

Dear Editor,

We accept all changes to the manuscripts the reviewers suggested, and we modified the manuscript accordingly. We attach our answers to the reviewers' comments and concerns. We also improved the discussion section inserting the clarifications the reviewers suggested.

We also attach the modified manuscript, where we highlighted the modifications in blue.

We think that the manuscript greatly improved and we are thankful to the reviewers for their help.

Best regards,

Fabio Cresto Aleina on behalf of all the co-authors

Interactive comment on “Upscaling methane emission hotspots in boreal peatlands” by F. Cresto Aleina et al.

Anonymous Referee #1

Received and published: 15 October 2015

We thank the Anonymous Referee 1 for his relevant comments which will help in raising the quality of the manuscript and in clarifying its message. Our answers are below Referee’s comments (in italics).

1) The new Hotspot model configuration somewhere is referred as parameterization, somewhere as new numerical approach. This is a bit confusing maybe the author could choose the best definition of what they did.

We thank the reviewer for the suggestion, and we chose the definition “parameterization” consistently throughout the text.

2) Equations (1) and (2): how is the lateral flux estimated in the two cases? Does the spatial distribution of the Hotspots have an influence on the soil moisture flux and thus, indirectly on soil saturation and methane emission?

Equation (2): if there is only one bucket, what is lateral flux R? Eventually, they could provide a schematic representation of the three configurations within Figure 1. Are there hummocks and hollows in the Single Bucket configuration? How is the spatial distribution of Hotspots in the Hotspot configuration?

The lateral flux is implemented in the same way in the two versions, but in the explicit micro-topography representation the water can flow from cell to cell, while in the Single Bucket version the water simply flows out of the system. We included this information in the revised version of the text.

Hummocks and hollows are not represented in the Single Bucket version, which works at the resolution of the whole domain. Hummocks and hollows are not explicitly represented in the Hotspot parameterization either, since its configuration is identical to the Single Bucket version. Nevertheless, the effect of the micro-topography on water table level is included in the Hotspot parameterization according to Equations 4 to 7.

It is difficult to represent these differences graphically, and Figure 1 is a schematic of the HH model in the Microtopography configuration (we modified this information in the revised version of the paper). We think that the differences among the three versions can be better highlighted in a table, and therefore we listed them in Table 1.

3) Equations (4) and (7): q is used for fraction of saturated surface and for methane emission. Change symbols to avoid confusion.

We used the same symbol because it is the same parameter. We assumed a linear relationship between methane emitting area and the emitted fluxes, and therefore we simply substitute the term $F_{CH_4}(W_t)$ to the term A in Equation 4. We inserted this information explicitly in the revised text to clarify this passage.

4) Figure 3: The Hotspot configuration mimic the Microtopography when methane emission is very high, and the Single Bucket when the Hotspot are not active (if I

understood correctly, at low methane emission), underestimating the methane flux, apparently. Could you comment on that?

The beginning and the end of the simulation is where the fraction of saturated area q (Equation 7) has its minima, and therefore the Hotspot parameterization is less effective. We included this information in the text. As we discussed in paragraph 3.2, also other variables could play a role in these time slices. For example, peat depth is still averaged over the whole domain.

5) Equation (6): is the methane flux from the HH model in the Single Bucket version estimated by averaging over the whole model domain or over the unsaturated part of the domain only? Please specify and comment on that.

The Single Bucket model provides only an average flux from the whole domain, i. e., it is not possible to distinguish between saturated or unsaturated part. We assumed the fluxes from the Single Bucket model to be correspondant to the ones of an unsaturated area because of the too deep water table simulated in this configuration.

6) Section 3.1, second line: specify what are the three surface classes.

Thank you for the comment, we inserted this information.

7) Finally, a few comments on the ecological relevance of the results presented in the manuscript under discussion as well as a discussion on the reason why we need such accurate estimation of methane emission could be added. Would similar literature models predict the same results?

We thank the reviewer for this suggestion. The results are relevant for the magnitude of the differences in fluxes. The Hotspot parameterization doubles the cumulative fluxes over the season in respect to the Single Bucket version, despite its low computational costs. From an ecological perspective, modelling CH₄ fluxes more accurately will help our estimates of carbon stocks, which may help constrain dynamic vegetation models, bacterial C consumption models, and potential feedbacks with the atmosphere. Also, modelling hydroecology effects of “slower” runoff from a peatland can potentially influence vegetation dynamics of mosses in models including moss dynamics, e. g., Porada et al., 2013.

The HH model is novel in the physical representation of lateral fluxes of water among hummocks and hollows, but other models representing surface heterogeneity controls on methane fluxes (e. g., Bohn et al., 2013), display similar effects. Therefore, and because of the process-based nature of the HH model, we are confident in hypothesizing similar results if a Hotspot-like parameterization was to be applied to other models. We included this extended discussion in the revised version of the text.

References:

Porada, P., Weber, B., Elbert, W., Pöschl, U., and Kleidon, A.: Estimating global carbon uptake by lichens and bryophytes with a process-based model, *Biogeosciences*, 10, 6989–7033, doi:10.5194/bg-10-6989-2013, 2013.

Interactive comment on “Upscaling methane emission hotspots in boreal peatlands” by F. Cresto Aleina et al.

Anonymous Referee #2

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We thank the Anonymous Referee 2 for the comments and the requests for clarifications. We considered the comments modified the text according to the reviewer's suggestions, and we think that these modifications increased the quality of the manuscript. Our answers are below Referee's comments (in italics).

1) I suggest writing out more explicitly how the three different models depended on forcing data in the different simulations.

- The Hotspot model was parameterized using years 1976-2005. So did you use for all the years 2006-2099 this same temporal pattern of q , i.e. was the area density of saturated surface always as shown by the dotted line in Fig. 2? Or did it change with climate in the future projection runs?

Yes, we used the same parameterization of the saturated area fraction q (showed in Figure 2 as you noticed) also for the future simulations 2006-2099. This robustness test showed that despite the hotspot parameterization being tuned for the 1976-2005 period, it still holds for future simulations.

- Did the water tables of the saturated areas change with meteorological forcing in the Hotspot simulations? Or was the water table in the saturated areas always randomly something between -10 and 15 cm as shown in Eq. 5? How about the non-saturated areas, did the water table vary there?

In the HH model with the Hotspot parameterization the water table changes according to the precipitation input in the non-saturated area $(1-q)A$, whereas in the saturated area qA it is computed randomly between -10 and 15 cm. We included this observation in the revised version of the text.

- Did the Microtopography (HH) version simulate the water tables continuously, depending on the input data?

Yes, it did. All versions of the model continuously compute water table according to Equations 1 (Microtopography) and 2 (Single Bucket and Hotspot). The main difference is that in the Hotspot parameterization the water table dynamics is the result of a weighted mean of the water table computed in Equation 2 and the water table in saturated area, which does not depend on the input data.

- You could discuss this: is it probable that the saturated surface area would change in the future and does it affect the results?

It is possible that in the future the saturated area will change. In the RCP simulations, though, even though precipitation changes in respect to present day and among the scenarios, the differences are not so large to cause significant effects on methane emissions. We show this result in Figure 4. In panels a, c, and e, the black and the red lines, i. e., the outputs of the Microtopography and the Single Bucket versions, have

water table explicitly depending on precipitation simulated in the RCP scenarios. The blue lines (i. e., the Hotspot parameterization), despite using the saturated area dynamics for the years 1976-2005, are quite close to the methane emissions from the Microtopography version. We then conclude that the potential bias introduced by using a fixed saturated area dynamics (the one for the period 1976-2005) and not a dynamic one is negligible.

We included this discussion in the revised version.

