Supplementary December 19, 2012

Biogeosciences Discussions

Manuscript: "Impact of an 8.2-kyr-like event on methane emissions in northern peatlands"
by S. Zürcher et al.

Author Reply to Referee #1:

We would like to thank the two referees for their time and care in providing comments on our manuscript. Our comments are presented in blue font, the Referee's original comments are in black. *Italics* are used for the quotations of changed or added text in the manuscript.

Anonymous Referee #1

Overview
This study aims to quantify the role of Northern peatlands in the 80ppbv reduction in atmospheric CH4 documented during the 8.2kyr abrupt cooling event. A process-based model of northern peatland CH4 emissions (Bern LPJ) has been driven with climate model simulations with NCAR CSM1.4, which have been perturbed with freshwater forcing, causing a widespread cooling over the Northern Hemisphere. The results show a small contribution (24ppbv) from northern peatlands and so the authors suggest that tropical wetlands may play an important role in the decline in CH4 during the 8.2kyr event.

General comments

The authors make use of a vegetation/peatland model which resolves many processes missing in previous paleo-CH4 modelling (e.g. vertically resolved soil temperature, CH4 transport processes, permafrost). Additionally the model appears to have been carefully evaluated against site data which increases confidence that it can realistically resolve the latitudinal and seasonal changes in peatland methane emissions. The model output is carefully analysed and a thorough forcing and parameter sensitivity analysis is provided.
We are happy to hear that the referee feels our project to be of interest.

However, the climate scenario is not representative of the 8.2kyr event, since it is based on pre-industrial boundary-conditions. The climate simulations were performed and analysed by Bozbiyik et al. (2011), but there they are compared with the Younger-Dryas (Y-D) cooling event (∼12kyr), which has a much stronger change in atmospheric CH4 . This calls into question the use of these simulations as 8.2kyr -like events, as done here, and this undermines the primary conclusions of the work. Unfortunately I cannot comment on the new ebullition mechanism described in section 2.2 and the appendix as this falls outside of my area of expertise.

I suggest that the authors should change the title and abstract to more faithfully represent the simulations performed, namely the response of the modern peatlands to a freshwater hosing or AMOC shutdown. The authors can then go on to relate their experiments to events in the paleoclimate record, such as the 8.2kyr or Younger-Dryas

(as did Bozbiyik et al., 2011), but discussing the limitations involved in this. Once this is clarified in the text, I believe that this work would be of interest to many. Therefore I recommend publication after moderate revisions.
We followed the suggestion to change the title (*Impact of an abrupt cooling event on interglacial methane emissions*) and the strong connection to the 8.2 kyr event only. We formulated the results more general for an idealised freshwater hosing experiment. We then related these results to concrete abrupt events in the discussion and conclusion section, mentioning the limitations of the comparison (different distribution of peatlands, different climate pattern, different CO_2 level etc.). See also comment on this subject to Referee 2. Our motivation for the comparison to the 8.2-kyr-event was the similar overall temperature drop and the temperature decline over Greenland. We agree that a comparison to a specific event would require closer constraints on the boundary conditions of that time.

Specific comments

- The authors suggest that the freshwater forced pre-industrial climate simulation can be used as an 8.2kyr-like event. This is difficult to justify especially in the context of CH_4 emissions modelling. At 8.2kyr BP incident solar insolation had a more pronounced seasonality over the Northern Hemisphere compared to the pre-industrial. This may have had an influence on both the climate response to freshwater forcing as well as on the vegetation productivity and hence the response of peatland CH_4 emissions. Since neither of these influences is quantified in this study it becomes difficult to assess the significance of the primary conclusion of the paper (as it is framed), namely that only 23% of the atmospheric CH_4 reduction during the 8.2kyr event can be explained by Northern peatlands.

