Clim. Past Discuss., doi:10.5194/cp-2016-31-RC1, 2016

Dear Reviewer,

Thank you for your thorough review and comments!

Interactive comment on "Disentangling the effect of ocean temperatures and isotopic content on the oxygen – isotope signals in the North Atlantic Ocean during Heinrich Event 1 using a global climate model" *by* Marianne Bügelmayer-Blaschek et al.

Anonymous Referee #1

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This study analyses three simulations of Heinrich Event 1 with an isotope-enabled model of intermediate complexity. Time series of simulated d18O seawater and calculated d18O calcite (based on simulated d18O seawater and simulated seawater temperatures) are then analysed and loosely compared to four sediment cores. The three different simulations differ in the length of the iceberg calving episode and have different impacts on the Atlantic Overturning Motion. The authors conclude that the duration of the simulated Heinrich event causes a strong and non-linear response in the AMOC.

I have several major problems with this study.

First, a very similar study appeared last year (Bagniewski et al., 2015, "Quantification of factors impacting seawater and calcite d18O during Heinrich Stadials 1 and 4", Paleoceanography, 30(7), 895-911). Bagniewski et al. conducted several simulations of Heinrich Events with an isotope-enabled model of intermediate complexity. They disentangled the effect of ocean temperature and isotopic content on d18O calcite in the North Atlantic and worldwide. They took this study one step further and also disentangled the pure d18O seawater meltwater signal and the changes in d18O seawater due to changes in circulation and climate. They then compared their simulated values with over 20 sediment records at the surface and at depth (including time series in their supplementary material). Bagniewski et al.'s research questions and conclusions are similar to what is presented here.

We first want to address your concern that our paper is very similar to the Bagniewski et al. (2015). You are right, we unfortunately missed its publication, but we have added the missing citation in our manuscript. We studied the paper by Bagniewski et al. (2015) closely and would argue that it is not very similar, as our study provides important additional insights due to the direct computation of the dynamics of icebergs.

It should be noted that our study does not concentrate on the maximum signal of the Heinrich event and how well this is captured in our model, since this was done before by Roche et al (2014). Instead, we were interested in the development of the d18O_calcite's signal at the beginning and during Heinrich event 1, since different factors affect this signal.

Please find a detailed list of differences between the two papers in the table below.

Bagniewski et al. (2015)	Bügelmayer-Blaschek et al. (2016)
RESEARCH QUESTIONS	
Analyse the respective impacts of: 1) addition of d18O depleted meltwater in the North Atlantic and its propagation; 2) anomalies in seawater d18O due to changes in ocean circulation, evaporation, precipitation, river discharge, sea ice formation and melt; changes in water temperatures → concentrate on maximum change between ocean states during the HE compared to the control state	*(1) What is the impact of the duration of the iceberg discharge on the climate's response? (2) To what extent does the simulated signal in d18O calcite during Heinrich event 1 depend on its location? (3) How do the changes in ocean temperatures and d18O seawater caused by the iceberg discharge and related changes in ocean circulation impact the d18O calcite recorded in proxies?* → concentrate on complete time series to analyse the signal of d18O_calcite during Heinrich event 1
EXPERIMENTAL SET-UP	
Saltfluxes equivalent of 0.2 Sv freshwater	Calving flux (ice) equivalent of 0.2 Sv freshwater that is used to generate icebergs
Saltfluxes are added in the North Atlantic	Iceberg calving takes place along the estimated margin of the Laurentide ice sheet
Isotopic ratios -20‰ / -30‰ /-40‰ → -20 ‰ fits best to paleoproxy data	Fixed isotopic ratio of -30‰
Duration of 1800 years	Duration of 300 / 600 / 900 years
Add artificial addition of salt to the North Atlantic to trigger AMOC recovery	No artificial salt addition. Test how long iLOVECLIM needs to start the AMOC again
Compute modelled d18O calcite using the simulated d18O seawater by adding the temperature effect using simulated surface and bottom temperatures (following Shackleton 1974 and Marchitto et al., 2014)	Compute modelled d18O using the modelled d18O seawater and temperatures following the equation of Shackleton: d18O calcite = 21.9 – 0,27+d18Oseawater (SMOW)-sqrt(310,61-10*Tmodelled)
Compute paleoproxy d18O seawater by removing the temperature effect from the paleoproxy-derived d18O calcite	
Investigate North Atlantic Deep Water Formation, North Pacific Deep Water formation (restricted impact to North Pacific), Antarctic Bottom Water	Investigate AMOC only
Compare 36 cores	Compare 4 cores
Determine surface and benthic d18O HS anomalies = difference of 500 year d18O average before and during HE for each core	Display complete time series of cores
Compute difference of 10 year averages of control state and end of HE	Display difference of 100 year averages of control state and end of the HE and complete time series of experiments
RESULTS	
NADW shut down after 200 years	AMOC strongly weakened after 300 years, shutdown after 400 years of iceberg calving
Investigate maximum difference between HE state and ctrl state in various depths (10 year averages)	Investigate maximum difference between HE state and ctrl state at the surface (100 year averages)
Surface: Maximum change in d18O seawater / calcite, SST in the Iceland Sea and the eastern North Atlantic	Maximum change in d18O seawater / calcite in the Labrador Sea and the central North Atlantic, SST in the central North Atlantic and Iceland Sea