We thank the reviewer for the comments and we clarified the points more explicitly in the revised version of the text.

2) P. 8523 and 8526: *Can you clarify the relationship between water table level W and surface S . Is W negative below the surface? Are the equations on page 8526 (the ones defining the surface types) correct? What is S there?*

We clarified this information in the revised version when describing the water table dynamics. Water table below the surface is negative, and it is positive above it. Equations on page 8526 contain a mistake, it should simply be W_t instead of $S - W_t$, since the water table is always computed in respect to the surface level S . Thank you for the observation.

3) P. 8523, Eq. 1 and its explanation: *is snowmelt denoted with S_n or S ?*

It should be S_n , we modified it in the text, thank you.

4) Page 8526, l 17: *should the W^{sat} be W^s like in Eq. 5?*

Yes, it should be W^s everywhere, we modified it.

5) P. 8524 l. 20: *Add a reference to a paper that uses the Walter & Heimann model.*

We added the references to Schuldt et al., 2013, Petrescu et al., 2008, and Zhang et al., 2002.

Page 8528, l. 5: *Add a basic reference to what is RCP.*

We added the reference to Taylor et al., 2012.

6) Table 2: *It was difficult to understand the parameterization of the Hotspot model (P. 8529) since the text in Table 2 is slightly confusing. E.g. “initial day of the year of maximum saturation” sounds like there was a “year of maximum saturation”, which apparently is not the case. I suggest you re-formulate these somehow, for instance “Initial date of maximum saturation” if it seems appropriate*

Thank you for the comment, we modified the parameter names according to your suggestion.

7) Page 8531, line 5: *should it be “... simulated by the models”? Same page, lines 8-10; can you re-formulate the sentence, it is unclear.*

Yes, it should be plural. We reformulated the sentence as:

... Melton et al. (2013) did not find a large significant trend in methane emissions simulated by the models participating in the inter-comparison project because of increased temperature or of precipitation trends. We use these two variables to force the HH model coupled with the methane emission model.

References:

- Petrescu, A. M. R., van Huissteden, J., Jackowicz-Korczynski, M., Yurova, A., Christensen, T. R., Crill, P. M., Bäckstrand, K., and Maximov, T. C.: Modelling CH₄ emissions from arctic wetlands: effects of hydrological parameterization, *Biogeosciences*, 5, 111-121, doi:10.5194/bg-5-111-2008, 2008.
- Schuldt, R. J., Brovkin, V., Kleinen, T., and Winderlich, J.: Modelling Holocene carbon accumulation and methane emissions of boreal wetlands – an Earth system model approach, *Biogeosciences*, 10, 1659-1674, doi:10.5194/bg-10-1659-2013, 2013.
- Karl E. Taylor, Ronald J. Stouffer, and Gerald A. Meehl, 2012: An overview of cmip5 and the experiment design. *Bull. Amer. Meteor. Soc.*, **93**, 485–498.
doi: <http://dx.doi.org/10.1175/BAMS-D-11-00094.1>
- Zhang, Yu, Li, Changsheng, Trettin, Carl C., Li, Harbin, Sun, Ge, 2002. An integrated model of soil, hydrology, and vegetation for carbon dynamics in wetland ecosystems. *Global Biogeochem. Cycles*, 16(4); 1-17

Anonymous Referee #3

Received and published: 9 November 2015

We thank the Anonymous Referee #3 for the constructive comments. We modified the text according to the reviewer's suggestions, and corrected the mistakes in the text and in the formulas spotted by the Referee. Our answers are below Referee's comments (in italics).

There are several errors in the formulae, such as inconsistent use of S_n and S for snowmelt, $W_s t$ vs. $W_{sat} t$, and the definitions of wet, saturated or dry surfaces. Most of these have already been mentioned by Referee 2. For the definitions of the three surface types, it would be useful to define the sign convention. (This is likely obvious, but in trying to make sense of the erroneous equations I tried various things, as it wasn't defined in the text. A definition would make this more clear.)

Thank you for this comment. As we described in our answer to Referee #2, we made a mistake in the formulas and we corrected it in the revised version of the paper. Water table is positive if above the surface, negative below. We inserted this clarification in the text and we corrected the errors.

While it's clear that it's not realistic to have theodolite microtopographic measurements globally, it would be useful to the reader to have a bit more discussion about how such an upscaling might be upscaled further, to improve the model on a global scale. Are there any remote-sensing products that might provide similar information, at least stochastically, about the distribution of surface elevation? Perhaps airborne lidar? Of course the application to this scale is beyond the scope of the current study, but some discussion of how this could practically be done would aid the discussion.

Aerial photographs provide some information on micro-topography, but generally at a too coarse scale. Statistical downscaling methods as the ones used, e. g. by Muster et al. (2013) give us information on surface heterogeneities, but not necessarily on micro-topography elevation. Airborne measurements could aid in giving qualitative and stochastic information also on structural peatland patterns, such as the ones described by Couwenberg and Joosten (2005). This information could be used by the HH model to realize non random configurations, potentially investigating the influence of structured patterns on hydrology and methane emissions. We inserted this information in the discussion, as the Referee suggested, and we added the references.

Figure 4: The caption describing panels b, d, and f is rather unclear, especially the sentence "We illustrate the ratio between the methane emitted from the Microtopography configuration and from the Single bucket configuration (red lines) and from the Microtopography configuration and from the Hotspot parameterization (black lines)." This implies that the ratio is the opposite of what (I think) it is. I would suggest instead "We illustrate the ratio of methane emissions with respect to the Microtopography configuration for the Hotspot parameterization (in BLUE) and the Single Bucket configuration (in red)." As indicated by this suggestion, I think the line

for the ratio of Hotspot/Microtopography should be blue, to be more consistent with panels a, c, and e. Furthermore, the labelling of panels b, d, and f is unnecessarily complicated. The y-axis is unitless: it's a ratio. Perhaps change it to "ratio of fluxes to Microtopography configuration", and then the legend could simply read "Single Bucket" and "Hotspot".

Thank you for this comment, we think that the modified sentence suggested by the Referee greatly improves the clarity of the message of our figure. We included these modifications in the revised version of the paper.

Technical comments:

P8520, L8: remove comma P8520, L10: add comma after "century"

P8520, L22: insert "have" between "studies" and "focused"

P8521, L15: landscape -> landscapes P8521, L16: non linear -> nonlinear

P8521, L23: "e. g. by Baird" -> "by e.g. Baird"

Done, thank you.

P8522, L8: "part of methane" -> "part of the methane"

Done, thank you.

P8523: In the introduction of Equation 1, the reader is referred to the Biogeosciences paper of Cresto Aleina et al. (2015), but this paper does not include the snowmelt term. Perhaps this difference should be explicitly mentioned?

Thank you for the comment. It is true that we did not consider snowmelt in the Biogeosciences paper, since we started the simulation later on in the year and we initialized the water table to match the observed water table position at the end of April. We do not have any data to match in this paper, and therefore we included the snowmelt. We discussed this difference between this paper and the one in Biogeosciences more in detail in the revised version of the paper.

P8523: L 19, L22: S -> Sn

P8523: L22: Appendix -> Appendix A

Thank you, we modified them.

P8524, L11: Here it is a bit unclear what is meant by "overly deep". This could sound like the water table position is too high (i.e. deep water), whereas I think the opposite is meant. Perhaps "too low" would be clearer.

We modified this part of the sentence to “too low” in the revised text.

P8524, L19: Model -> Models

P8525, L8: "of water" -> "of the water"

Done, thank you.

P8525, L15: Similar to previous comment, instead of saying that the water table "deepens" quickly, perhaps say it "drops" quickly?

We changed “deepens” to “drops quickly below the surface” in the new version of the text.

