

We thank the reviewers for their constructive feedback and suggested corrections. Below we have addressed each individual comment from reviewers 1 and 2, as well as comments by the executive editor (reviewer and editor comments are shown in italics; our responses are shown in bold). All manuscript changes are highlighted as ‘tracked changes’ in the revised manuscript (the bracketed line numbers denote the corresponding line numbers in the revised manuscript). We believe that the following revisions have substantially improved the overall quality of our manuscript.

Referee 1

The authors aim at providing a dataset for methane emissions by wetlands which includes not only estimates of fluxes by biogeochemical models (the bottom-up approach) but also information on error covariance patterns. This information may be useful for performing inversions of methane fluxes through atmospheric data assimilation (i.e. for the top-down approach).

General comments

To my knowledge, this is the first time it is explicitly attempted to provide information on the uncertainty patterns together with bottom-up estimates of methane fluxes. As I am working with atmospheric data assimilation, I think the method and results of this study are very interesting. I have nevertheless two main remarks:

(1.1) the 6-member ensemble is too small to allow for statistics, so I would recommend only mentioning that “more classical” (i.e without the uncertainty patterns) methane flux estimates are available in EE for those who need a long period of time - and simplifying the text and figures accordingly in the Results and Discussion Sections

We acknowledge that relative to FE, the EE ensemble size may limit statistical representations of wetland CH₄ model uncertainty. We now elaborate on this point in the discussion section of the revised manuscript: “due to the smaller ensemble size and the use of only one carbon model (see Table 1), the 2001-2015 EE emission variability should be interpreted with caution, and - where possible - evaluated against the FE ensemble during the 2009-2010 period” (P16 L3-6).

However, we have chosen to keep the EE evaluations, as these may be beneficial for the users of EE. We also note that - in response to comment 1.8 - we have expanded the EE ensemble (EE ensemble size = 18) to explicitly represent the uncertainty of the global wetland CH₄ source. Finally, at the request of the second reviewer, we have now included an evaluation of the EE emission inter-annual variability in the

revised manuscript (see response to comment 2.2). Given these changes, we are confident that the inclusion of EE evaluations is fitting for the main body of the manuscript.

(1.2) *The figures are potentially very nice and informative but presently difficult to read, even with a large zoom on a screen (see below for more specific comments on each).*

We have addressed the reviewer's comments relating to figures below; where appropriate, we have also increased font and panel sizes to improve figure legibility.

Specific Comments

General

(1.3) *The means of the ensembles are used. Why not use the median?*

For gridded and zonal emission estimates (Figures 1-3 and GEOS-Chem simulations), we chose to report the mean values in order to maintain consistency with the prescribed global wetland CH₄ source (166 Tg CH₄ yr⁻¹ during 2009-2010; see comment 1.4). We found that gridded and zonal FE and EE median values amount to substantially less than 166 CH₄ yr⁻¹; in contrast, mean FE and EE emissions amount to exactly 166 CH₄ yr⁻¹ during 2009-2010.

(1.4) *See if it is possible to update your Kirschke et al. (2013) reference with Sauniois et al. (2016) (available at <http://www.earth-syst-sci-data-discuss.net/essd-2016-25/>) in the whole text. In Section 2.1, p.7, l.17-18: would propagating the new smaller uncertainty for global mean wetland methane emissions (i) take much time and (ii) significantly change the results?*

As suggested by the reviewer, we have now updated the global mean wetland CH₄ emission estimate and the associated uncertainty (166 Tg/yr +/- 25% or 124.5 - 207.5 Tg/yr), which spans the Sauniois et al., (2016) mean (166 Tg/yr) and range (125 - 204 Tg/yr) of 2000-2009 wetland CH₄ emission estimates. We have updated the text (P5 L22-25; P7 L16-19; P15 L10-13), figures, Table 1 and the GEOS-Chem model simulations accordingly. We did not find any substantial changes in the results or evaluation of our dataset.

Section 1 Introduction

(1.5) *p.3, l.20-21: uncertainties are often formulated using correlation lengths in*

space (e.g. at the global scale, 500 km on land) and sometimes also in time (e.g. still at the global scale, one or two months) over a percentage of the prior emissions. This is especially done to take into account large patterns in the errors due to underlying controls as is the case with wetland emissions. Please check your references here and adapt the text. This does not change the fact that correlation lengths are always an issue because the value at which they are set is derived from expert-knowledge, which is mainly valid at the global scale.

We acknowledge our oversight: we omitted to mention the use of prior spatial and temporal correlations on total CH₄ emissions, such as those used in the Bousquet et al., (2011) and Pison et al., (2013) studies. We have rephrased the sentence to better summarize the use of prior error covariances among inversion efforts: “typically CH₄ inversions do not explicitly formulate wetland CH₄ emission uncertainty correlations: rather, prior wetland CH₄ uncertainty correlations are either absent or implicitly prescribed through space-time correlation lengths on total CH₄ emissions” (P3 L21-23).

(1.6) p.4, l.8-11: I don't understand here what is meant by the “further constrained” ensemble. Do you mean that the top-down approach could retrieve the controls of biogeochemical processes instead of fluxes from atmospheric data assimilation? It seems it is what is meant in Section 4.2, p.15, l.6-8.

We have now re-worded this sentence: “Top-down CH₄ emission estimates can then be used to quantify (a) the probability of individual ensemble members; and (b) the combined probability distribution of carbon models, CH₄:C temperature dependencies and wetland extent scenarios” (P4 L12-14).

Section 2.1

(1.7) p.5, l.20: using the word “ensemble” for a six-member sub-set and deriving statistics over such a small number of members does not seem very appropriate. See if it is possible to leave EE aside for most of the paper and only mention it as a “more classical” set of estimates (see also General comments).

We have revised our manuscript text and figures to better convey the limitations of the extended ensemble (see response to comment 1.1). We also note that the EE ensemble is now comprised of 18 members (see response to comment 1.8)

(1.8) p.7, l.18-19: why 1000 perturbations?

In response to the reviewer's question, we investigated the impact of the number of

perturbations, and found no substantial impact on reported FE percentile intervals and error correlation values. In light of this, we now use a simpler approach to explicitly represent global wetland source uncertainty: we expand both FE and EE emission ensembles by deriving three scaling factors corresponding to global annual wetland emissions of 124.5, 166 and 207.5 Tg/yr; these span the range of the Sauniois et al., (2016) emission estimates. The number of ensemble members for FE and EE are now 324 and 18. We have amended Table 1 and the methods section (P5 L22-25; P7 L16-19), and we have removed the description and calculation of FE_{exp} , since it is now obsolete.

Section 2.2

(1.9) p.9, l.4-6: I understand the idea of keeping mostly sites where the vertical mixing in the model is not too much of an issue but using only the altitude (a.s.l.?) of the site seems to be too simple. Could you detail a bit more?

Our statement was erroneous, as we did not actually use an altitude threshold (the text was a remnant of a previous analysis); we have modified the sentence accordingly (P9 L1).

Section 3

(1.10) see if it is possible to leave EE aside (see above and General comments)

See response to comment (1.1).

