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Interactive comment on "Impact of a 30 % reduction in Atlantic meridional overturning during 2009–2010" *by* H. L. Bryden et al.

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Response to Reviewers 1 and 2

Thank you for the critical reviews of our manuscript and for the complimentary comments on the writing quality. Each of you raised similar points that we answer first, followed by our responses to your detailed criticisms.

Both Reviewers asked that the colours and labeling be made consistent for Figures 1 and 2. We have revised Figure 2 to make the colours and labeling consistent with Figure 1.

Both Reviewers asked for an explanation on why the Rapid event was extraordinary in comparison with coupled climate models. This is difficult to address directly in the paper because it is based on work done by Chris Roberts who has analysed 11 CMIP5 models to show that the model year-to-year variability in AMOC transport is substantially less than the 5 Sv signal in the Rapid event. Only 6 years out of 6000 control model years had year-to-year variability in AMOC as large as the 4.7 Sv observed by Rapid between 2008-09 and 2009-10; and the standard deviations for the model variability are small, of order 1.5 Sv. We have a marvelous slide of the Roberts analysis, he has talked about it at EGU (http://www.nature.com/news/atlantic-current-strength-declines-1.15209), but it is not published yet. McCarthy et al (2012) gave some evidence in their supplemental material and that is the only published reference including Roberts as an author that we found for the extraordinary nature of the Rapid event.

Both Reviewers asked for more information on the depth distribution of the heat content anomaly changes during the event; and for how this depth distribution affects our argument that the reduction in ocean heat transport was more important than the anomalous air-sea fluxes in causing the heat content changes in the surface layers. We now describe the vertical structure of changes in heat content anomaly north and south of 25°N in a new paragraph at the end of section 3:

"As suggested by the profiles of temperature anomaly in Figure 5, the vertical structure for changes in heat content anomaly is different for the regions north and south of 25°N. North of 25°N, the changes in heat content anomaly during the event penetrate down to 1000 dbar and they decrease only slowly down from the surface, amounting to 3.6 x 1021 J for the interval 0 - 200 dbar decreasing to 2.6 x 1021 J for 400 - 600 dbar and to 1.2 x 1021 J for 800 - 1000 dbar. South of 25°N, the changes in heat content anomaly during the event are concentrated in the upper ocean, amounting to 3.4 x 1021 J for the interval 0 - 200 dbar, decreasing to 0.6 x 1021 J for 400 - 600 dbar and to 0.1 x 1021 J for 800 - 1000 dbar. The heat content anomaly changes (and hence the temperature anomaly changes) in the interval 0 - 200 dbar are similar in magnitude but opposite in sign north and south of 25°N during the event."

Then, in Section 4 when comparing air-sea flux anomalies with upper ocean heat con-

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tent anomalies north of 25°N, we have added 2 sentences to the middle of the third paragraph:

" The anomalous air-sea flux cooling north of 25°N during the event of about 1.2 x 1021 J is the same size as the reduction in heat content anomaly in the upper 0 - 60 dbar and is a factor of 3 smaller than the reduced heat content anomaly of 3.6 x 1021 J in the upper 200 dbar, which we consider a reasonable layer thickness over which air sea fluxes have direct effect. Thus even for the upper ocean, the reduction in heat content anomaly is larger than the anomalous air-sea flux cooling during the event."

Finally in the paragraph on ocean heat content anomaly changes for the region south of 25°N, we have inserted a sentence

"The increase in ocean heat content anomaly in the upper ocean (0 - 200 dbar) of 3.4 x 1021 J during the Rapid event is the same size but of opposite sign to the anomalous air-sea heat flux cooling of order 2.5 x 1021 J, suggesting that the effects of the reduction in northward heat transport during the event were partially compensated by an adjustment in air-sea heat exchange."

Thank you for your reviews which helped us improve the paper, especially with respect to the depth structure of the changes in ocean heat content anomalies and their relation to air-sea heat flux anomalies.

Response to Reviewer 2

2. Because the Rapid time series started at the end of March 2004, Rapid papers have tended to define year-long averages from 1 April to 31 March. This is the basis in McCarthy et al. (2012) and in Smeed et al. (2013). When we looked carefully at the Rapid time series, we judged that the event started in early 2009, maybe in February, so we decided to define the normal period to be 1 April 2004 to 31 December 2008. Defining exactly when the event starts and the "normal" period ends has little effect on estimating the size of the event.