P8525, L16-17: "the Appendix" -> "Appendix B"

P8525, L20: Remove "though," it's redundant. P8526, L8: "of the oxidation to happen" -> "oxidation"

P8526, L12: "translates" -> "results"

P8526, L20: "where r is a random number" -> "where r is a random number between 0 and 1"

We changed the text accordingly, thank you for the comments.

P8526, L21: I think this should be referring to Equation 2.

Yes, Equation 2 indeed. We corrected the text.

P8527, L16: "Appendix" -> "Appendices"

P8530, L24: "in respect" -> "with respect"

P8531, L4: "model" -> "models"

P8531, L5: "or of" -> "or"

Done, thank you.

P8531, L11-19: The section starting with "If we include" should be rewritten for clarity, so it can be easily read aloud. Perhaps start with something like "If we include the Hotspot parameterization, the simulated annual methane emissions range from $2.831 - 4.321 \times 10^4 \text{ mgm}^{-2}$ with the RCP8.5 forcing. This is 83.9-101.5% of the emissions simulated by the Microtopography configuration." And so on. And really, are all those digits significant?

We modified the sentences according to the Reviewer's suggestions. The digits are indeed significant.

P8531, L26: "between Microtopography" -> "between the Microtopography"; "configuration" -> "configurations"

P8532, L1: "between in the" -> "between the"

P8532, L11-12: "being near to 1 for this period" -> "is near one" (The period was already specified explicitly in the same sentence.)

Done, thank you.

P8532: Based on the graphs that are shown, it's clear that the Microtopography fluxes are higher than the Hotspot fluxes in the spring and fall, and that the ratios shown in Figure 4 (panels b, d, and f) are the Hotspot and Single Bucket fluxes divided by the Microtopography fluxes (which are generally larger, thus the ratio is generally less than one). However this is exactly the opposite of what is stated in the

text. This really needs to be fixed. You divided the daily emissions from the Single Bucket and Hotspot runs by the Microtopography fluxes, and not the other way around. Likewise, when you refer to the ratio between A and B, it means A/B (and not B/A). These errors are found in the caption to Figure 4 as well, as mentioned above.

We fixed the information in the text, now it reads correctly.

P8532, L23: "hollow" -> "hollows"

P8534, L6: "micro-relieves" -> "micro-relief"

P8534, L17: insert "and" before "Runkle"

P8534, L20: "surface. Evapotranspiration" -> "surfaces. The evapotranspiration"

P8534, L24: "Gregorian" -> "the Gregorian"

P8535, L4: "if water" -> "if the water"

P8535, L6: "evapotranspiration" -> "the evapotranspiration"

P8535, L14: "Other parameters" -> "Another parameter"

P8536, L24: Update reference, no longer in discussion.

Done, thank you.

P8541: Here the caption specifies that days are calculated using the Julian calendar, in Appendix A it said the time step was in days of the Gregorian calendar. So which is it? Or are these not using the same calendar?

It is the Julian calendar. We now specify this information in the Table, and we corrected this mistake in the Appendix A in the Evapotranspiration description.

Upscaling methane emission hotspots in boreal peatlands

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Abstract. Upscaling properties and effects of small-scale surface heterogeneities to larger scales is a challenging issue in land surface modeling. We developed a novel approach to upscale local methane emissions in a boreal peatland from the micro-topographic scale to the landscape-scale. We based this new parameterization on the analysis of the water table pattern generated by the Hummock-Hollow model, a micro-topography resolving model for peatland hydrology. We introduce this parameterization of methane hotspots in a global model-like version of the Hummock-Hollow model that underestimates methane emissions. We tested the robustness of the parameterization by simulating methane emissions for the next day, forcing the model with three different RCP scenarios. The *Hotspot* parameterization, despite being calibrated for the 1976-2005 climatology, mimics the output of the micro-topography resolving model for all the simulated scenarios. The new approach bridges the scale gap of methane emissions between this version of the model and the configuration explicitly resolving micro-topography.

pel, 2008). In turn, small-scale heterogeneity could influence the land-atmosphere fluxes on larger scale. Several studies have addressed the hydrological cycle in drylands, where water recycled by vegetation may play an important role in the local water budget (Dekker and Rietkerk, 2007; Janssen et al., 2008). In particular, Baudena et al. (2013) showed that the amount of water transferred through transpiration may change up to 10 % if one considers different vegetation patterns, even with the same biomass density and the same spatial scale. Recent efforts have also been focused on downscaling remote sensing information to simulate subgrid surface heterogeneities (e. g., Peng et al., 2015; Stoy and Quaife, 2015), and to scale up information across scales using network techniques (Baudena et al., 2015).

Effects of small-scale heterogeneities on land-atmosphere fluxes are of especial interest in northern peatlands because of the great amount of carbon stored in the soil (Hugelius et al., 2013; Tarnocai et al., 2009). Recent studies have shown that greenhouse gas fluxes, in particular of methane, strongly depend on the micro-topographic features of such environments (Gong et al., 2013; Couwenberg and Fritz, 2012), and that local hydrology is regulated by micro-reliefs (Shi et al., 2015; Gong et al., 2012; Bohn et al., 2013; Van der Ploeg et al., 2012). In particular, a typical feature of methane emitting landscapes is the non linear relationship between fluxes and emitting surface area. A small fraction of the total landscape can therefore function as a "hotspot" for methane fluxes. Recent eddy covariance measurements in northern peatlands showed how the saturated surface, with water table near to the surface level, despite covering only 10 % of the total landscape, is responsible for up to 45 % of the total methane emissions (Sachs et al., 2010).

This "hotspot" feature of methane emissions potentially constitutes a large local and even regional feedback to the climate system, which is neglected in the current Global Circu-

1 Introduction

Land surface is a heterogeneous mixture of vegetation types, lakes, wetlands, and bare soil. Correct representation of such small-scale heterogeneities in climate system models is a challenge. How can models better account for the small-scale features in the large-scale climate system? Proposing a new parameterization to fill a scaling gap between local and larger scales is the main focus of this paper. Many recent studies have focused on different approaches to simulate local small-scale characteristics of the land surface, with climate enforcing evolution of different soil surface heterogeneities and small-scale vegetation patterns (Shur and Jorgenson, 2007; Couwenberg and Joosten, 2005; Rietkerk and van de Kop-

lation Models (GCMs), as shown by e. g. Baird et al. (2009). Because of the complexity of the small scale biogeochemical and hydrological interactions that regulate this "hotspot" effect, it is computationally feasible to represent such non-linear phenomena only in local mechanistic models (i. e., Nungesser, 2003; Acharya et al., 2015; Cresto Aleina et al., 2013), with a fine grained resolution ($10^{-2} - 10^0$ m). The "hotspot" effect is due to the nonlinear relationships between decomposition and its drivers (e. g., soil temperature and water level), and therefore a spatially explicit model able to identify such "hotspots" is likely to perform better in representing methane emissions (Schmidt et al., 2011).

Cresto Aleina et al. (2015) developed the Hummock-Hollow (HH) model, a model for resolving micro-relief features in a typical boreal peatland (hummocks and hollows) and coupled this hydrological model to a process-based model for methane emissions developed by Walter and Heimann (2000). They found that a micro-topography representation is necessary to correctly capture hydrology dynamics and methane fluxes, as the water table position regulates the depth of the oxic zone, where part of the methane coming from the anoxic zone is oxidized and emitted to atmosphere as CO_2 .

Global land surface models such as JSBACH (Raddatz et al., 2007; Reick et al., 2013), the land component of the Max Planck Institute Earth System Model MPI-ESM (Giorgetta et al., 2013), operate at a spatial resolution analogous to the atmospheric one, which is of about $50 \text{ km} \times 50 \text{ km}$ at the finest feasible scale. To include a representation of the "hotspot effect" on this scale, new sub-grid scale parameterizations are needed.