(1.11) p.10, l.5: could you quantify “considerable”?

We now explicitly state the peak CH₄ emission month for each dataset (P10 L12-13).

(1.12) p.10, l.19-21: could you explain in more detail why you expect inter-annual variability to be smaller than your uncertainty?

We have now revised this sentence to clarify that our expectation is based on previous wetland CH₄ process modelling efforts. For the sake of clarity, we also support our statement with a quantitative comparison between the FE and EE uncertainties and the maximum inter-annual variability of the 1993-2004 WETCHIMP models (P10 L26 - P11 L4).

(1.13) p.11, l.16-seq.: this paragraph is difficult to read with all the figures embedded in the text. Could you put them in a Figure or Table?

In the revised manuscript, we have split the paragraph into two, as two separate figures are being presented (P12 L10-24), and we have omitted the 5th - 95th percentile results, as these are depicted graphically in Figure 8.

Section 4.1

(1.14) p.14, l.8-11: more and more atmospheric data of mixing ratios of methane isotopes are available and data assimilation systems try to make use of these and isotopic signatures of the various sources to improve the inversion of methane fluxes. Do you think not only the total methane fluxes but also the isotopic composition could be improved?

We agree that our ensemble estimates can be used to better represent the biogeochemical process uncertainty in isotopic CH₄ studies; however, we have chosen not describe the potential advantages of using our datasets in isotopic CH₄ investigations, as these are beyond the scope of our manuscript. In case the reviewer is specifically referring to lakes and wetlands: to the best of our knowledge, lake and wetland isotopic CH₄ signatures are not sufficiently distinct to resolve between the two sources.

(1.15) p.14, l.16: the global uncertainty is always smaller than the smaller scale uncertainties, could you quantify “substantially”?

We have revised this sentence and now explicitly state that regional scale uncertainties (shown in Figure 4) span a factor of 2 – 156 (P15 L8).

Technical Corrections

General

(1.16) check “Kirschke” everywhere (and not “Kirshke”)

Done

(1.17) check all references in the form of “based on the Bloom et al., (2016) methodology”: it looks like there shouldn’t be a comma before the year between parenthesis.

Done

(1.18) “primary” is used for “main” or “dominant” e.g. p.7, l.26 or p.11, l.20, and it seems a bit strange to me, non-native English speaker.

In reference to the “primary uncertainty” estimates, we have now replaced “primary” by “dominant” throughout the revised manuscript.

Section 1 Introduction

(1.19) p.4, l.9: “based top-down CH4 emission estimates” → based ON top-down CH4 emission estimates?

This sentence has been edited in the revised manuscript.

Section 2.1

(1.20) p.5, l.10: “heterotrophic respiration at time for a” → delete “at time”?

Now changed to “heterotrophic respiration per unit area at time t” (P5 L13).

(1.21) p.6, l.18: *h* should be *h*?

h is now written in bold-italics as “***h_{*,j}***” is a vector. We note that in the revised manuscript mathematical notations are now consistent with the Geophysical Model Development journal requirements.

(1.22) p.7, l.4: “freshwater bodies in *w_i(x)* section 4” → delete *w_i(x)*?

Typo corrected (P7 L8)

Section 3

(1.23) p.9, l.18: if FE emissions are intended, it seems that it should be Figure 1a; if it is Figure 1b which is commented, it should be “High-latitude EE emissions”.

In the revised manuscript we have re-worded this paragraph in order to (a) correctly reference the spatial distributions of FE and EE emissions; (b) add explicit references to panels c and d, as recommended by the reviewer in comment 1.24 (P9 L21 - P10 L3).

(1.24) p.9, l.19-20: add references to panels c and d in Figure 1 to guide the reader.

Done (P9 L25)

(1.25) p.9, l.22: “(EE) *s*; the FE” → delete “*s*”?

Typo corrected

(1.26) p.10, l.14: *Chang et al. (2014) should be “Alaska Wetlands” to be consistent with the whole sentence.*

Done (P10 L20-21)

(1.27) p.10, l.24-25: *“dominated carbon decomposition” → “dominated BY carbon de- composition”*

Done (P11 L19)

(1.28) p.13, l.8: *“is able capture” → “is able TO capture”*

Done (P13 L28)

Figures

(1.29) *Figure 1: difficult to read, even on a screen. Larger maps and discrete colour scales would make it easier. It seems that panels e and f are never referred to in the text.*

As recommended by the reviewer, we have now enlarged the font sizes, increased the map sizes, and have used a discrete (9-color) scale. We have also included explicit references to panels e and f in the results section of the revised manuscript (P9 L16-19).

(1.30) *Figure 2: - it is almost impossible to distinguish pale grey fine lines from darker grey larger lines! - put FE ensemble and FE mean in the legend since it is used in the whole text (instead of “Ensemble” / “Mean” alone in the top panel or “This study” in the bottom panel) - if following the recommendation of not commenting too much on EE in the body of the article, the top panel could be in Supplementary material (or Appendix?)*

For the sake of clarity, we have now removed the top panel in Figure 2; we now show the means and full ranges of FE and EE emissions in a single panel along with GC and BL emissions. We have updated the figure legend accordingly.

(1.31) *Figure 3: a discrete colour scale would make it easier to read, together with larger panels if possible.*

We have now revised the figure to include a discrete color scale; as recommended, we have also expanded the panel sizes.

(1.32) *Figure 4: you may use box plots to make the legend clearer and shorter; could you enlarge the map?*

As recommended, we have substantially enlarged the map in the revised figure and shortened the legend.

(1.33) *Figure 6: the colour scale is a bit strange since the ticks every 0.2 do not fit the limits of shades*

We have revised the color scale to match the ticks (now Figure 7).

(1.34) *Figure 8: a discrete colour scale would make it easier to read C6*

The revised figure (now Figure 9) includes a discrete color scheme.

(1.35) *Appendix B: - p.16, l.10: “ensemble. the “cor()”” → “ensemble. The “cor()””*

Typo corrected

- p.16, l.11: “For Figure 6, $A_{l,m}$ we aggregate”: do you mean that Fig 6 shows the $A_{l,m}$ coefficients?

Sentence revised: the start of this sentence now reads “For Figure 7, we aggregated...” (P17 L25).

(1.36) *Appendix C: p.17, l.4: “R100,1,1” should probably be R100,3,1*

Typo corrected (P18 L18)

Anonymous Referee 2

This study describes and evaluates a new global dataset of CH₄ emissions from natural wetlands. The method follows an ensemble approach, which has the advantage that the computation of uncertainties, including spatio-temporal covariances, is straightforward. The dataset is meant to serve as a first guess in inverse modeling for which the uncertainty quantification has a clear advantage over other methods.

(2.1) *It is not entirely clear what the evaluation using the GEOS-CHEM model brings, other than the notion that this dataset is in reasonable agreement with datasets that were used in the past. Obviously, flux measurements are better suited to test the performance of a methane emission model, although scale dependencies com-*

plicate that approach also. Since this holds for the other datasets as well, it would nevertheless provide additional information.

