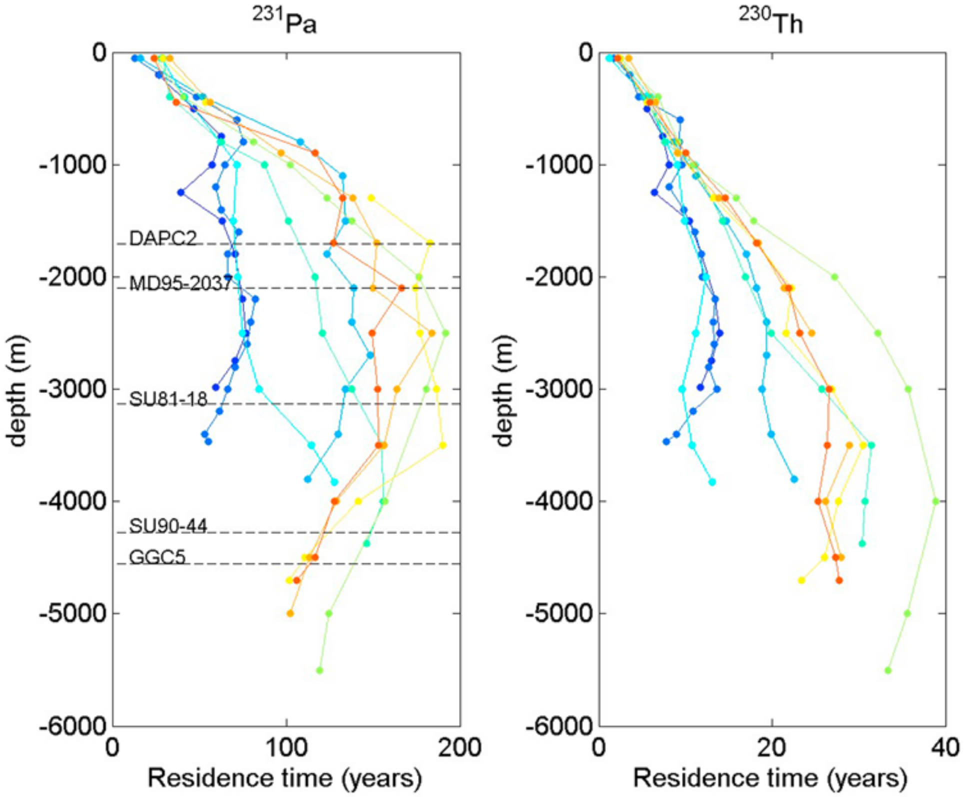

Figure 2. Residence time of ^{231}Pa and ^{230}Th in the North Atlantic water column computed following the definition of *Yu et al.* [1996] and based on data from *Luo et al.* [2009]. Colors of profiles correspond to station locations in Figure 1. Dashed black lines show depths of cores used in the G09 study.

lowest concentrations in near-surface waters and higher concentrations at depth.

[12] What are the implications of spatial variability in residence time? A much shorter residence time for ^{231}Pa in the upper water column of the North Atlantic than at depth could mean that the same strength of overturning circulation would export less ^{231}Pa in shallower water than at depth, which could cause an increase in sedimentary ^{231}Pa/^{230}Th at shallower depths. There is evidence that the ^{231}Pa and ^{230}Th exported to seafloor sediments equilibrates with water within about 1000 m of the local seafloor [*Thomas et al.*, 2006]. In order for the Holocene sedimentary ^{231}Pa/^{230}Th values documented by G09 at depths < 2500 m (0.093) to be consistent with the observed vigorous overturning circulation in this depth range, an extremely low export of ^{231}Pa (and hence an extremely low residence time of ^{231}Pa) in the 1000–2500 m depth range would be required. Are ^{231}Pa residence times at 1000–2500 m depth in the present-day North Atlantic sufficiently small that the G09 observation of sedimentary ^{231}Pa/^{230}Th near production ratio (0.093) above 2500 m depth could be consistent with the observed vigorous overturning in today's ocean?