Analyse the time development of d18O anomalies (seawater & calcite) in the North Atlantic, North Pacific at top and bottom	Analyse d18O seawater/ calcite / SST signal at different locations to investigate the time development of the d18O_calcite signal during the iceberg calving and the impact of the SST and the d18O_seawater respectively
Investigate the impact of the circulation and climate signal, meltwater signal & temperature effect signal	Investigate the impact of SST and d18O_seawater signal on d18O_calcite

There is however one exciting new aspect in this study: the simulation of more realistic meltwater pattern and the fact that seawater temperature changes due to latent heat loss of melting icebergs are taken into account. To make this study more original, one solution might be to rewrite the paper and focus on the impact of a more realistic parameterization of iceberg drift and melting on d18O seawater and d18O calcite (i.e. compare pure hosing experiments with the same amount of total freshwater with the simulations presented here). Given that most modeling studies of Heinrich events are based on simplified meltwater hosing scenarios, such a study would be of great interest to the modeling community. An in-depth discussion on how well such a coarse resolution model can be expected to capture iceberg drift should also be included.

As stated above, there are substantial difference between the present study and the paper of Bagniewski et al. (2015), therefore, we do not agree that it is necessary to rewrite the paper. However, we do agree with the good comment of the reviewer that a comparison between a hosing and an iceberg experiment should be included. Thus, we added a paragraph where we compare the hosing experiment – LS 0.2Sv - conducted by Roche et al. (2014) to our ICE-300 experiment, please see general comments.

Further, we don't agree that an in-depth discussion on how well such a coarse resolution model can be expected to capture iceberg drift should be included because this issue has already been discussed in detail previous publications (Jongma et al., 2009; Bügelmayer et al., 2015)

Second, the authors cannot conclude that it is the length of the Heinrich Event that causes the non-linear response of the AMOC. To make this conclusion, one additional simulation should be integrated which introduces the same overall volume of icebergs released in ICE-900 over only 300 years. I would not be surprised if the impact on the AMOC in such a simulation is similar to ICE-900, but I might be wrong. There are many publications discussing the hysteresis behavior of the AMOC for a whole zoo of models (including model intercomparison studies), and I would strongly encourage the authors to cite the original literature when discussing this aspect. Most of these publications base their analysis on the total volume of freshwater added. If LOVECLIM shows a significantly different behavior based on the duration only (and not on total volume) then this might be an interesting and publishable result. Otherwise, there is nothing new about this result.