We agree with the reviewer that - relative to the regional flux constraints (Figure 4) - the GEOS-Chem evaluation only provides supporting evidence on the plausibility of wetland CH₄ emissions relative to previous datasets: we now clarify this point in the revised manuscript (P9 L3-5). In addition, we now recognize the value of in-situ methane CH₄ measurements in the revised manuscript: while the direct comparison between global-scale fluxes and in-situ measurements is a challenging task (and beyond the scope of our work), we now highlight the importance of measurement-based regional estimates for the evaluation and improvement of future global wetland CH₄ emission ensembles (P15 L10-13).

(2.2) Otherwise I was missing the dimension of inter-annual variability, which brings a clear advantage for the EE dataset - although it remains unclear what that variation looks like and how realistic it is.

We have now incorporated an evaluation of the EE inter-annual variability (IAV), including an additional manuscript figure: in particular, we compare 2001-2015 EE IAV against 2009-2010 FE emissions and the WETCHIMP model ensemble during 2001-2004 (see Figure 5 and P11 L6-11). We also include an evaluation EE IAV against observationally constrained Alaska CH₄ emissions during 2012-2014 and Amazon emissions during 2010-2011 (P11 L11-15). Our evaluation indicates that EE IAV is broadly consistent with both modeled and observationally constrained wetland CH₄ emission estimates.

Otherwise I have only a list of technical corrections, which should be relatively easy to tackle.

(2.3) page 4, line 9: 'based top down'

This sentence has been edited in the revised manuscript

(2.4) page 5, eq. 20: Mention that there are 6 scenarios for EE (which helps the reader to make sure he/she understands table 1 correctly)

Done (P5 L24): we note that EE now consists of 18 ensemble members (see response to comment 1.8)

(2.5) eq 2: what is done when $w(x)$ is not covered by $h(x)$ and vice versa?

We have revised the description of equation 2 to clarify that $w(x)$ represents the wetland extent fraction, while $h(t,x)$ is the relative temporal variability (P6 L15-16). In the revised manuscript, we also clarify that when $h(t,x)w(x) > 1$, $A(t,x)$ is set to a maximum value of 1 (P6 L22-24).

(2.6) eq 3: *how is this done for the EE time series, every year 175Tg/yr or just the mean over the whole period? In the latter case: how do the global emissions compare for 2009-2010? It would also be useful to know how much of a correction is needed to get to 175 Tg/yr.*

For both EE and FE, s_c is derived such that each ensemble member's global emissions amount to an average annual flux of 124.5, 166 or 207.5 Tg/yr during the 2009-2010 time period (previously 175 Tg/yr; see comment 1.8). We have now clarified this in the revised manuscript (P7 L16-17). In response to comment 2.2, we also include an evaluation of EE throughout 2001-2015 (P11 L6-11 and Figure 5). For the sake of brevity, individual FE and EE s_c values (spanning 4 - 100% relative to the maximum s_c value) are not reported in the main body of the manuscript; however, we highlight that individual s_c values can be derived using the WetCHARTs code (now included in the supplementary material).

(2.7) page 7, line 26: *'uncertainty. The derivation' i.o. 'uncertainty; the derivation'*

Done (P8 L1).

(2.8) page 8, line 11: *'been in a'*

Sentence revised (P8 L8)

(2.9) page 8, line 15: *'Commission' i.o. 'Comission'*

Typo corrected (P8 L12).

(2.10) page 8, line 17: *'). The non-wetland' i.o. ') .The non-wetland'*

Done (P8 L13).

(2.11) page 9, line 23: *'significantly lower (with' i.o. 'significantly (with' and remove 'lower' in the next line.*

Done (P10 L1)

(2.12) page 10, line 20: *'estimated' i.o. 'estimate'*

Changed to “emission uncertainty estimates are” (P10 L23).

(2.12) page 10, line 25: ‘by carbon’ i.o. ‘carbon’

Done (P11 L19)

(2.13) page 11, line 15 - bottom: *This part is hard to read due to all the numbers. It would be better to put the numbers in a Table.*

See response to reviewer comment 1.13

(2.14) page 13-14: *How much emissions are derived from rivers/lakes using the current approach?*

As discussed in the “model limitations” section, we are unable to report emissions from rivers and lakes as we have insufficient information to disentangle the relative CH₄ contribution of non-wetland freshwater bodies within each grid-cell. We have re-worded this section to clarify this point in the revised manuscript (P14 L24 - P15 L1).

(2.15) page 28: ‘Contribution’ i.o. ‘Contribution’

Done

(2.16) figure 1: bottom panels: *how can the units be compared?*

All color bar labels now include units in the revised version of Figure 1.

(2.17) figure 3: *the legend title misses a unit area*

Wetland CH₄ emissions (Tg/month) are reported as total emissions across 5-degree bins within each region shown on the inset map. We have modified the figure caption to clarify this.

Astrid Kerkweg

(3.1) *In my role as Executive editor of GMD, I would like to bring to your attention our Editorial version 1.1: <http://www.geosci-model-dev.net/8/3487/2015/gmd-8-3487-2015.html>. This highlights some requirements of papers published in GMD, which is also available on the GMD website in the ‘Manuscript Types’ section: http://www.geoscientific-model-development.net/submission/manuscript_types.html. In particular, please note that for your paper, the following requirements have not*

been met in the Discussions paper:

“Inclusion of Code and/or data availability sections is mandatory for all papers and should be located at the end of the article, after the conclusions, and before any appendices or acknowledgments. For more details refer to the code and data policy” (Editorial v1.1, Appendix A1)

“Papers describing data sets designed for the support and evaluation of model simulations are within scope. These data sets may be syntheses of data which have been published elsewhere. The data sets must also be made available, and any code used to create the syntheses should also be made available.” (Editorial v1.1, Appendix A5).

For these papers the same criteria as for model description papers apply, i.e., “The main paper must give the model name and version number (or other unique identifier) in the title.” (Editorial v1.1, Appendix A2) In this case the “model” is the “data set”

Please add a data availability section and include the data sets name and version number in the title in your revised submission to GMD.

The data availability section is now positioned at the end of the article before the acknowledgments and appendices sections (P16 L21). We have now added a model name and version number (WetCHARTs version 1.0) in the title of our manuscript. We have included the WetCHARTs matlab code in the supplementary material of our revised manuscript. The final dataset (>50 MB) has been submitted to the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC): the dataset is linked to the manuscript via a digital object identifier (Bloom et al., 2017; doi: 10.3334/ORNLDAAC/1502) and will become publicly accessible upon publication. The data availability section has been expanded to include information on the ancillary datasets used in this study.

Additional changes

– We identified a minor bug in our code related to the timing MsTMIP heterotrophic respiration outputs; we have updated the results throughout the manuscript accordingly. We note that the outcome had a minimal impact on the results presented in our manuscript. However, for the sake of clarity, the WetCHARTs code – now included in the supplementary material of the revised manuscript – also includes the subroutines used to read MsTMIP heterotrophic respiration outputs.

– We now report the correct CH₄ emission units in Figure 3 (Tg/month, instead of Tg/yr).