We added these considerations under the paragraph of the uncertainties of a comparison between our idealised freshwater hosing and the conditions at the 8.2 kyr event. (See also comment above and to reviewer #2)

- A further difficulty arises in using the pre-industrial simulation as an 8.2kyr-like event, because there is no comparison between the simulated climate anomaly and the reconstructed paleo-climate changes. If the modelled climate anomaly is much smaller or larger than the real event, then this may also explain the mismatch between the simulated CH4 emissions and ice-core record of atmospheric concentrations. The authors should elaborate how well the model simulation compares with the reconstructions of the climate anomalies during the 8.2kyr event, e.g. Kobashi et al. (2007) or Morrill and Jacobsen (2005), and possibly compare this briefly with previous modelling studies (e.g. LeGrande et al., 2008; Tindall and Valdes, 2011).

We added in the discussion section a paragraph providing more information about the reconstructed climate anomalies, compare them to our input and shortly discuss previous modeling studies as suggested by the Referee. It will be a summary of the following:

Kobashi et al., 2007 find that the Greenland temperature cooled by 3.3° ± 1 C (decadal average) in 20 years. Our input has a decline in Greenland temperature by 4° C over 20 years.
Johnsen et al., 1989 find a 2.7° C cooling, Alley et al. (1997a) estimated the magnitude of 8.2 kyr cooling to be 6° C and Leuenberger et al. (1999) estimate 7.4° C with a range of 5.4–11.7° C. Further, Kobashi et al., 2007 state that if they assume that during the 8.2 kyr event average northern temperature cooled by 1-2° C as inferred from many paleo-data from Europe, this would correspond to a 10-20 Tg/yr methane emission reduction from the northern area.

Morrill and Jacobsen (2005) discuss their detection system for climate anomalies during the 8.2-

kyr-event. In an additional table (ftp://ftp.agu.org/apend/gl/2005GL023536/) they name the 52 sites they investigated – few of them provided a temperature change at the investigated location over the 8.2-kyr-event. We compared the temperature drops from these measurements (Northern Germany, Estonia, Greenland, Norway) to our model input. The magnitude of the cooling was comparable. For example, von Grafenstein et al., 1998 reconstruct a cooling of 1.7° C from measurements in Ammersee, the corresponding grid-cell value of our input data is 1.5° C; Seppä and Poska, 2003 measure a cooling in Estonia of 1.5-2° C, we have a 2 °C cooling; Rosen et al., 2001 find a cooling in Norway of almost 2° C, while our input data has a decline of almost 3° C. Alley and Agustsdottir, 2005 (Figure 6) simulate a similar temperature change pattern to our input.

LeGrande et al.,2008 find surface temperature anomalies from -0.1 - -0.6° C in North America, -0.3 to -0.6° C in Middle Europe and 1-1.4° C in Scandinavia and Siberia. These values and also the temperature decline patterns are similar to our input data (Fig. 5).

Tindall and Valdes, 2011 simulate temperature anomalies of -1.33 ° C in Siberia, -1.33 to -4 ° C in Scandinavia, no changes in Mid Europe and wide parts of North America. Further, they find generally a slight precipitation decline (max. 17 %, but mostly much less in the area where we simulate peatlands). The precipitation change in our input data is in most grid cells 1-2 %, at maximum 5 %.

- Introduction: In a few sentences previous studies are referenced but not discussed in much detail. Previous studies have found it difficult to replicate the magnitude of change in atmospheric CH_4 for the G-IG and abrupt events. How might the present study fit in with this prior literature?

We changed the text slightly and added a short discussion in the introduction how our study fits in the prior literature.
Previous paleo-modeling studies have shown that simple methane models are capable of simulating emissions on long-term glacial-interglacial time scales (Valdes et al., 2005; Kaplan et al., 2006; Weber et al., 2010; Singarayer et al., 2011) and are also able to capture methane emissions during abrupt events (van Huissteden, 2004; Hopcroft et al., 2011), but find it difficult to replicate the magnitude of change in atmospheric CH_4 for abrupt events (Hopcroft et al, 2011).
Hopcroft et al., 2011 simulate D-O-events and find a too small global emission change from wetlands. They conclude that either their model is too insensitive to a change in climate or that further mechanisms are needed to be included in their consideration. LPJ is able to capture variations of methane emissions to abrupt climate changes. As we only simulate northern peatlands in our current study and not all wetlands, we can not finally decide whether the model captures the full magnitude or not.