As suggested by the reviewer, we have performed one additional experiment where we added 0.6 Sv over 300 years. The AMOC shuts down immediately when applying such a strong forcing. It increases to about 5 Sv for 300 years and then drops to 4 Sv. In total it takes 800 years in iLOVECLIM for the AMOC to recover from a 0.6 Sv iceberg forcing applied for 300 years.
*The non-linear behavior of the AMOC in iLOVECLIM can be seen in Figure 1 and also Table 1. First, the same amount of freshwater (3*ICE-300 and ICE-900) results in very different recovery times (800 vs 2200 years). Second, the recovery time does not increase linearly from ICE-300 to ICE-600 and ICE-900 (immediate recovery, 850 year delay and 2200 year delay). Therefore, we conclude that the recovery time of the AMOC depends strongly, but non-linearly on the duration of the forcing applied.*

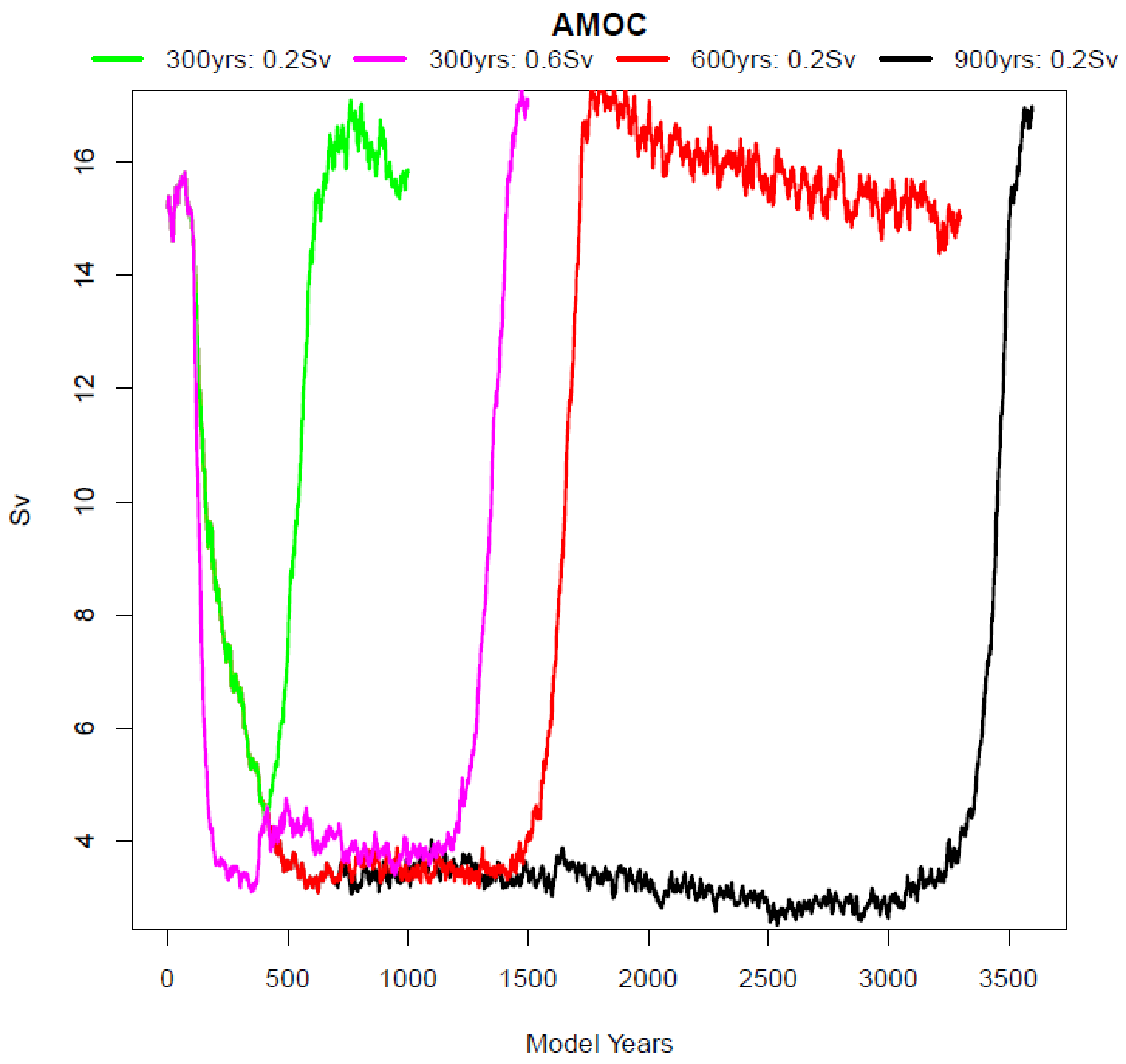

Figure 1: AMOC of 0.6Sv experiment (0.6Sv applied for 300 years – pink line); ICE-300: green line; ICE-600: red line; ICE-900: black line