– In the revised manuscript, Figure 1e now correctly shows the FE 5th - 95th percentile values (in the discussion manuscript, the figure was inadvertently showing FE standard deviation values).

A global wetland methane emissions and uncertainty dataset for atmospheric chemical transport models ([WetCHARTs version 1.0](#)).

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Abstract. Wetland emissions remain one of the principal sources of uncertainty in the global atmospheric methane (CH₄) budget, largely due to poorly constrained process controls on CH₄ production in waterlogged soils. Process-based estimates of global wetland CH₄ emissions and their associated uncertainties can provide crucial prior information for model-based top-down CH₄ emission estimates. Here we construct a global wetland CH₄ emission model ensemble for use in atmospheric chemical transport models ([WetCHARTs version 1.0](#)). Our 0.5°×0.5° resolution model ensemble is based on satellite-derived surface water extent and precipitation re-analyses, nine heterotrophic respiration simulations (eight carbon cycle models and a data-constrained terrestrial carbon cycle analysis) and three temperature [dependence](#) parameterizations for the period 2009-2010; an extended ensemble subset – based solely on precipitation and the data-constrained terrestrial carbon cycle analysis – is derived for the period 2001-2015. We incorporate the mean of the full and extended model ensembles into GEOS-Chem and compare model against surface measurements of atmospheric CH₄; model performance (site-level and zonal mean anomaly residuals) compares favourably against published wetland CH₄ emissions scenarios. We find that uncertainties in carbon decomposition rates and wetland extent together account for more than 80% of the [dominant](#) uncertainty in the timing, magnitude and seasonal variability of wetland CH₄ emissions, although uncertainty in the temperature

CH₄:C dependence is a significant contributor to seasonal variations in mid-latitude wetland CH₄ emissions. The combination of satellite, carbon cycle models and temperature dependence parameterizations provides a physically informed structural a priori uncertainty critical for top-down estimates of wetland CH₄ fluxes: specifically, our ensemble can provide enhanced information on the 5 prior CH₄ emissions uncertainty and the error covariance structure, as well as a means for using posterior flux estimates and their uncertainties to quantitatively constrain global wetland CH₄ emission biogeochemical process controls.

1 Introduction

10

Methane (CH₄) is a potent greenhouse gas, with a global warming potential of more than 25 times that of CO₂ on a 100-year time horizon (Myhre et al., 2013). The global CH₄ budget and growth rate remain poorly understood, largely due to poorly resolved evolution of atmospheric CH₄ sources and sinks (Nisbet et al., 2014). Wetland CH₄ emissions are the largest natural source of atmospheric CH₄, 15 amounting to roughly 20 – 40% of global CH₄ emissions (Ciais et al., 2013). The large disparities between a range of top-down and bottom up wetland CH₄ estimates (Kirschke et al., 2013; Melton et al., 2013) arise from large uncertainties in the timing, distribution and the underlying processes controlling net wetland CH₄ production.

In wetland soils, CH₄ is produced by the decomposition of organic matter in anaerobic (oxygen 20 depleted) environments. The dominant processes controlling the seasonal and inter-annual variations include carbon availability (soil C substrate) and decomposition rate, wetland inundation extent, and temperature (Yvon-Durocher et al., 2014). Other important controls on wetland CH₄ emissions include the presence of macrophytes (Laanbroek 2010), organic C decomposition rates (Miyajima et al., 1997) and soil pH (Singh et al., 2000), amongst other factors. The link between terrestrial carbon-water 25 cycling and wetland CH₄ emissions is of particular interest from a terrestrial greenhouse gas emissions standpoint: inter-annual variations in terrestrial carbon cycling (Le Quéré et al., 2013) can affect wetland CH₄ emissions on seasonal-to-century timescales (Hodson et al., 2011). The role of carbon cycle dynamics in global wetland CH₄ emissions is increasingly recognized: temporal variations in

gross primary production influence short-term carbon supply (such as carbon inputs from root exudates and fine litter), as well as long-lived carbon stores (such as wood litter turnover or soil organic C) in wetland soils (Riley et al., 2011; Bloom et al., 2012; Melton et al., 2013). The combined response of CO₂ and CH₄ fluxes to climatic variability remains poorly characterized. For example, increasing temperatures in boreal ecosystems could lead to higher carbon uptake, increased respiration and drier soils (Watts et al., 2014), and it is currently unclear whether these processes amount to an amplifying or dampening effect on boreal CH₄ emissions. From a greenhouse gas balance standpoint, quantifying the global-scale process links between terrestrial carbon cycling and wetland CH₄ emissions is crucial to characterizing the combined terrestrial biosphere CO₂ and CH₄ flux response to climatic variability.

10 Quantification of regional wetland CH₄ emissions remains challenging. While wetland CH₄ emissions are relatively well constrained on a global scale (Kirschke et al., 2013; Saunois et al., 2016), regional CH₄ fluxes are difficult to detect, due to their comparatively diffuse nature – relative to anthropogenic point sources – and the scarcity of direct measurements of wetland CH₄ emissions. From a bottom-up perspective, challenges in wetland CH₄ modelling stem from order-of-magnitude
15 uncertainties on wetland CH₄ emissions factors and their spatio-temporal dependence on biogeochemical process controls. Nonetheless, for top-down CH₄ emission estimates, prior knowledge of wetland CH₄ emissions and their associated uncertainty is critical in the formulation of Bayesian atmospheric CH₄ inversions. Atmospheric inversions combine CH₄ measurements from surface, aircraft and satellites (Wecht et al., 2014b; Jacob et al., 2016) and the prior probability on the magnitude and
20 uncertainty characteristics of CH₄ emissions (Bousquet et al., 2011; Pison et al., 2013; Fraser et al., 2013; Turner et al., 2015): typically CH₄ inversions do not explicitly formulate wetland CH₄ emission uncertainty correlations: rather, prior wetland CH₄ uncertainty correlations are either absent or implicitly prescribed through space-time correlation lengths on CH₄ emissions. However, inter-model similarities reveal significant levels of emergent correlations in the timing, magnitude and spatial
25 variability of wetland CH₄ emissions. For example, the Wetland CH₄ Inter-comparison of Models Project (WETCHIMP) model ensemble (Melton et al., 2013) reveals varying levels of spatial and temporal agreement between models; these correlations stem from large-scale patterns in biogeochemical process controls (such as temperature, inundation and carbon cycling). Given the

relatively large WETCHIMP CH₄ emission uncertainties (model range is typically 150-300% of model mean over major wetland areas, and greater elsewhere), this prior ‘biogeochemical covariance’ can potentially amount to a critical constraint on atmospheric CH₄ inversions: such a covariance structure can be incorporated in an atmospheric inversion cost-function (Michalak et al., 2005) or as a means for
5 improving attribution of posterior CH₄ fluxes to wetland CH₄ emissions (Wecht et al., 2014a).