[13] Taking recently published dissolved ^{231}Pa and ^{230}Th data from the North Atlantic Ocean [*Luo et al.*, 2009] and computing residence times using equation (1) (values of constants taken from *Yu et al.* [1996]) gives the profiles of τ_{Pa} (residence time of ^{231}Pa) and τ_{Th} (residence time of ^{230}Th) shown in Figure 2 (profile colors correspond to station locations in Figure 1). At all the stations, there is a strong gradient in residence time of ^{231}Pa in the upper 1000 m of the water column. There is no clear increase in τ_{Pa} between 1710 m and 4550 m (the depths of the shallowest and deepest cores used by G09 in their reconstructions) at any of the stations where dissolved ^{231}Pa was measured. In fact, the difference in residence time between stations is in general far greater than that at a given station as a function of depth (below 1000 m or so). This indicates that perhaps spatial variability in the residence time of ^{231}Pa might be something that should also be taken into account when using sedimentary ^{231}Pa/^{230}Th as a proxy for ocean circulation.

[14] An additional check on the validity of the Holocene sedimentary ^{231}Pa/^{230}Th profile presented by G09 can be made by looking at other existing Holocene (core top) data. A plot of compiled core top sedimentary ^{231}Pa/^{230}Th from throughout the North Atlantic basin (G. Henderson, 2009, http://climotope.earth.ox.ac.uk/research/oceanic_u-series_database/holocene_231pa230th_dataset_notes_and_references) is shown in Figure 3 (G09 Holocene data points overlain in black). A general decrease in sedimentary ^{231}Pa/^{230}Th with increasing water depth is apparent, as is a general agreement with the G09 data. It is, however, clear that there is significant scatter in sedimentary ^{231}Pa/^{230}Th values throughout the water column, and certainly no evidence for values at pro-

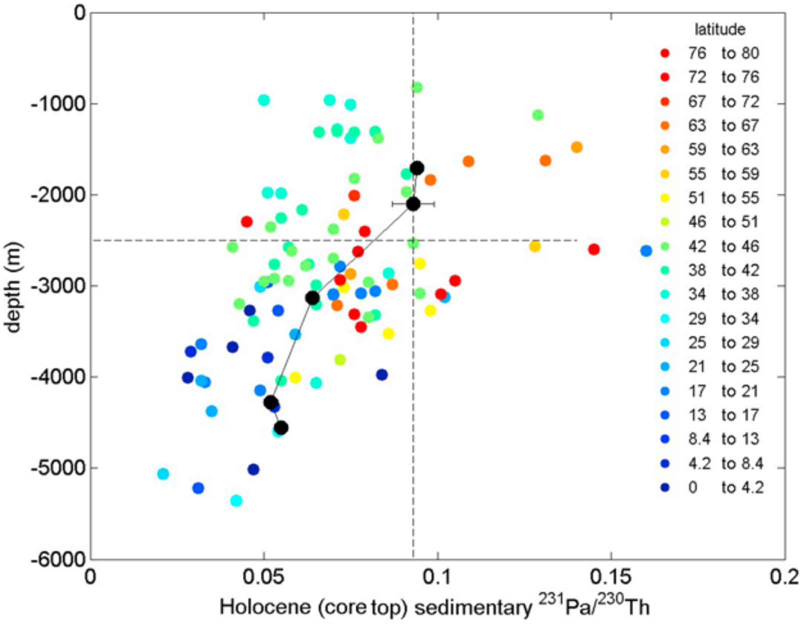

Figure 3. Holocene (core top) North Atlantic sedimentary $^{231}Pa/^{230}Th$ plotted as a function of water depth (cores at depths < 800 m excluded from plot). Colors indicate latitude. Data were obtained from G. Henderson (2009) (http://climotope.earth.ox.ac.uk/research/oceanic_u-series_database/holocene_231pa230th_dataset_notes_and_references). Depths were computed from core latitude and longitudes using the ETOPO5 database [*NOAA*, 1988]. Vertical dashed line indicates the production ratio of $^{231}Pa/^{230}Th$.

duction ratio everywhere in the upper 2500 m of the North Atlantic water column.

[15] An alternative to a purely data based approach to understanding controls over sedimentary $^{231}Pa/^{230}Th$ is to use models to guide understanding. However, until models can accurately represent the observed values of dissolved ^{231}Pa and ^{230}Th in the water column, it will be hard to have faith in their predictions of sedimentary $^{231}Pa/^{230}Th$. A case in point are the recent results of *Luo et al.* [2009], where a 2-D zonally integrated model of the Atlantic was used to try and place constraints on sedimentary $^{231}Pa/^{230}Th$. The model showed significant offsets between observed and modeled dissolved ^{231}Pa and ^{230}Th at certain locations (not surprising given the variability in the data), and used adsorption and desorption rates for ^{231}Pa and ^{230}Th which varied by over an order of magnitude with location and depth. The model also predicted significant spatial variability in fractionation factors. Given both the impossibility of capturing the observed spatial variability in a two-dimensional framework, and the ad hoc nature of prescribed parameters, it is very difficult to use such a simplistic modeling framework to further understanding of data.