In the present paper we propose a novel method to fill the scaling gap from local mechanistic models to large-scale mean field approximations, using the output of the local fine grained model to tune and modify the coarse grained bucket-like model, in order to upscale the local information ($10^0 - 10^1$ m) to the landscape-scale (e. g., 10^3 m).

We present an application of this upscaling method to the HH model, where we analyze the dynamics of the area which we assume being a hotspot for methane emissions. We then use this information to modify a version of the HH model without micro-topography representation, which originally failed to represent the magnitude of methane fluxes. In this paper we present (i) results for the average climatology of the past 30 years, for which we calibrated the parameterization, and (ii) for the next century, testing the robustness of the parameterization under a different forcing.

2 Methods

2.1 The HH Model

The Hummock-Hollow (HH) model (Cresto Aleina et al., 2015) simulates peatland micro-topographic controls on

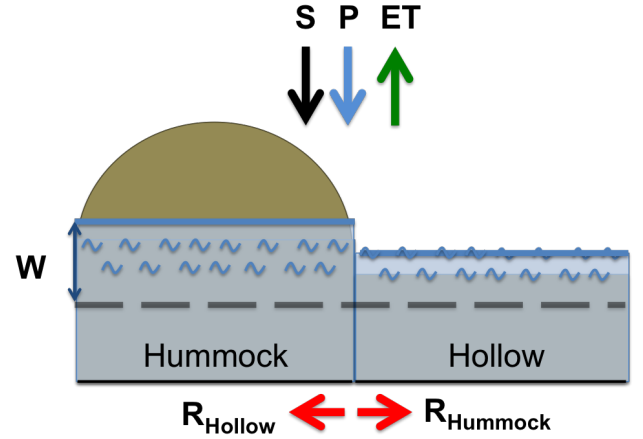


Figure 1. Schematics of the HH model showing two grid cells, a hummock and a hollow. The model represents a $1 \text{ km} \times 1 \text{ km}$ peatland, and works at a $1 \text{ m} \times 1 \text{ m}$ grid cell. It is therefore able to resolve the micro-topographical features such as hummocks and hollows. The figure shows two typical grid cells, a hummock and a hollow, and the variables needed for the water table dynamics (Equation 1 in the text). Each grid cell has an elevation which is randomly assigned from the distribution of elevation data collected in situ. For each grid cell we simulate a dynamical water table, which changes with snowmelt (Sn), precipitation (P), evapotranspiration (ET), and lateral runoff among the different grid cells ($R_{\text{hummock/hollow}}$). These quantities regulate the change in water table depth (W).

land-atmosphere fluxes. It is suited to work at a $1 \text{ m} \times 1 \text{ m}$ resolution, which is the typical spatial scale of peatland micro-topography. Each grid cell of the HH model represents just one micro-topographic feature, namely a hummock or a hollow. The model simulates a $1 \text{ km} \times 1 \text{ km}$ peatland and its parameters are tuned with values for a typical peatland in Northwest Russia. In particular, we use the model to simulate the Ust-Pojeg mire in the Komi Republic ($61^\circ 56' \text{N}$, $50^\circ 13' \text{E}$, 119 m a.s.l.). The site has been extensively studied, and recent efforts described peat characteristics (Pluchon et al., 2014), fluxes of water vapor (Runkle et al., 2012), carbon dioxide (Schneider et al., 2012), and methane (Gažovič et al., 2010), as well as energy and water balance (Runkle et al., 2014) and spatial distribution of dissolved organic carbon (DOC) (Avagyan et al., 2014, 2015). The micro-topography is initialized with micro-topographic data collected through surveying with a theodolite. An elevation distribution is derived from the data, and it is possible to randomly assign an elevation at each grid cell (for more information, Cresto Aleina et al., 2015). Depending on the elevation, the grid cell is therefore either a hollow or a hummock (Fig. 1).

For each grid cell (i. e., for each micro-topographic unit) we compute the water balance as:

$$\frac{dW_{i,j}}{dt} = \frac{Sn + P - ET_{i,j} - R_{i,j}}{s_{i,j}} \quad (1)$$

Configuration	Properties	Resolution
<i>Microtopography</i>	Explicitly resolves micro-topography. Computationally expensive and requires fine scale data for initialization.	1 m × 1 m
<i>Single Bucket</i>	Averages quantities over the domain. Does not consider micro-topography. Computationally fast and requires minimal information for initialization.	1 km × 1 km
<i>Hotspot</i>	Averages quantities over the domain. Considers micro-topographic information. Computationally fast and requires minimal information for initialization.	1 km × 1 km

Table 1. Description of the different configurations of the Hummock-Hollow (HH) model used in the present paper.

where $W_{i,j}$ is the water table level in the grid cell at the position (i,j) relative to the surface level, Sn is the snowmelt, P is the precipitation input, $ET_{i,j}$ is the evapotranspiration, $R_{i,j}$ is the lateral runoff, $s_{i,j}$ is the drainable porosity, and t is time. The time step is $\delta t = 1$ day. Terms without the indices (i,j) are applied uniformly over the model domain. Water table is computed in respect to the micro-topographic surface, and it is positive above the surface, and negative below it. For a description of the parameterization of Sn and $ET_{i,j}$ see Appendix A. This version of the model with the explicit representation of hummocks and hollows is called the *Microtopography* configuration.

The HH model can also run in a *Single Bucket* configuration, where all quantities are averaged over the model domain. Equation 1 becomes therefore:

$$\frac{dW}{dt} = \frac{Sn + P - ET - R}{s} \quad (2)$$

The lateral flux is implemented in the same way in the two versions, but in the *Microtopography* version the water can flow from cell to cell, while in the *Single Bucket* version the water simply flows out of the system. Cresto Aleina et al. (2015) showed that the *Single Bucket* configuration, despite being computationally much faster, fails to represent the peatland hydrology, constantly underestimating the water table position in comparison to measurements. This is due to the strong runoff that washes away the water at the beginning of the simulation. Because of the more rugged, hummocky surface represented in the *Microtopography* version, the runoff is delayed. This behavior better agrees with in situ measurements for water table position (Schneider et al., 2012), whereas the water table position simulated by the HH model in the *Single Bucket* configuration is too low. Table 1 describes the main differences between the two configurations of the HH model, and the *Hotspot* parameterization we present in this paper.

2.2 Coupling to a process-based methane emission model

The HH model is coupled to a process-based model for methane emissions, in order to quantify the effect of surface heterogeneities on GHG fluxes. The model developed by Walter and Heimann (2000) is a quite general model for methane emissions, and can be applied to peatlands in different environments. It is the same model that is used and coupled with some Dynamical Global Vegetation Models (DGVMs) (e.g., Kleinen et al., 2012; Schuldt et al., 2013; Petrescu et al., 2008; Zhang et al., 2002). We tuned the model to perform in a typical peatland at the latitude of the Ust-Pojeg mire complex. In the *Microtopography* configuration, we computed methane fluxes locally and we averaged over the model domain in order to upscale the local fluxes at the landscape-scale. The process-based model for methane emissions provides an output of methane fluxes $F_{CH_4}^{i,j}$ as a function of the water table (computed by the HH model), net primary productivity (NPP), and soil temperature (T):

$$F_{CH_4}^{i,j}(t) = f(W_{i,j}(t), NPP(t), T(t)) \quad (3)$$

Where $W_{i,j}$ is the water table depth with respect to the surface computed at each position (i,j) . All variables are represented at the daily time step. We force the model with time series of T and NPP taken from CMIP5 experiments performed by the MPI-ESM model. We then considered the model output for the grid cell which corresponds to the Ust-Pojeg mire (see Sect. 2.4). The amount of methane which is emitted by each kind of surface class changes according to the relative position of water table and surface. In the process-based methane emission model developed by Walter and Heimann (2000), the water table is a key variable in methane fluxes, because of the oxidation processes simulated as the water table drops below the surface and as the oxic zone deepens. The HH model in the *Microtopography*

configuration reasonably represents the hydrological interactions among hummocks and hollows and the variability of emissions within the peatland. In the *Single Bucket* configuration the water table drops quickly below the surface after the snow melt due to a strong runoff, and thus most of the methane transported from below ground is oxidized. Parameters for the methane emission model are described in Appendix B.