Here we propose a process-informed wetland CH₄ emission and uncertainty dataset for atmospheric chemistry and transport modelling (WetCHARTs) based on multiple terrestrial biosphere models, wetland extent scenarios and CH₄:C temperature dependencies. In contrast to a conventional
10 process-based model inter-comparison approach, our wetland CH₄ emission ensemble members are derived by exhaustively combining a range of temperature, carbon and wetland extent parameterizations. An advantage of our approach is that it provides a prior probability distribution of biogeochemical process control uncertainty. Top-down CH₄ emission estimates can then be used to quantify (a) the probability of individual ensemble members; and (b) the combined probability
15 distribution of carbon models, CH₄:C temperature dependencies and wetland extent scenarios.

We formulate a full (2009-2010) and extended (2001-2015) estimate of wetland CH₄ emission magnitude and its associated biogeochemical covariance structure, based on knowledge of the global wetland CH₄ source and the primary biogeochemical process controls. We validate and compare the
20 wetland CH₄ emissions ensemble against a suite of regional flux estimates; we use a global atmospheric chemical transport model (GEOS-Chem, Bey et al., 2001) to evaluate the CH₄ emissions ensemble mean relative to existing wetland CH₄ emission models (sections 2 and 3). Finally, we summarize the strengths and limitations of our wetland emissions ensemble and outline its potential applications in global atmospheric inversion frameworks (section 4).

2. Wetland CH₄ model ensemble

25

The wetland CH₄ emissions ensemble provides CH₄ fluxes and associated uncertainty estimates based on four wetland extent parameterizations, nine terrestrial biosphere models of heterotrophic respiration and three CH₄:C temperature parameterization. Global monthly 0.5°×0.5° emissions and

their associated uncertainty structure span 2009-2010 (full ensemble, henceforth FE); we also evaluate a subset of the model ensemble spanning 2001-2015 (extended ensemble, henceforth EE). We validate FE and EE emissions against a range of regional CH₄ emission estimates. Finally, we incorporate FE, EE and existing wetland emission inventories into GEOS-Chem and evaluate the atmospheric CH₄ simulations against 104 surface CH₄ measurement sites.

2.1 Wetland CH₄ emissions & uncertainty

We derive wetland CH₄ emissions F ($mg\ CH_4\ m^{-2}\ day^{-1}$) at time t and location x as:

$$F(t, x) = s A(t, x) R(t, x) q_{10}^{\frac{T(t, x)}{10}} \quad (1)$$

where $A(t, x)$ is the wetland extent fraction, $R(t, x)$ is the C heterotrophic respiration per unit area at time t , $q_{10}^{T(t, x)/10}$ is the temperature dependence of the ratio of C respired as CH₄ (where q_{10} is the relative CH₄:C respiration for a 10°C increase and $T(t, x)$ is the surface skin temperature) and s is a global scale factor. This empirical parameterization provides first order constraints on the role of carbon, water and temperature variability on the global spatial and temporal variability of wetland CH₄ emissions. Variants of the equation 1 parameterization have been used within a range of wetland CH₄ emission models (e.g., Hodson et al., 2011, Pickett-Heaps et al., 2011, Bloom et al., 2012; Melton et al., 2013 amongst others).

In our approach, wetland CH₄ emissions statistics within and across 0.5°×0.5° gridcells are derived based on an ensemble of wetland CH₄ emission simulations: the 324-member FE is based on 3 CH₄:C temperature dependencies, 9 heterotrophic respiration configurations, 4 wetland extent scenarios and 3 global scale factor configurations ($3 \times 9 \times 4 \times 3 = 324$); the 18-member EE ensemble is a subset of FE, based on data availability during 2001-2015 (see Table 1 for details).

The heterotrophic respiration configurations are derived from 8 terrestrial biosphere models used in the Multi-scale Synthesis and Terrestrial Model Intercomparison Project (MsTMIP BG1 simulations, see Huntzinger et al. 2013 and Wei et al. 2014 for model and experiment details) and the global

CARbon DATA-MOdel fraMework (CARDAMOM) terrestrial carbon analysis (Bloom et al., 2016). V1.0 outputs from the MsTMIP are available for the period 1900-2010 (Huntzinger et al., 2016); the CARDAMOM analysis was extended to span 2001-2015 based on the Bloom et al. (2016) methodology (see Appendix A for details). Since MsTMIP and CARDAMOM respiration estimates vary intrinsically as a function of temperature, q_{10} only accounts for the temperature dependence of the fraction of C respired as CH₄. We prescribe three CH₄:C temperature dependencies (Table 1) which are broadly equivalent to a ±50% range on the CH₄:CO₂ temperature dependence reported by Yvon-Durocher et al. (2014).

Here we use two spatial ($i = 1,2$) and two temporal ($j = 1,2$) wetland extent parameterizations approaches to represent the uncertainty associated with the role of hydrology on wetland CH₄ emissions. Each temporal and spatial wetland extent parameterization, $A_{i,j}(t,x)$ is derived as:

$$A_{i,j}(t,x) = w_i(x)h_{i,j}(t,x), \quad (2)$$

where $w_i(x)$ represents the wetland extent fraction, and $h_{i,j}(t,x)$ represents the temporal variability relative to $w_i(x)$. $w_1(x)$ is the sum of all GLOBCOVER wetland and freshwater land cover types (all flooded, water-logged, and inland water body land-cover types; Bontemps et al., 2011); $w_2(x)$ is the Global Wetland and Lakes Database (GLWD) maximum recorded wetland and freshwater body extent map by Lehner & Doll (2004).

For $h_{i,j}(t,x)$, we use (a) the Surface Water Microwave Product Series (SWAMPS) multi-satellite surface water product (Schroeder et al., 2015; $j = 1$), and (b) monthly ERA-interim precipitation ($j = 2$): for $i = 1$ ($i = 2$), $h_{i,j}(t,x)$ is normalized such that mean (maximum) $h_{i,j}(t,x)$ is equal to 1. In order avoid physically unrealistic outcomes, we derive $A_{i,j}(t,x)$ as $\min\{w_i(x) h_{i,j}(t,x), 1\}$, where the “min{ }” function represents the minimum between the two bracketed values.

We note that the two hydrological proxies provide contrasting advantages and disadvantages. Satellite-retrieved surface water extent provides an observation-based constraint on the spatial and temporal extent of wetlands and freshwater bodies. While our temporal scaling of static wetland and freshwater extent mitigates the role of spatial biases in satellite-retrieved inundation, vegetation cover

remains a major confounding variable in satellite-constrained wetland extent (Schroeder et al., 2015). Moreover, satellites cannot directly observe subsurface soil saturation, even though these soils amount to significant CH₄ fluxes to the atmosphere (Turetsky et al., 2014). On the other hand, precipitation does not provide a direct constraint on the wetland and freshwater extent; however, it provides an aggregate constraint on ecosystem hydrological variability and wall-to-wall coverage across the globe. We henceforth refer F as “wetland CH₄ emissions”; however, we recognize that lakes, rivers and reservoirs account for ~20% of the total wetland and freshwater body extend (Lehner and Döll, 2004). We discuss the implications of including non-wetland freshwater bodies in section 4.