Table 1: Summary of the impact of the duration of the iceberg forcing on the recovery time of the AMOC

Experiment	Strength of forcing (Sv)	Length of forcing (years)	Sea level rise (m)	Recovery time AMOC (years)
3*ICE-300	0,6	300	15,8	800
ICE-300	0,2	300	5,3	0
ICE-600	0,2	600	10,5	800
ICE-900	0,2	900	15,8	2200

Third, the comparison with only 4 sediment cores is deceptive. There are more cores in the North Atlantic that recorded d18O calcite changes over this period with high enough sedimentation rates. These cores should be taken into account in this analysis.

Please see general comments.

Finally, time series of the model results at the location of these cores should be shown with the sediment data in the same figure (for the better or worse) and discrepancies should be discussed. Nobody would expect a perfect fit, but this one-on-one comparison is still important to validate the model simulations.

As we clearly stated in the manuscript, we do not show the model – data comparison at the core locations, because first, we can't expect the ocean model with a 3°x3° resolution to explicitly reproduce the correct location of local and regional features, such as frontal systems. In our view, it is more important to compare grid cells that represent these features in the model with appropriate core data. In other words, our study focuses on an improved understanding of the system rather than to validation of the model results.

Other comments:

Proxy data reconstructions and a few model simulations suggest that the main source of dense waters in the North Atlantic during the last glacial was the Nordic Seas. Labrador Sea Water seems to have played a small (or maybe even absent) role. LOVECLIM simulates an important convection site in the Labrador Sea for the control run. During the transient simulations, this convection site shuts off and influences d18O seawater, temperatures and, of course, the strength of the AMOC discussed in this paper. The fact that this convection site might or might not be realistic and how this impacts the results should be discussed in the paper.

Thank you for pointing this out, you are correct that iLOVECLIM wrongly simulates a convection site in the Labrador Sea, which should be located in the Irminger Sea, during the control state. However, as you also pointed out, it is immediately shut down as soon as the iceberg forcing starts and its effect on the results is much smaller than the impact of the icebergs generated.
Moreover, it is important to notice that we didn't perform transient simulations to compute the evolution of HS1, since the fronts are not at the exact right position in iLOVECLIM due to its coarse resolution.

Along the same lines, wouldn't one expect Baffin Bay to be completely ice covered and at freezing point just before and during Heinrich Event 1? How realistic are the simulated warm conditions in this region (probably related to the near-by convection site) at this point of time? See for example Gibb et al. 2015, "Diachronous evolution of sea surface conditions in the Labrador Sea and Baffin Bay since the last deglaciation", The Holocene 25 (12), 1882-1897

Please note that in the ctrl state (figure 4) the Baffin Bay is at 0°C and ice covered, the dark blue area in Fig. 2b corresponds to 0°-3°C and starts just below Baffin Bay and the white area in Fig. 4e corresponds to ice free conditions.

What is the equivalent sea level rise for each of the 3 simulations and how does this compare to data/reconstructions?

We have added the sea level rise in Table 1.

Which equation is used to calculate d18O calcite in the model?

The equation of Shackleton (1976) is used and we added this information in the methods section.

Line 36: “ocean cores” should probably read “sediment cores”

Thank you for pointing this out, we changed it.

Line 55: IRD transported by sea ice?

You are right, it should only state transported by icebergs.

Line 56: Should read “>63um”?

Yes, we changed it accordingly.

Line 158-159: How can the value of iceberg d18O not be important for a study that analyses changes in d18O during a Heinrich event?

This was badly formulated, we wanted to express that we implement a fixed value of -30‰, it would be more accurate to receive the value from an ice sheet model itself, but for the current study we don’t concentrate on the uncertainties related to this assumption.

Line 187: it is not obvious (Fig 2) that ICE-600 recovers 700 years later

This is correct, the (not shown) in line 188 corresponds to both, ICE-600 and ICE-900 recovery time, but we added (please see supplement material) in line 187 to clarify that both, the 700 years and 2,200 are not displayed in Figure 2.

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