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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

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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 1

We have discussed the title many times, changed it for various presentations but in the end we prefer to use "Impact . . . " Impact is intended to be somewhat open-ended. It is first the impact on northward ocean heat transport, then on heat content north and south of 25°N. We suggest there are impacts on wintertime weather and hurricane strength through the upper ocean temperature anomalies produced by the slowdown. Longer term, there are likely to be impacts on air-sea heat fluxes though we have not firmly observed them.

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We keep the last sentence of the Abstract because warmer upper ocean temperatures in the hurricane formation region are documented as one of the principal contributions (along with wind shear) to strong hurricanes during an anomalous hurricane year.

We have changed the title of Section 3 to "Impact of the Slowdown on Ocean Heat Content".

We have revised Section 4, hopefully to make it clearer. We have tried to adjust 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 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 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 with new final sentences. And 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". Also as stated earlier, we have tried to improve our analysis in Section 4 according to the comments by both Reviewers about the depth penetration of the changes in ocean heat content anomalies.

In our experience, atmospheric scientists almost always attribute changes in upper ocean temperatures to air-sea fluxes. We agree with the Reviewer that formally changes in heat content are due to a combination of air-sea heat exchange and heat transport divergence. Because ocean heat transport divergence is so difficult to estimate (even in models), the default approach is to attribute changes in upper ocean temperatures to air-sea fluxes. We retain the sentence.

With respect to the Taws et al. 2011 results, we agree on their argument for the "re-emergence" of the winter 2009-10 temperature anomalies to produce the winter 2010-11 anomalies that they say led to the NAO-negative winter conditions over Europe.

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Taws et al. considered the winter 2009-10 temperature anomalies to have been set by the NAO-negative conditions in that winter. In contrast, we think the 2009-10 temperature anomaly pattern (at least two-thirds of it) was a result of the Rapid event and, using Taws et al's argument, this temperature anomaly pattern helped to produce the Winter 2009-10 NAO-negative conditions. Thus, we see a role for the Rapid event in both the wintertime 2009-10 and wintertime 2010-11 NAO-negative conditions.

We use a 10-year reference period for the air-sea fluxes because a longer period is better for removing the sizeable seasonal signal before examining anomalies. We have now stated explicitly: "We use the 10-year (1999-2008) baseline fluxes rather than the shorter 2004-2008 time period in an effort to remove the sizeable seasonal cycle in heat flux." The lack of notable trends in the 10-year accumulated flux anomaly time series in figure 6 gives us confidence in the choice of reference period.

Absence of Gulf of Mexico Argo profiles and heat content severely limits our ability to fully account for heat content anomaly changes "south of 25°N". The Gulf of Mexico is a sizeable area just "south" of 25°N that we do not account for in the changes in heat content anomalies.

We have moved the paragraph describing the temperature anomaly pattern (Figure 7) to section 5 "Response of the Atmosphere to the Rapid Event" because it represents our ideas on how the Rapid event influenced the atmosphere.

We maintain the paragraph on ocean state estimation because it does represent our approach (philosophy) that prediction of changes associated with a slowdown in the AMOC is more important than a hindcast that a slowdown did occur. We eliminated the old last sentence of this paragraph and replaced it with the following to end the section

" 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 tempera-

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tures 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."

Technical corrections We now define "Rapid" by adding the phrase "within the Rapid programme" in the first sentence of the Introduction.

We have changed "heat content" to "heat content anomaly" in many places throughout the text. We do not use "anomaly" in some places where it is not needed (eg in general physical arguments).

We do not annotate Figure 1 as suggested. Figure 1 of McCarthy et al 2012 is published so it is available to be examined. The start and end of the event are fuzzy, and we decided not to make the timing exact by adding vertical bars or by adding a grid.

We have made the colours and labeling of Figure 2 consistent with those in Figure 1.

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

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