For each of the 324 FE ensemble configurations ($c = 1 - 324$), and 18 EE ensemble configurations ($c = 1 - 18$), we derive s_c such that:

$$s_c = \frac{G}{\sum_t \sum_x F_c(t,x) a(x) \frac{\Delta t}{n}} \quad (3)$$

where $F_c(t,x)$ are the c th ensemble member emissions at grid-cell x and time t , $a(x)$ is the area of grid-cell x , Δt is the timestep (1 month), n is the number of years, and G is the global total CH₄ emitted from wetlands. We derive s_c such that FE and EE ensemble members amount to a mean global annual flux of $G = 124.5, 166$ or 207.5 Tg CH₄ yr⁻¹ during 2009-2010. The prescribed range of total wetland CH₄ emissions spans the Saunois et al. (2016) mean 2000-2009 top-down wetland CH₄ emission estimates (166 Tg CH₄ yr⁻¹; 125 – 204 Tg CH₄ yr⁻¹).

We attribute the uncertainty of the timing and magnitude of $F_*(t,x)$ (namely maximum CH₄ emission month, mean CH₄ emissions and CH₄ emission variability) to carbon decomposition, wetland extent and CH₄:C temperature dependence uncertainty. The derivation of the “dominant uncertainty” within each zonal band (i.e. the dominance of carbon, water or temperature as the dominant source of uncertainty) is fully described in Appendix C.

2.2 GEOS-Chem atmospheric CH₄ simulations

We evaluate the FE and EE wetland CH₄ emission means against the World Data Centre for Greenhouse Gases (WDCGG) CH₄ measurement sites by incorporating these into the 4°×5° resolution GEOS-Chem atmospheric chemical and transport model (version 10.01; acmg.seas.harvard.edu/geos). We benchmark the FE and EE runs against GEOS-Chem simulations with the GEOS-Chem wetland CH₄ emission inventory (Pickett-Heaps et al., 2011; [2009-2010 derivation described in Turner et al., 2015](#); henceforth GC) and the Bloom et al. (2012) satellite-constrained wetland emissions (henceforth BL), as these emission estimates have been used in a range of atmospheric chemical transport model simulations (Fraser et al., 2013; Turner et al., 2015; Wilson et al., 2016 amongst others). We perform each GEOS-Chem forward run for the period 2009-2010 with a four-year (2005-2009) spin-up period. The non-wetland CH₄ sources in GEOS-Chem consist of biofuel, fossil fuel, livestock, waste, Rice (EDGAR v4.2; European [Commission](#), 2011), fires (Global Fire Emissions Database version 4; van der Werf et al., 2010), soil C sinks and termites (Fung et al., 1991). The non-wetland CH₄ fluxes are the same in each run, with the exception of rice source in run BL (as global wetland and rice emissions are treated as one source by Bloom et al., 2012). While model CH₄ surface concentrations are strongly influenced by wetland CH₄ magnitude, timing and distribution (Bloom et al., 2012, Meng et al., 2015), comparisons between GEOS-Chem outputs and surface CH₄ measurement may also be affected by errors in non-wetland CH₄ emissions and in transport. However, Wecht et al. (2012) and Turner et al. (2015) show that the GEOS-Chem emissions and transport provide an unbiased representation of the observed latitudinal background. The global inversion of Turner et al. (2015) using GEOS-Chem emissions as prior further shows no large errors in non-wetland emissions that would confound the analysis presented here.

For each of the four runs (FE, EE, GC and BL), we use the Wecht et al. (2014a) 1st Jan 2005 initial conditions for atmospheric CH₄ concentrations in GEOS-Chem. For each simulation, we performed a four-year spin-up period (2005-2009) using 2009 emissions to reduce the potential inconsistency between initial conditions and the global distribution of wetland CH₄ emissions; this spin-up ensures that the relative variations in Jan 1st 2009 CH₄ concentrations for each run are broadly consistent with each emission scenario. We save GEOS-Chem atmospheric CH₄ concentrations every 3

hours. We compare mean monthly GEOS-Chem output against all WDCGG sites (104 sites with monthly 2009-2010 data in total). For each site, the nearest 4°×5° GEOS-Chem grid-cell is used for comparison. We note that the GEOS-Chem analysis outlined here is not a direct validation of FE and EE; rather, it provides supporting evidence on the plausibility of FE and EE emissions relative to existing wetland CH₄ emissions datasets.

3. Results, Comparison and Validation

Mean full ensemble (FE) global wetland emissions are largely accounted for by three high-latitude regions, three tropical regions, and sub-tropical southeast Asia (Figure 1). North America, Scandinavia and Siberia median (5th – 95th percentiles) CH₄ fluxes amount to 10% (3 – 30%), 2% (1 – 6%) and 2% (1 – 6%) of global emissions; Amazon wetland emissions amount (29%; 20 – 37%) account for the largest tropical emission source, followed by the Indonesian archipelago (13%; 7 – 23%), and central Africa (12%; 7 – 23%); subtropical southeast Asia emissions account for 5% (1 – 10%). High-latitude (>50°N) and tropical emissions amount to 12% (5 – 31%) and 66% (43 – 83%) of global wetland CH₄ emissions, respectively. Gridded FE uncertainties (shown as the 5th – 95th percentile ranges; Figure 1e) are largely comparable in magnitude to FE emissions (Figure 1a). Relative FE uncertainties (shown as the ratio of 90% confidence range to mean emissions in Figure 1f) are lowest in high-emission areas, notably wetland regions in the Amazon and Congo basins, North America and western Eurasia.

Mean FE and extended ensemble (EE) CH₄ emission patterns exhibit close agreement across all tropical continents and the high northern latitude wetland regions (Figures 1a and 1b). The comparison between zonal mean emissions (Figure 2) reveals differences of less than 1 Tg/yr/°lat between FE and EE. On Continental scale FE and EE emission patterns are in broad agreement with the Pickett-Heaps et al., (2011) wetland CH₄ emissions (GC; Figure 1c) and the Bloom et al. (2012) emissions (BL; Figure 1d). High-latitude FE and EE emissions peak roughly between 45 - 60°N (Figure 2), in agreement with GC and BL emission peaks (~60°N and ~50°N respectively), and tropical emissions for all four emission datasets peak within 0° – 5°S. The FE zonal mean is comparable to the BL in the near-equatorial tropics

and significantly lower (with respect to the FE model ensemble 90% confidence range) everywhere else; the FE zonal mean is comparable to GC in high-latitude and temperate regions, but significantly lower than GC in the tropics and southern hemisphere.

5 All CH₄ emission models show similar patterns in the temporal distribution of CH₄ emissions in high-latitude and temperate regions (with CH₄ emissions peaking between July and September, Figure 3). We note that the larger CH₄ fluxes in the BL emissions over Asia and Oceania are due to rice paddy CH₄ emissions. All emission models exhibit high-latitude (>50°N) maximum CH₄ emissions between June and August. In tropical South America (0° – 20°S), FE and EE emissions peak between February and April, which is comparable to BL (February – March); and overall earlier than GC (5°S – 20°S emission peak in September). There is a considerable disagreement between northern tropical Africa emission variability amongst all models, with 0° – 15°N emissions peaking in February (GC), April – October (FE, EE), and September- November (BL). Subtropical Asia FE and EE emissions (20°N – 30°N) peak in June-July, earlier than BL emissions (August-September) and comparable to GC
10
15 emissions (June).