- Page 13263, line 24. As mentioned in the text, MacDonald et al. (2006) reconstructed a smaller peatland area at 8ka BP than during the pre-industrial, but predicted that the total CH_4 emission was of a similar level to modern. Could an altered spatial distribution (especially over North America where warming is simulated) alter the overall model sensitivity of the peatlands to the types of climate anomalies applied in this work?

In general, an altered spatial distribution would affect the sensitivity. In the range of our possibilities to predict the actual distribution at 8.2 kyr, it would not. In the new version of the manuscript, we will treat our simulations more clearly as an idealised freshwater input event as suggested. We added this uncertainty to the discussion section.

- Page 13245: Lines 25-28: I think it should be emphasized that abrupt climate variations are not understood well, for example see Clement and Peterson (2008).

We added this statement to the manuscript.

- Page 13247: Lines 6-9. What about ice-core based top-down approaches (e.g. Fischer et al., 2008)?

They can explain the inter-hemispheric gradient but are not able to explain distributions within a Hemisphere, i.e. northern low-latitude versus northern high-latitude sources. This has been added to the manuscript.

- Page 13247: Lines 10-12: Did van Huissteden (2004) or Hopcroft et al. (2011) explain the full magnitude or rapidity of abrupt events? If not, what explanation(s) were given, and could you here address any of these here?

Hopcroft et al, 2011 can not explain the full magnitude or rapidity of methane emission changes during D-O-events and believe their model to be too insensitive for abrupt events or to be missing important mechanisms. Van Huissteden, 2004 finds that his simulations (north European wetlands only) demonstrate that the methane flux from northern wetlands can be doubled during interstadials due to temperature change alone. He attributes the biggest uncertainties to the peatland area. He believes the absolute magnitude of the fluxes to be quite uncertain due to uncertainties in the input data, but the relative effect of changes to be represented well. We agree on the statement that the uncertainties of the input data have to be considered. We added this point to the the text.

- Page 13247: Line 20. The CH_4 model used by Singarayer et al. (2011), explicitly includes functions of both surface air temperature and water table, following the Cao et al. (1996) formulation, and so this sentence is incorrect.

We corrected this mistake in the text. Many thanks.

- Page 13247: Line 20. Valdes et al. (2005); Kaplan et al. (2006) and Singarayer et al. (2011), all consider changes in the atmospheric CH_4 lifetime in order to explain G-IG change in CH_4 , but this is not commented on here.

We added this fact to the text. However, according to latest chemistry model studies these changes in CH_4 lifetime appear to be very limited (Levine, 2011a, b).

- Page 13248, lines 1-4: The authors mention that ICE-5G indicates relatively little coverage of peat grid-cells at the time of the 8.2kyr event. Would it be worthwhile to use ICE-5G to mask out emissions in LPJ simulations to assess how important this could be?

We compared total CH_4 emissions to a test calculation where we masked out grid cells covered by ice. Global emissions where only lower by 6 % in this case and the sensitivity was unchanged. We added this explanation to the manuscript.

- Section 2.3, lines 1-8: It is not clear from the description of the site-level comparison, whether you use the actual climate years relating to the observations in your comparison, or whether the years used are average equilibrium conditions. Please clarify and justify your choice if you have opted for the latter.

We use the actual climate years. We clarified the text accordingly.
We use CRU-data [...] of the corresponding grid cell and year for the other sites.

- Page 13523, Lines 8 onwards. How did you choose the parameter values that you evaluated?