2.3 The Hotspot parameterization

The HH Model has a critical scale of about 0.01 km² at which seasonal results do not change for finer resolutions (Cresto Aleina et al., 2015). Even at this resolution it is unfeasible to include a micro-topography parameterization in the current GCMs.

The general purpose of our *Hotspot* parameterization is to upscale information from the local to the atmospheric scale. The HH model identifies different surface types depending on the relative position of the water table W and the surface:

$$\begin{aligned} W > \epsilon_a &\Rightarrow \text{wet surface} \\ -\epsilon_b \leq W \leq \epsilon_a &\Rightarrow \text{saturated surface} \\ W < -\epsilon_b &\Rightarrow \text{dry surface} \end{aligned}$$

Here we assume, after Couwenberg and Fritz (2012):

$$\begin{aligned} \epsilon_a &= 15 \text{ cm} \\ \epsilon_b &= 10 \text{ cm} \end{aligned}$$

because of the importance of such thresholds for methane emissions. We assume the *saturated* surface to be the surface class which dominates the methane emission dynamics, as a water table near to the surface prevents oxidation.

After obtaining the seasonal behavior of the desired surface class, we aim to parameterize of the area covered by the *saturated* surface class with a fractional number q , which represents the fraction of the total surface which is saturated at each time step. This information results in a different water table behavior which in turns controls methane emissions. By knowing the fraction q of saturated surface at each time step t we implicitly subdivide the domain of the HH model in the *Single Bucket* version A in unsaturated surface A_{unsat} and saturated surface A_{sat} :

$$A = (1 - q)A_{unsat} + qA_{sat} \quad (4)$$

The position of the water table in A_{sat} stays between $-\epsilon_b \leq W_t \leq \epsilon_a$, which is given by the definition of the saturated surface, and therefore we assume:

$$W_t^s = -\epsilon_b + (\epsilon_a + \epsilon_b)r \quad (5)$$

where r is a random number between 0 and 1. The position of the water table in A_{unsat} , instead, is the one computed by the HH model in the *Single Bucket* configuration, i. e.,

W in Eq. 2, which responds to precipitation and evapotranspiration. Methane fluxes are calculated as a function of the water table assuming a linear relationship between emitting area and methane fluxes:

$$F_{CH_4} = (1 - q)F_{CH_4}^{SB}(W) + qF_{CH_4}^{sat}(W_t^s) \quad (6)$$

where F_{CH_4} is the methane flux from the whole domain, $F_{CH_4}^{SB}$ the flux from the HH model in the *Single Bucket* version, and $F_{CH_4}^{sat}$ the flux from the saturated area A_{sat} . The saturated area fraction q is defined in Eq. 4. The other forcing variables for F_{CH_4} stay unchanged, as in Eq. 3.

The specific form of q as a function of time will be inferred by the analysis of the saturated area dynamics, an output of the HH model in the *Microtopography* configuration.

2.4 Forcing data

The HH model is forced with prescribed snowmelt, precipitation, and evapotranspiration (Equation 1). The simulated Sn is a stochastic input that functions as initialization parameter for the water table. It is parameterized to gain the same magnitude of the observational data (Schneider et al., 2012; Runkle et al., 2014). Evapotranspiration is simulated according to observations of Runkle et al. (2014) using an empirical parameterization. All parameterizations are described in more detail in the Appendices. In Equation 1 we assumed Sn and P to be uniform over the whole simulated domain and we did not apply any downscaling further.

We forced the process-based model for methane emissions developed by Walter and Heimann (2000) (Equation 3) and the water balance (Equation 1) with prescribed time series of NPP and T , and of precipitation P respectively. The time series are computed from simulations performed for the CMIP5 experiments with the MPI-ESM model at T63 resolution for the grid cell which corresponds to the Ust-Pojeg mire. The potential bias introduced by using NPP of C3 grasses and not the one for mosses (not included in the MPI-ESM model) is negligible as discussed by Cresto Aleina et al. (2015).

We used the P , T , and NPP from the last 30 years of the IPCC historical simulations and forced the model to infer a parameterization of the saturated area (Equations 4 and 6) for the past 30-year climatology. To assess the robustness of our parameterization for future simulations we chose three Representative Concentration Pathways (RCP) scenarios (Taylor et al., 2012), and we therefore considered the identical set of variables from the RCP2.6, RCP4.5, and RCP8.5 experiments from year 2006 to 2099 on daily resolution (Giorgetta et al., 2013).

3 Results and Discussion

3.1 Hotspot area dynamics

By averaging the output of the model over 30 years of simulations, from 1976 to 2005 we calculated the average dy-

Symbol	Meaning	Value
t_0	Initial day of simulation	79
t_1	Initial day of maximum saturation	110
t_2	Final day of maximum saturation	170
t_3	Initial day of minimum saturation	260
q_{in}	Initial saturation area density	0.52
q_{max}	Maximum saturation area density	0.8
q_{min}	Minimum saturation area density	0.5

Table 2. Parameter values for Equation 7. We infer the values from the dynamics of the grid cells belonging to the *saturated* surface class as in Figure 2. Days are computed according to the Julian calendar.

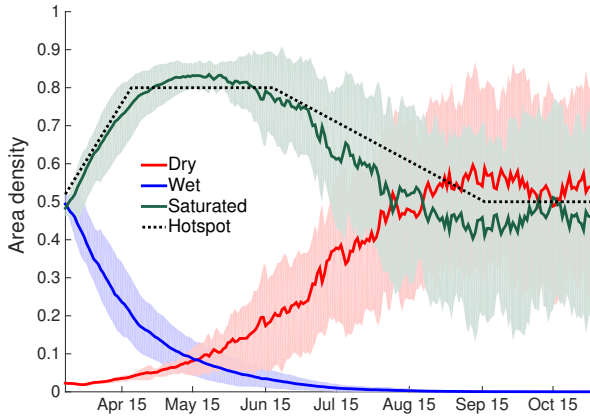


Figure 2. Area densities for *dry* (red line), *wet* (blue line), and *saturated* (green line) grid cells. The solid lines represent the different surface class dynamics averaged over 30 years, from 1976 to 2005. Shaded areas represent standard deviations over the same period of time. The dynamics of the *saturated* grid cells are mimicked by the empirical *Hotspot* parameterization (black dotted line), Equation 7 in the text.

namics of the three surface classes, *wet*, *saturated*, and *dry*. In particular, we are interested in the 30-year average of the *saturated* area A_{sat} dynamics (Eq. 4). After snowmelt, most of the simulated peatland surface is either *saturated*, or *wet* (Fig. 2). As the simulations continue, surface and subsurface runoff wash water out of the peatland, changing the relative composition of the area densities. More and more cells become *dry* by having a water table lower than 10 cm below the surface. Grid cells belonging to the *wet* surface class, with a high water table, become saturated and towards the beginning of August virtually no grid cell displays a water table higher than 15 cm above the surface level. At the end of the simulations, almost in all grid cells the water table lays more than 10 cm below the surface level, and the peatland is relatively dry by the end of October.