We calculate the accumulated deficit until April 2011, which was the end of the Rapid time series when we started this analysis. Smeed et al (2013) indicated that the year April 2010 to March 2011 had an MOC transport of 16.7 Sv not very different from the values in the first 5 years, April 2004 to March 2009. Thus, we feel justified in defining the "event" in terms of the accumulated transports as starting in early 2009 and ending in early June 2010. There is a continuing decline in the MOC as reported in Smeed et al (2013) but that decline becomes more apparent with the decline in the MOC after Spring 2011. Up to April 2011, the event is the major feature in the time series (see comments in Smeed et al (2013) on how to account for the event in terms of long term trends).

We prefer not to add arrows or shading. We agree that the exact start and end of the 'event" are fuzzy and we prefer not to make definite boundaries. To our eyes accustomed to looking at the time series, the long period of reasonably strong, steady UMO values of about -20 Sv from early 2009 through June 2010 represent the strengthening mid-ocean circulation.

3. We did examine 30-day maps, they smoothly vary in time but that is partially due to their autocorrelation time of 50 days. We concentrated on seasonal (3-month averages) because they are independent based on the 50-day autocorrelation time scale for heat content anomalies and they represent a meaningful time interval for winter, spring, summer, autumn anomalies.

We are currently examining the correlation between MOC variations and SST anomaly patterns over the North Atlantic including the Gulf of Mexico. We did not use SST in the Gulf of Mexico for this analysis because we do not know how to relate SST anomaly to heat content anomalies in the absence of Argo profiles informing the vertical structure of the anomalies.

4. We have tried to improve our discussion of the role of air-sea heat flux anomalies so it is clearer that they are smaller than the changes in ocean heat content anomalies

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over the upper 200 m which we argue is a typical value for the layer over which air-sea heat flux anomalies have direct effects.

We have split the first long paragraph of Section 3 into 2 paragraphs: first an introduction, second a technical description as to how the anomalies in air-sea fluxes are determined. Next we describe the changes north of 25°N and south of 25°N in separate paragraphs. Then we finish the section with the heat budget paragraph including new final sentences.

"During the slowdown of the AMOC in 2009-10, northward ocean heat transport across 25°N decreased, causing temperatures in the northern subtropics to decrease substantially (as has also been demonstrated by Cunningham et al., 2013) and temperatures in the tropics to increase. Air-sea fluxes contributed little to the observed temperature changes. The slowdown in the overturning circulation produced the spatial pattern of cooler waters north of 25°N and warmer waters south of 25°N that peaked in Summer 2010."

We have moved the discussion of Figure 7 (pattern of 50 m temperature anomalies) into the next section "Response of the Atmosphere to the Rapid Event"

It now reads "maximum cooling". Thank you for spotting the error.

We are trying to compare the size of changes in ocean heat content with the changes in air sea fluxes. Our primary argument is that MOC slowdown and associated ocean heat transport anomaly causes the changes in ocean heat content anomalies, both north and south of 25°N. The reduction in ocean heat transport is the same size (and sign) as the changes in ocean heat content anomalies. Here we are trying to show that the air sea heat flux anomalies are smaller than the changes in ocean heat content anomalies, so they cannot account for the changes in ocean heat content anomalies. We hope Section 4 has been made clearer.

We have eliminated the old last sentence of Section 4. Instead we now finish that last paragraph with 3 sentences:

" During the slowdown of the AMOC in 2009-10, northward ocean heat transport across 25°N decreased, causing temperatures in the northern subtropics to decrease substantially (as has also been demonstrated by Cunningham et al., 2013) and temperatures in the tropics to increase. Air-sea fluxes contributed little to the observed temperature changes. The slowdown in the overturning circulation produced the spatial pattern of cooler waters north of 25°N and warmer waters south of 25°N that peaked in Summer 2010."

6. We have changed the title of Section 6 from Conclusions to Discussion

Interactive comment on Ocean Sci. Discuss., 11, 789, 2014.