We compare mean FE and EE (2009-2010) wetland emissions against a range of independent wetland CH₄ regional emission estimates (Figure 4). Emissions from Siberian wetlands (Glagolev et al., 2011) Hudson bay lowlands (Pickett-Heaps et al., 2011), and Amazon river basin (Melack et al., 2004) are
20 within 25th – 75th percentile estimates of FE and EE wetland CH₄ emissions; Alaska wetland emissions (Chang et al., 2014; May-September) are higher (2.1 Tg CH₄ yr⁻¹) but within the 5th – 95th percentile range of FE and EE wetland CH₄ emission estimates. With the exception of Amazon river basin estimates, the FE and EE emission uncertainty estimates are larger than the Melton et al. (2013) wetland CH₄ emission model (WETCHIMP 1993-2004) range. BL (2009-2010) and GC (2009-2010) estimates
25 are also within all regional 5th – 95th percentile ranges. We note the temporal mismatch between modelled and regional wetland CH₄ emission estimates in Figure 4: however, based on a range of process model approaches (e.g. Bloom et al., 2010; Melton et al., 2013), we expect inter-annual variation in wetland CH₄ emissions to be substantially smaller than the FE and EE estimate uncertainty.

5 For example, the maximum-to-minimum ratios of WETCHIMP 1993-2004 annual emissions are ≤ 5.1 across the three extratropical regions and ≤ 1.4 in the Amazon river basin; in contrast, FE and EE uncertainty intervals span factors of 5.8 – 156.3 in the extratropics and 2.3 – 3.9 in the Amazon river basin.

10 FE and EE ensemble models exhibit a median of 6.7% and 7.2% increase in global emissions between 2009 and 2010 (Figure 5). BL and GC 2009-to-2010 changes (+1.8% and +3.2%) are within the FE uncertainty range (-2.6% to +13.4%). Uncertainties in the WETCHIMP inter-annual variations (IAV, relative to the 2001-2004 model means) are larger than EE IAV uncertainty throughout 2001-2015 (relative to 2009) and smaller than the 2009-to-2010 FE change uncertainty. For the 2003-2013 period, BL IAV is generally lower or within the range of EE IAV. In comparison to regional top-down constraints, we find that regional EE IAV is comparable to the Miller et al., (2016) 2012-2014 annual Alaska wetland emission variability (coefficient of variation: observed = 4.9%; EE = 4.2 – 6.9%), and within the Wilson et al. (2016) constraints on 2010-to-2011 change in annual Amazon wetland
15 emissions (coefficient of variation: observed < 20%; EE = 0.5 – 2.9%).

20 On a zonal basis, the “dominant uncertainty” – i.e. the dominant source of uncertainty within each band – in mean CH₄ emissions and the timing of maximum CH₄ emissions is almost completely dominated by carbon decomposition and wetland extent uncertainties (Figure 6). Seasonal variability of CH₄ emissions is also largely dominated by carbon and extent uncertainties, although the temperature CH₄:C dependence is the dominant source of uncertainty in temperate latitudes. At latitudes > 20°N, wetland extent is the dominant source of uncertainty in mean CH₄ emissions, while temperature CH₄:C dependence accounts for $\leq 5\%$ of the dominant uncertainty attribution. Across tropical latitudes (23°S – 23N) and northern high latitudes (>45°N), carbon decomposition is the dominant source of uncertainty
25 in the timing of wetland CH₄ emissions.

We summarizing the FE global error covariance structure as an error correlation matrix between mean monthly 2009-2010 emissions across boreal & arctic (>55°N) temperate (23°N – 55°N), tropical (23°S

– 23°N) and southern hemisphere (<23°S) latitudes (Figure 7); the error correlation matrix quantitatively summarizes similarities in the spatial and temporal patterns between ensemble members, relative to the ensemble mean (see appendix B for description and interpretation). The FE error correlation matrix highlights positively correlated ensemble member CH₄ emissions within each region, with larger correlations (generally Pearson's $r > 0.8$) between emissions separated by 1-2 months. Tropical emissions exhibit the largest overall temporal correlations ($r > 0.5$). Tropical emissions exhibit negative correlations against temperate emissions ($r < -0.3$) and boreal & arctic CH₄ emissions ($r < -0.1$).

10 Mean 2009-2010 observed and GEOS-Chem forward model run CH₄ concentrations (with FE, EE, BL and GC wetland emissions) are broadly consistent on a latitudinal basis. The observed and modelled zonal atmospheric CH₄ concentration anomaly (relative to mean global 2009-2010 CH₄ concentrations) is shown in Figure 8 (zonal profile root-mean-square errors – RMSE – are 6.5 ppb, 6.6 ppb, 8.4 ppb, 9.2 ppb for FE, EE, BL and GC relative to the observed CH₄ anomaly zonal profile). Within the primary
15 wetland CH₄ emission latitudes (10°S – 80°N; Figure 2), all mean CH₄ model estimates are within the mean standard deviation of observed CH₄, except for GC at >60°N and all models at 80°N.

The median site-level correlation (Pearson's r) between observed and model de-trended CH₄ concentrations (Figure 9) is highest for BL (0.75), followed by EE (0.74), FE (0.73) and GC (0.72). The
20 median RMSE between observed and model de-trended CH₄ concentrations for FE (11.78 ppb) and EE (11.89ppb) are lower than BL (12.42 ppb) and GC (median = 13.27 ppb). FE and EE improvements (relative to GC and BL Pearson's r and RMSE) are primarily in northern hemisphere high-latitudes latitudes (>50°N; Figure 9). In southern hemisphere extra-tropical latitudes (<23°S) FE and EE exhibit a comparable performance relative GC, while BL outperforms both FE and EE.

25

4. Discussion

4.1 Model limitations

Densely vegetated wetland areas are likely to amount to a large component of the global wetland CH₄ sources; high-carbon density (and high temperatures in the case of tropical wetlands) result in high CH₄ emissions under inundated conditions. However, satellite-derived observations of surface water area (Schroeder et al., 2015) are ill-equipped to observe densely vegetated wetland areas, as the passive microwave sensors become increasingly sensitive to vegetation moisture within high biomass ecosystems (Sippel et al., 1994). For example, [FE](#) estimates of Amazon river basin wetland CH₄ emissions [amount to](#) 16% - 29% (5th – 95th percentiles) of the global wetland emissions source; high biomass density in this region (Saatchi et al., 2011) may be a significant source of inundation area bias.

10 Therefore, while we incorporate prior information on the mean and maximum wetland extent to scale the satellite-derived inundation fraction, we anticipate that errors in seasonal and inter-annual inundation variability are likely to be larger within densely vegetated wetland areas. We are optimistic that current and upcoming missions such as SMAP and BIOMASS (Entekhabi et al., 2010; Le Toan et al., 2011) combined with data integration approaches (Schroeder et al., 2015; Fluet-Chouinard et al., 2015) can potentially provide additional constraints required to extend current inundation datasets and to improve current surface inundation detection capabilities.