We used the output of the spatially explicit HH model to describe the dynamics of methane emission hotspots, assuming that the *saturated* grid cells are the ones where methane emissions are higher. We therefore infer the dynamics of the *saturated* grid cells from Figure 2, and obtain the following parameterization for methane emission hotspots:

$$q(t) = \begin{cases} q_{in} + \frac{q_{max} - q_{in}}{t_1 - t_0} (t - t_0) & \text{if } t \leq t_1 \\ q_{max} & \text{if } t_1 < t \leq t_2 \\ q_{max} + \frac{q_{min} - q_{max}}{t_3 - t_2} (t - t_2) & \text{if } t_2 < t \leq t_3 \\ q_{min} & \text{otherwise} \end{cases} \quad (7)$$

where t is the daily time step of the simulation, and the parameters t_i and q_j are tuned quantities obtained according to the dynamics of *saturated* grid cells in Figure 2. Values for the parameterization are described in Table 2. We slightly overestimate the amount of *saturated* grid cells in order to take into account the potential methane emission hotspots belonging to the *wet* surface class.

We illustrate the empirical parameterization of the area density computed by Equation 7 in Figure 2 (black dotted line). This parameterization represents the average dynamics of methane emission hotspots for the 30-year-period 1976-2005.

3.2 Methane emissions for 1976-2005

We compared methane emissions from the Ust-Pojeg mire simulated over a 30 year period (1976-2005) in the three versions of the HH model (Table 1). We then averaged the 30 simulations and studied the differences in dynamics among the different HH model versions. The *Microtopography* configuration (black line in Figure 3) produces seasonal fluxes that more than double the cumulative methane fluxes produced by the HH model in the *Single Bucket* configuration (red line in Figure 3). In particular towards July and August, when temperatures are higher and methane fluxes larger, the

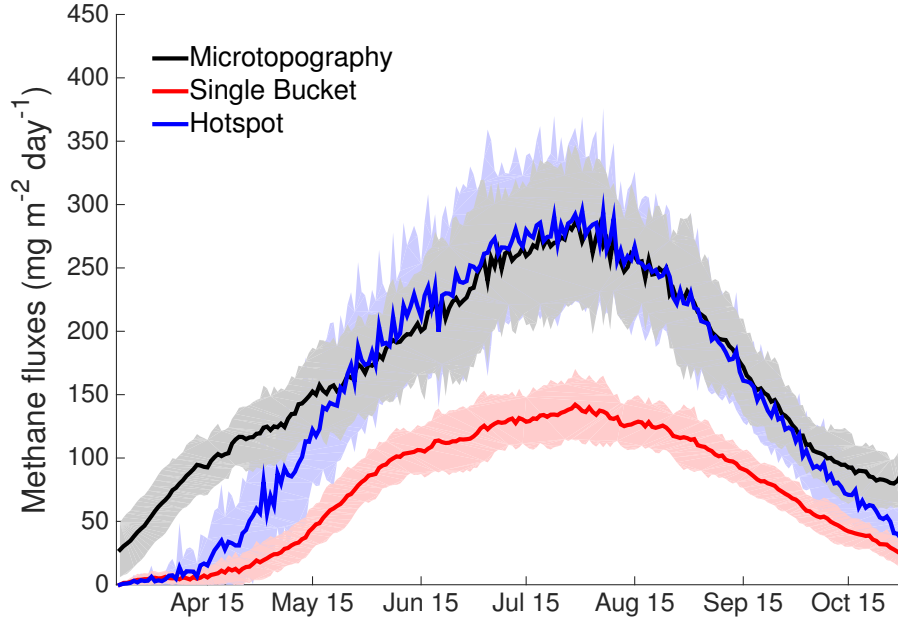


Figure 3. Methane emissions from the HH model coupled with the Walter and Heimann (2000) model. Solid lines are averages over 30 years (1976-2005) and shaded areas represent standard deviations. Emissions are computed using the HH model in the *Microtopography* configuration (black line), in the *Single Bucket* configuration (red line), and in the *Single Bucket* configuration with the *Hotspot* parameterization (blue line).

Symbol	Meaning	Value	Units
CH_4^{SB}	Cumulative emissions from the <i>Single Bucket</i> configuration	$1.70 \pm 0.11 \times 10^4$	mg m^{-2}
CH_4^{Mic}	Cumulative emissions from the <i>Microtopography</i> configuration	$3.82 \pm 0.30 \times 10^4$	mg m^{-2}
CH_4^{HS}	Cumulative emissions from the <i>Single Bucket</i> configuration with the <i>Hotspot</i> parameterization	$3.47 \pm 0.25 \times 10^4$	mg m^{-2}

Table 3. Cumulative emissions from different model configurations. The *Single Bucket* configuration produces less than the half of the cumulative methane emissions with respect to the model with micro-topography representation. By inserting a simple parameterization of the *saturated* surface dynamics, we improve significantly the seasonal methane emissions.

two versions of the HH model diverge in flux estimation and the *Single Bucket* configuration largely underestimates methane fluxes (Cresto Aleina et al., 2015).

Combining Equations 4 and 6, and the empirical parameterization of the hotspot area density $q(t)$ (Equation 7), we obtain a new flux dynamics (blue line in figure 3). The new parameterized fluxes display similar magnitude and dynam-

ics as the fluxes simulated by the *Microtopography* configuration, but at a much lower computational cost. The main difference between the emissions from the *Single Bucket* and the *Microtopography* configuration is the large underestimation in the central part of the summer season, i. e. in July and August. The *Hotspot* parameterization, by changing the saturated area, improved this feature. The visual improvement

is confirmed by the large differences in the seasonally cumulated methane emissions. The differences in cumulative emissions from the three model configurations are summarized in Table 3.

The *Hotspot* parameterization mimics the general magnitude and dynamics of the emissions from the *Microtopography* configuration, but fails to capture the whole amplitude of methane emissions at the beginning and at the end of the simulations. Such discrepancies might be caused by other variables which, differently from the water table, remain averaged over the domain. In particular, peat depth is uniform and the model does not have a heterogeneous peat profile as in the *Microtopography* configuration. This difference may influence the carbon available for methane emissions.

The *Hotspot* parameterization doubles the cumulative fluxes over the season with respect to the *Single Bucket* configuration, despite its low computational costs. From an ecological perspective, modeling CH_4 fluxes more accurately will improve our estimates of carbon stocks, which may help constrain dynamic vegetation models, bacterial C consumption models, and potential feedbacks with the atmosphere. Also, modeling hydroecological effects of "slower" runoff from a peatland can potentially influence vegetation dynamics of mosses in models including moss dynamics, e. g., Porada et al. (2013). The HH model is novel in the physical representation of lateral fluxes of water among hummocks and hollows, but other models representing surface heterogeneity controls on water table (e. g., Shi et al., 2015) and methane fluxes (e. g., Bohn et al., 2013), display similar effects. Therefore, and because of the process-based nature of the HH model, we are confident in hypothesizing similar results if a *Hotspot*-like parameterization was to be applied to other models.