[16] To summarize section 2.1, G09 (p. 1) were incorrect in their statement that "The $^{231}Pa/^{230}Th$ ratio measured in upper Holocene sediments indicates slow water renewal above ~2500 m and rapid flushing below, consistent with our understanding of modern circulation." In the modern-day ocean there is a significant amount of flow above 2500 m depth which is part of the Atlantic MOC. In order for the G09 measured Holocene sedimentary $^{231}Pa/^{230}Th$ to be consistent with modern circulation, unless one looks to changes in particulate flux or fractionation factors to account for some of the observed variability, one must invoke much shorter residence times of ^{231}Pa in the upper water column than at depth in the North Atlantic, and this appears to be inconsistent both with modern-day water column data (Figure 2), and with other shallow Holocene core top data from the North Atlantic (Figure 3).

3. Location of Cores

[17] The meridional overturning circulation (MOC) is defined as the zonally integrated circulation [*Wunsch*, 2002]. G09 compare sedimentary $^{231}Pa/^{230}Th$ from five North Atlantic cores at different geographic locations and depths (Figure 1), and use these cores to provide reconstructions of the AMOC at different periods in time, from LGM to Holocene. They do this by computing average sedimentary $^{231}Pa/^{230}Th$ for each core at each time period, and then constructing a single composite depth profile of sedimentary $^{231}Pa/^{230}Th$ at each time period. In order for the G09 method to work, changes in the sedimentary $^{231}Pa/^{230}Th$ ratio at any given site must be representative of changes in the zonally integrated circulation, and all cores at the same depth in the North Atlantic (regardless of geographic location) must record the same sedimentary $^{231}Pa/^{230}Th$ signal at a given time.

[18] The DWBC is a very narrow, fast boundary current that hugs the coastline of the Western United States for much of its traverse down the Atlantic [*Schott et al.*, 2004]. It shows high levels of temporal variability [*Cunningham et al.*, 2007]. The lower branch of the AMOC is set in

large part by the strength of the DWBC. Inverse methods designed to infer the time-mean circulation from hydrographic observations reveal extremely high spatial variability in the ocean circulation, with velocities changing sign many times across the width of the Atlantic basin [*Ganachaud*, 1999]. All existing tracers with a residence time of order 100 years or longer (e.g., oxygen, silicate, phosphate) show strong spatial variability on a given depth surface in the Atlantic basin (http://www.ewoce.org/gallery/index.html). It seems highly improbable that a tracer such as ^{231}Pa with a residence time of 50–200 years in the subthermocline North Atlantic Ocean (Figure 2) would fail to show spatial variability at a given depth.

[19] Variability in dissolved ^{231}Pa at a given depth will translate into variability in particulate and sedimentary ^{231}Pa/^{230}Th at a given depth, regardless of whether there is some degree of vertical integration inherent in the particulate sedimentary ^{231}Pa/^{230}Th values. Further support for the variability on a given depth surface comes from the Holocene core top sedimentary ^{231}Pa/^{230}Th database (Figure 3). The variability at a given depth appears to be about as large as the difference in mean values between 1500 m and 5000 m depth.

[20] If there is spatial variability in sedimentary ^{231}Pa/^{230}Th at a given depth in the North Atlantic Ocean at a given time, then the methodology of G09 (namely taking single cores from various depths across the basin and using these to construct a composite sedimentary ^{231}Pa/^{230}Th profile at different time slices) cannot work.

4. Concluding Remarks

[21] The major points raised in this paper are as follows.

[22] 1. G09's description of the Holocene AMOC does not agree with our understanding of the modern North Atlantic overturning circulation; nor does their Holocene reconstruction of circulation based on sedimentary ^{231}Pa/^{230}Th appear to be consistent with the modern AMOC.

[23] 2. The cores used by G09 to reconstruct the AMOC are spread across the entire North Atlantic Ocean (Figure 1). It seems highly improbable that sedimentary ^{231}Pa/^{230}Th is constant at a given depth and time throughout the North Atlantic, which is the assumption implicit in their analysis.

[24] **Acknowledgments.** Thanks to G. Henderson for the Holocene core top sedimentary ^{231}Pa/^{230}Th database and to G. Dickens for helpful comments on the manuscript. This work was funded by NSF through NCAR.

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