See page 13252, line 9. The chosen parameters showed to be the most important "free" parameters to control methane emissions (Wania et al., 2010). In their study, they checked 7 parameters that have the largest effect on CH_4 emissions. They used additional four parameters, namely the tiller

porosity (of which they write to have the same effect as a variation of the tiller radius), the fraction of exudates, exudate turnover rate and moisture response (the latter three show to have only small effects on emissions). For these four parameters we use the same values as in Wania et al., 2010. We reformulated the text to make this more clear.
Other factors controling methane emissions are the exudate turnover rate, the moisture response, which is also used to calculate decomposition rates, the leaf-to-root ratio, which influences the cross-sectional area of aerenchyma available for plant-mediated gas transport, the tiller porosity which influences the area for plant-mediated transport and parameters regulating the frequency when ebullition occurs and the volume released in a single ebullition event. Except for the two new parameters of our ebullition routine, we use the same values as Wania et al., 2010 for these four parameters that have proven to be less important.

- Page 13253: Lines 5-7 and figure 2: Can you describe in more detail how the improved ebullition scheme changes the seasonal timing of emissions and therefore improves the model-data comparison compared to the previous work of Wania et al. (2010)?

There is not a general improvement of the seasonality. Our simulated CH_4 emissions tend to start a bit to late, while Wania et. al., 2010 show both too early and too late occurrence of emissions. However, we find slightly improved agreement of total annual CH_4 emissions as described in the comment for Referee #2:

RMSE of spline functions (as in Fig. 2):

	Wania	Zürcher	Improvement
Michigan	226.4	209.0	8%
Minnesota	146.7	132.0	10%
Salmisuo	75.4	42.3	44%
Degeroe	50.7	43.7	14%
Boreas	61.3	59.7	3%
Abisko	62.8	41.9	33%

If we weight each site with the time length of the measurement we get an improvement of 30% for the site evaluation. The new ebullition routine is from the physical point of view more realistic. If we redo for example the simulation done for Fig. 7 in Spahni et al., 2010 where the old adapted version of Wania et al., 2010 was used, we get a very similar seasonality and a slightly higher overall magnitude. We added the comparison of the RMSE to the manuscript.

- Page 13255: lines 10-19: This paragraph needs clarification, the climate simulations are pre-industrial plus water hosing. Perhaps provide a reference paper for the climatology of CCSM1.4.

We pointed out that the simulations are pre-industrial plus the water hosing and added a reference to CCSM1.4 climatology (Kiehl et al., J. Climate, 2006)

- Page 13260, line 5: What would the reduction in CH_4 emissions have been if it was a fixed proportion of NPP?

See also comments for Referee #2 – about 13% instead of 19%. We added this to the text.

- Page 13260, lines 9-14, Given that the proportions of different components remains similar in different climatic states what does this imply for sensitivity of the model and the inclusion of these processes? How does this relate to the changing ratio of CH4 emitted to NPP?

We clarified the message of this part of the manuscript (see also answer to Referee #2).
The heterotrophic respiration and NPP drop from 840 TgC to 740 TgC. A simple approach using

the drop in RH as scaling for the drop in methane would therefore lead to only a decline in methane emissions by about 13%. The extended modeling approach gets about 19 % (table 1). It implicates that the more complex structures are better able to catch the effect of an abrupt event in our model. Further, the more complex process modeling will be useful for isotopic analysis and to include further constraints.

- Page 13261, line 15: Does this imply that the exploration of parametric uncertainty has been too conservative?

The parameter choices for the sensitivity studies cover the range of observations. Otherwise we would be violating assumptions from measurements (ratio of dissolved and gaseous methane, measured bubble volumes, realistic tiller radius).

- Page 13262, line 28: A reference for the climate conditions referred to here would be helpful.

We added some references as suggested.
(Peltier, 2004 for the ice cover; early Holocene climate: Renssen et al., 2011: Global characterization of the Holocene Thermal Maximum; Seppä et al., 2009: Last nine-thousand years of temperature variability in Northern Europe).

- Page 13263, line 2. The reference to Weber et al, here does not really make sense, please check.