3.3 Future projections with the *Hotspot* parameterization

The *Hotspot* parameterization mimics the simulated methane emissions of the *Microtopography* configuration for the 1976–2005 period for which it has been tuned. We now force the model for the 2006–2099 period with data from the CMIP5 experiments. The HH model does not simulate an increasing trend for methane emissions for the next 100 years, despite the generally higher temperatures (panels (a), (c), and (e) in Figure 4). Even in the RCP8.5 scenario, despite an increase of 4 K in average temperature in year 2099 in respect to the RCP4.5 and the RCP2.6 simulations, we can not find any significant trend. This result is in agreement with the findings from the The Wetland and Wetland CH_4 Inter-comparison of Models Project (WETCHIMP) experiments (Melton et al., 2013), which did not find a large significant trend in methane emissions simulated by the models participating in the inter-comparison project because of increased temperature or of precipitation trends. We use these two variables to force the HH model coupled with the methane emis-

sion model. Such an increase is suggested to reduce stomatal conductance, with the same amount of evapotranspiration, thus increasing waterlogged surface area. In particular, Melton et al. (2013) did not find a large significant trend in methane emissions simulated by the models participating in the inter-comparison project because of increased temperature or precipitation trends, which are the two variables we use to force the HH model coupled with the methane emission model.

Moreover, future changes in precipitation could potentially affect the water table position and therefore the saturated area fraction which could not correspond to the one described in the *Hotspot* parameterization. In the RCP simulations, even if precipitation changes in respect to present day and among the scenarios, the differences are not so large to cause significant effects on methane emissions. In panels (a), (c), and (e) of Figure 4, the outputs of the HH model in the *Microtopography* and in the *Single Bucket* configurations, i.e., the black and red lines, respectively, have water table explicitly depending on precipitation simulated in the RCP scenarios. The *Hotspot* parameterization (i. e., blue lines), despite using the saturated area dynamics for the years 1976–2005, are quite close to the methane emissions from the *Microtopography* configuration. We then conclude that the potential bias introduced by using a fixed saturated area dynamics (the one for the period 1976–2005) and not a dynamic one is negligible.

The *Single Bucket* configuration estimates 42.8 – 50.8 % of the methane emissions cumulated over the season simulated by the *Microtopography* configuration with the RCP8.5 scenario forcing. These estimates are very similar with forcing from the RCP4.5 scenario (44.3 – 50.4 %) and from the RCP2.6 scenario (43.0 – 50.6 %). If we include the *Hotspot* parameterization, the simulated annual methane emissions range from $2.831 - 4.321 \times 10^4 \text{ mg m}^{-2}$ with the RCP8.5 forcing. This is 83.9 – 101.5 % of the emissions simulated by the *Microtopography* configuration. As for the *Single Bucket* configuration, numbers are similar for the other forcing scenarios. The simulated emissions range from $2.771 - 4.056 \times 10^4 \text{ mg m}^{-2}$ (88.4 – 100.1 % of the emissions in the *Microtopography* configuration) for the RCP4.5 scenario, and $[2.648 - 4.102] \times 10^4 \text{ mg m}^{-2}$ (87.7 – 104.3 % of the emissions in the *Microtopography* configuration) for the RCP2.6 scenario. Amplitude and timing of year-to-year variability of cumulative methane emissions with the *Hotspot* parameterization are also comparable to the ones simulated by the *Microtopography* configuration in all simulated scenarios.

These results increase the applicability of the *Hotspot* parameterization. Despite being tuned for the 1976–2005 climatology, it works for the next century of simulations under very different forcing scenarios. This is due to the large differences in hydrological representations between the *Microtopography* and *Single Bucket* configurations. Such differences are almost totally overcome with the use of the *Hotspot* parameterization. These improvements make the parameter-

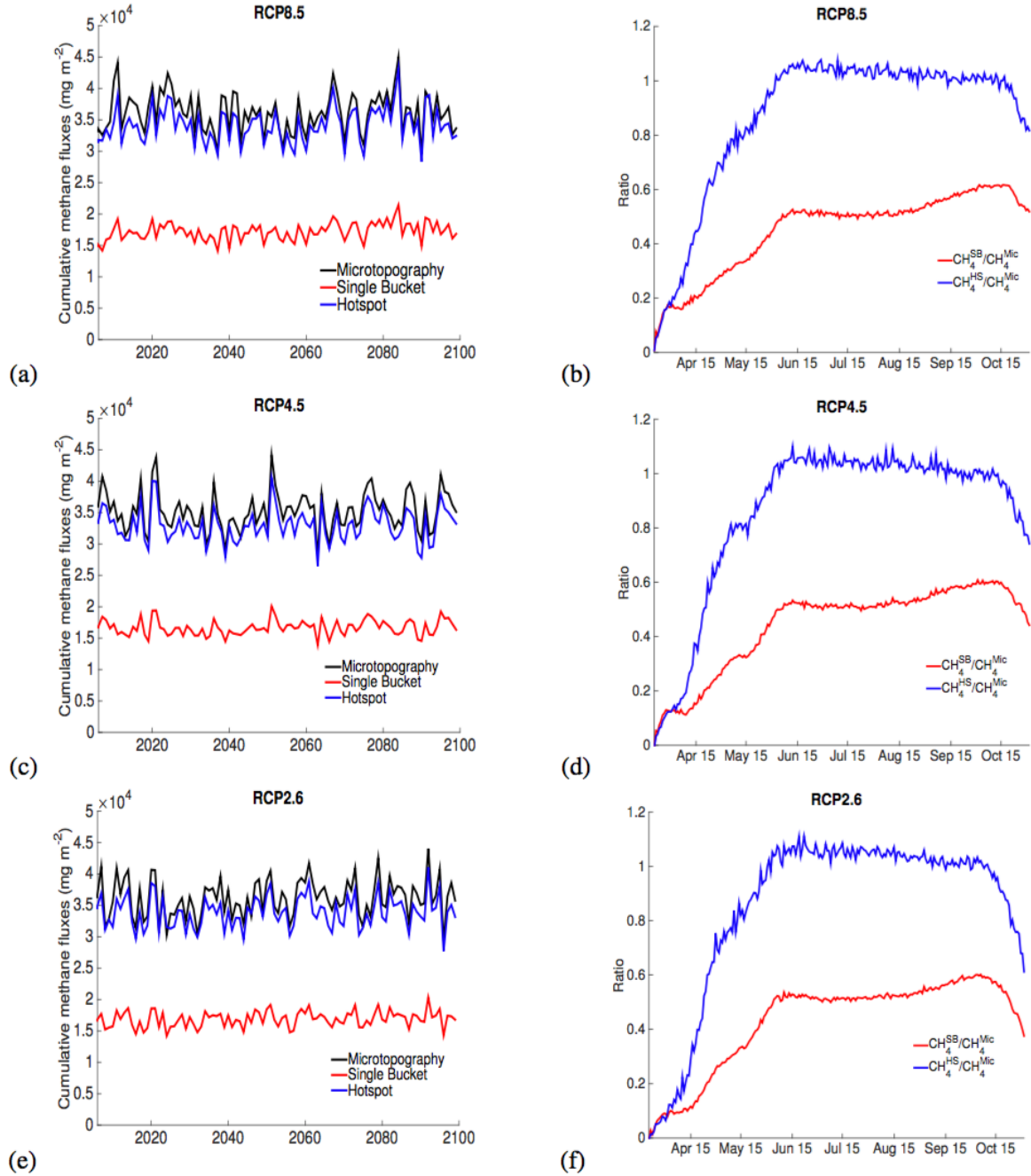


Figure 4. Performances of the three configurations of the HH model for future projections in different scenarios. Panels (a), (c), and (e) represent seasonally cumulated methane emissions computed by the HH model forced with CMIP5 data for the time period 2006–2099 from the RCP8.5, 4.5, and 2.6 experiments respectively. Panels (b), (d), and (f) represent the seasonal effectiveness of the *Hotspot* parameterization for future projections, forced with CMIP5 data for the time period 2006–2099 from the RCP8.5, 4.5, and 2.6 experiments respectively. We illustrate the ratio of methane emissions with respect to the *Microtopography* configuration for the *Hotspot* parameterization (in blue) and the *Single Bucket* configuration (in red). We averaged each day of simulation over the 2006–2099 period.

ization applicable also for future time slices, despite the differences in temperature, precipitation, and NPP forcing between the time period used for the parameterization tuning and the *scenario projections*.

We also tested the effectiveness of the *Hotspot* parameterization over the seasonal cycle. We averaged for each simulated day the methane emissions over the 2005–2009 period for all model configurations, and for all scenarios. We then divided the daily emissions from the *Single bucket configuration* and from the *Hotspot* parameterization by the emissions from the *Microtopography* configuration to investigate the impact of the new parameterization on the seasonal cycle. In all simulated scenarios, the *Hotspot* parameterization works very well during the mid season. From mid-May till the beginning of October, when methane emissions are higher, the ratio between the *Hotspot* parameterization and the *Microtopography* parameterization is near one (panels (b), (d), and (f) in Figure 4). The ratio between emissions from the *Single Bucket configuration* and the *Microtopography* configuration reaches its maximum only towards the end of the simulations, therefore missing the larger methane emissions peaks in June, July, and August.

4 Summary and Conclusions

We developed a new parameterization to bridge the scaling gap between a process-based, small-scale hydrological model for peatlands, and a mean field approximation, analogous to a large-scale parameterization in a DGVM. The *Hotspot* parameterization uses the output of the HH (Hummock-Hollow) model (Cresto Aleina et al., 2015) which simulates a $1\text{ km} \times 1\text{ km}$ peatland. The HH model can work in both configurations, a spatially explicit one working at $1\text{ m} \times 1\text{ m}$ scale, simulating explicitly hummocks and hollows (the *Microtopography* configuration) and a mean field approximation of it, where all quantities are averaged over the domain (the *Single Bucket* configuration). If coupled to a process-based methane emission model (Walter and Heimann, 2000) the *Microtopography* configuration simulates more realistic methane fluxes because of the better representation of hydrology due to the explicit description of processes at 1 m scale, but at a much higher computational cost. We assumed that the lack of representation of saturated areas in the *Single Bucket* configuration, which are methane emission hotspots, diminish the cumulative emissions over the season by half.

We inferred a parameterization of this hotspot area for emissions for the period 1976–2005, which are the last 30 years of the historical simulations from the CMIP5 experiments. We analyzed the spatial pattern of the HH model output in the *Microtopography* configuration averaged over the 30 simulated years. We introduced this information in the *Single Bucket* configuration, modifying the hydrology of the mean field approximation, obtaining the *Hotspot* parameter-

ization. This novel approach that takes into account the information from the spatially explicit simulations bridges the gaps between the simulated methane emissions. The *Hotspot* parameterization, due to its higher modified water table, is able to mimic the general magnitude and dynamics of the emissions from the model with micro-topography representation.

By forcing the model with time series of temperature, NPP, and precipitation for the next century from CMIP5 experiments in the RCP8.5, RCP4.5, and RCP2.6 scenarios, we assessed the robustness of the *Hotspot* parameterization under forcing for which it was not originally calibrated. The parameterization holds for years 2006–2009 for all three scenarios. Overall, the ratio between the seasonally cumulated emissions from the HH model in the *Microtopography* configuration and the ones simulated by the *Hotspot* parameterization ranges between 0.84 and 1.04. This is a substantial improvement in comparison to the methane emissions simulated by the *Single Bucket* configuration, which only produces between 43 and 51 % of the seasonally cumulated methane emissions. The *Hotspot* parameterization at almost no computational costs therefore qualitatively changes and improves the simulated system response for methane emissions.

We only applied this method to the HH model simulating a single peatland in west Russia. This method, though, uses the information of a mechanistic, spatially explicit model and it is a significant first step towards a full parameterization of the micro-topographic impacts on complex ecosystems at the DGVM-scale. In order to develop such a parameterization we would need a comprehensive and statistical analysis on the response of the mechanistic local-scale model to different climatic forcing, i. e. we would need HH-like models working at the micro-topographic scale applied at different peatlands in other climatic zones. Another limitation of the applicability of this study is its dependency on the availability of data to calibrate the original HH model in its *Microtopography* configuration, as accurate measurements of peatland micro-relief are needed to initialize surface height. While it is not realistic to have theodolite micro-topographic measurements globally, other methods and products could help provide similar information. Aerial photographs provide some information on micro-topography, but generally at an overly coarse scale. Statistical downscaling methods as the ones used, e. g., by Muster et al. (2012) and Stoy and Quaife (2015) are therefore needed to infer information on surface heterogeneities, but they are not necessarily useful in identifying micro-topography distribution. Airborne measurements could aid in giving qualitative and stochastic information also on structural peatland patterns, such as the ones described by Couwenberg and Joosten (2005). This information could be used by the HH model to generate non random configurations, potentially investigating the influence of structured patterns on hydrology and methane emissions.

Introducing the analysis of spatial patterns produced by different mechanistic models in multiple ecosystems is a powerful method to infer landscape-scale dynamics and characteristics of patterns.

Appendix A: Climatology parameterization

Cresto Aleina et al. (2015) did not consider the snow melt S_n , since they started the simulations later on, and therefore initialized the water table to match the observations at the end of April. S_n represents the water input at the beginning of the warm season. The cold season is not represented in the model, because we assume that snow covers the area (almost) uniformly. We compute the snowmelt as a random number varying between 200 and 300 mm. We used this range for S_n in order to obtain an initial water table level on the same order of magnitude of the one observed by Schneider et al. (2012) and Runkle et al. (2014).

Evapotranspiration is dependent on the soil dryness and patchiness. We refer to former studies (Nichols and Brown, 1980), which extensively analyzed the evaporation rate from sphagnum moss surfaces. The evapotranspiration rate depends on the day of the season, the surface wetness, and on the micro-topographic features.

$$ET_{i,j} = \begin{cases} \frac{ET_{i,j}^{max}}{fr(W_{i,j})} \sin\left(\frac{(t-4t_0)\pi}{6t_0} \frac{ET_{i,j}^{max}}{ET_{i,j}^{max}}\right) & \text{if } 180 < t < 300 \\ \frac{ET_{i,j}^{max}}{fr(W_{i,j})} & \text{otherwise} \end{cases} \quad (A1)$$

where t is the daily time step in days of Julian calendar, $t_0 = 30$ days is a time constant and $ET_{i,j}^{max}$ is a function of the micro-topographic features for the cell at the position i, j :

$$ET_{i,j}^{max} = \begin{cases} 6 \text{ mm d}^{-1} & \text{if Hummock} \\ 3 \text{ mm d}^{-1} & \text{if Hollow} \end{cases} \quad (A2)$$

$fr(W_{i,j})$ takes into account the fact that evaporation takes place at a higher rate if the water table is above the surface:

$$fr(W_{i,j}) = \begin{cases} 1 & \text{if } W_{i,j} \text{ above the surface level} \\ 2 & \text{if } W_{i,j} \text{ below the surface level} \end{cases} \quad (A3)$$

We use this very simple parameterization of the evapotranspiration rate in order to study the general response of the model to random climatic conditions and to produce quantities in the order of the ones measured by Runkle et al. (2014).

Appendix B: Parameters for the methane emission model

We tuned the parameters used in the process-based model for methane emissions (Walter and Heimann, 2000) in order to apply the model at the latitude of the Ust-Pojeg Mire complex, in the Komi Republic, Russia (61° 56'N, 50° 13'E, 119

m a.s.l.). Walter and Heimann (2000) used a tuning parameter for the model, R_0 , which we fix at 0.30. Another parameter needed for the coupling with the methane emission model is the soil depth, which we fixed at 150 cm following in situ observation.

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