We changed the reference (Yu et al., 2010, Global peatland dynamics since the last glacial maximum, Geophys. Res. Lett.)

- Page 13264, line 11. Which other estimates do you refer to here?

We added references to the estimates we refer to.
Kobashi et al., 2007 find that the total methane emissions decreased by 15 ±5 % during the 8.2 kyr event. Walter et al., 2001a and Christensen et al., 2003 found that a global temperature change of ±1° C leads to about 20 % changes in methane emissions.

- Page 13265. This final paragraph is a bit mixed up and could do with reorganisation. Refer to other comments above. I think more emphasis and discussion is needed in terms of relating this modern climate simulation to the past.

We reorganized the discussion and conclusion section, adding more content to explain to which extend our simulations can be compared to the 8.2 kyr event and what uncertainties have to be considered.

- Figure 3: It would be good to show error bars where possible on these point values.

The annual cumulative emission is the area under the splined curves in the period where measurements exist. The simulated error can hardly be captured as model parameters are optimized for the data and hardly have other constraints on their own. The errors of the measurements (mostly per hour) are at some sites up to 50 %. We added a short comment to the caption of the figure to give the order of the error for the measurements.

- Figure 5: Though it is subjective, I would plot the climate anomalies without masking the peat grid cells. This might make it easier to assess the overall magnitude and pattern of the simulated climate anomaly.

We agree that this information would be interesting. But the price would be that a comparison between changes in methane emissions per grid-cell and temperature or precipitation would not be possible anymore. For the overall magnitude and pattern of the simulated climate, we refer to Bozbiyik et al., 2011.

- Figure 7. The anomaly plot (b), might be clearer if it was given as % reduction.

We decided to plot the input anomalies and the emission anomalies consistent as absolute values.

- Figure 8. Could you remove 's1,' from the the legends and put it once elsewhere in these two plots?

We changed this as suggested.

Technical corrections

- Page 13246: Lines 19-22. Change regulating to regulates and affecting to affects in this sentence.
- Page 13249: Line 7. Sphagnum should be in italics.
- Page 13251: Line 15. Remove 'do'.
- Page 13257: Line 19. Write 'A slight warming is even simulated . . . '
- Page 13259: Line 6. Change '(GPP) by' to '(GPP) of'.
- Page 13259: Line 16. Remove 'of' from 'and not of a decrease'

All changed as suggested. Many thanks.

- Page 13259: Give these numbers to less significant figures, and possibly include plus-minus 1 standard deviation.

We gave less significant figures and added the standard deviation.
(GPP: ± 80 TgC, NPP: ± 40 TgC, HR: ± 30 TgC; Soil carbon: ±0.1 PgC; Production: ± 2 TgC, Oxidation ± 1 TgC)

- Page 13259: lines 16-19: This sentence starting with 'Note that the soil carbon' does not make sense.

We rephrased the sentence to be more clear. We wanted to emphasise that the soil carbon inventory is realistic for preindustrial conditions and overestimated for the 8.2 kyr event. We moved the statement for the 8.2 kyr event to the discussion section.
The soil carbon inventory in our simulations is in steady state under preindustrial conditions and realistic compared to available data (Tarnocai et al., 2009;Yu et al., 2010). Therefore it is actually higher than at the beginning of the 8.2 kyr event.

- Page 13261: Line 10. Change to 'after the freshwater perturbation barely depends'.
- Page 13261: Line 15. Change '. . . ebullition have as well a small . . . ' to '. . . ebullition also have a small..'.
- Page 13262: Line 12. Change to something like '.. ecosystems to the simulated climate change'.
- Page 13262: Line 22. Replace 'E.g.' with 'For example' or similar.
- Page 13264: Line 3. These brackets are not closed.
- Page 13264, line 15. Reword this sentence beginning 'Moreover temporal changes also ..' as it does not make sense, although I can see what you mean.
- Page 13265: Line 6. 'Extend' should be 'Extent', but see general comments regarding this concluding paragraph.

Changed as suggested. Many thanks.