The MsTMIP model ensemble provides a first-order estimate of the magnitude and variability of C decomposition within each 0.5°×0.5° grid-cell. Here we highlight 4 potentially major sources of error:

20 (a) differences in aerobic:anaerobic turnover rates of major (labile and recalcitrant) C pools (b) systematic differences in wetland and non-inundated area carbon uptake within each 0.5°×0.5° grid-cell, (c) systematic differences in dead organic matter C stocks and accumulation between wetland and non-inundated areas, and (d) lateral flows of C into (or out of) wetland areas. Top-down estimates of seasonal and inter-annual terrestrial CO₂ fluxes (e.g. Liu et al., 2014) could be used to independently assess the validity of heterotrophic respiration from the MsTMIP models and CARDAMOM. In turn, top-down CH₄ and CO₂ flux retrievals, and range of in-situ and regional-scale CH₄ flux estimates (Schriel-Uijl et al., 2011; Chang et al., 2014; Budishchev et al., 2014; amongst others) can be combined to assess whether our empirical parameterization is able [to](#) capture regional, seasonal and inter-annual

wetland CH₄ emission variability and their link to the broader terrestrial carbon cycle. Finally, in succession to eddy covariance tower site analyses of CO₂ respiration dependence on temperature (Mahecha et al., 2010), we anticipate that CH₄ eddy covariance measurements will provide critical site-level constraints on the temperature dependence of wetland CH₄ emissions.

5

Rice paddies likely amount to <20% of wetland CH₄ emissions, and the majority of rice paddy areas are implicitly excluded from our analysis: GLOBCOVER distinguishes between natural and irrigated water bodies, and GLWD explicitly excludes rice paddy extents in China (which alone accounts for a large portion of global rice paddy CH₄ emissions). However, satellite-based inundation fraction retrievals are
10 unable to distinguish the temporal variability of co-located agriculture and natural wetland inundation extent; moreover 0.5°×0.5° carbon cycle model resolution may be insufficient to resolve spatial differences in wetland and agricultural C cycling. Inadvertent inclusion of co-located rice CH₄ emissions is therefore a potential source of bias in our approach. We note that the distinction between wetland and rice CH₄ emissions has yet to be consistently addressed in global wetland CH₄ emission
15 quantification efforts (see Bloom et al., 2010; Hodson et al., 2011; Melton et al., 2013, and references therein).

CH₄ production in non-wetland freshwater bodies, such as very small ponds (Holgerson and Raymond 2016), lakes (Wik et al., 2016) and rivers (Bastviken et al., 2011) is potentially a significant – albeit
20 highly uncertain – term in the global CH₄ budget (Kirschke et al., 2013; Bridgham et al., 2013). Our approach implicitly accounts for non-wetland freshwater body emissions, since their extent is incorporated in grid-cell scaling factors (see Eq. 2). We recognise the challenge in explicitly distinguishing between wetlands and non-wetland freshwater body CH₄ emissions, as well as the associated physical and biogeochemical process controls: the quantitative distinction of CH₄ emissions from of wetland and non-wetland freshwater extent remains challenging from the current spatial resolution (~25km) of surface inundation retrievals (Prigent et al., 2007; Schroeder et al., 2015).
25 Equally, the current global carbon cycle model resolutions (≥0.5°) is insufficient to resolve spatial variations of heterotrophic processes across ≤1km wetland and freshwater land cover definitions

(Lehner and Döll, 2004). Contingent on future resolution enhancements in surface inundation and carbon cycle models, we recommend further investigation on the adequate distinction and estimation of non-wetland freshwater CH₄ emissions for atmospheric CH₄ chemical transport modelling applications.

5 | By constraining global emission estimates to the Saunois et al. (2016) model range, our approach does not challenge the global annual CH₄ source and uncertainty; rather, it places constraints on spatial and temporal wetland CH₄ source variability. Since the global uncertainty (166 Tg CH₄ yr⁻¹; range = ±25%) is substantially smaller than regional uncertainties (spanning a factor of 2 – 156; see Figure 4), new or improved constraints on the global wetland CH₄ source are unlikely to significantly influence our regional CH₄ flux confidence range estimates. We therefore anticipate that wetland CH₄ in-situ measurements and associated up-scaling efforts (e.g. Olefeldt et al., 2013; Turetsky et al., 2014; Sjörgesten et al., 2014; amongst others) will undoubtedly become critical for reducing emission and process uncertainty in future wetland emission model ensembles.

15 | 4.2 Applications

Based on comparisons against measured CH₄ concentrations and a range of regional and global CH₄ emission estimates (Figures 2-4, 7-8), we have shown that the FE and EE wetland CH₄ emission ensembles robustly represent the global magnitude and uncertainty of wetland CH₄ emissions. The ensemble configurations of inundation extent, carbon decomposition and temperature dependence have together provided a characterization of the dominant source of uncertainty in global wetland CH₄ estimates (Figure 6). The approach outlined here provides a framework for producing prior emission estimates and associated uncertainty. The error covariance structure – along with the CH₄ observing system capabilities (Wecht et al., 2014a) – can be used to devise an optimal strategy for spatially and/or temporally aggregating CH₄ fluxes in an atmospheric inversion framework. Retrieved CH₄ flux from assimilating atmospheric CH₄ observations in an inverse modelling framework (e.g. Fraser et al., 2013) could in turn provide a quantitative constraint on the wetland ensemble: the FE and EE model members can be treated as an ensemble of probable biogeochemical process hypotheses that can be weighted against atmospheric constraints. In contrast to conventional wetland CH₄ emission estimates (Riley et

al., 2011; Pickett-Heaps et al., 2011) and model inter-comparisons (Melton et al., 2013), top-down CH₄ flux estimates can constrain the joint probability distribution of FE carbon models, wetland extent parameterizations, and temperature dependencies. We note that due to the smaller ensemble size and the use of only one carbon model (see Table 1), the 2001-2015 EE emission variability should be interpreted with caution, and – where possible – evaluated against the FE ensemble during the 2009-2010 period.

We anticipate extensions of the FE beyond the 2009-2010 time period, contingent on the extensions of the MsTMIP and SWAMPS dataset beyond 2010 and 2012 respectively. In light of continued satellite CH₄ retrievals from GOSAT (Parker et al., 2011; Butz et al., 2011) and upcoming satellite CH₄ measurement from TROPOMI on-board ESA Sentinel 5 precursor (Veefkind et al., 2012), we anticipate that the FE and EE datasets will provide key process-based prior knowledge in future atmospheric CH₄ inversions.

Data availability

The full ensemble (FE), extended ensemble (EE) datasets (Bloom et al., 2017) are available on the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC; <http://dx.doi.org/10.3334/ORNLDAAC/1502>). MsTMIP monthly 0.5°×0.5° datasets (Huntzinger et al., 2016) were obtained from nacp.ornl.gov/MsTMIP.shtml. ERA-interim datasets were obtained from apps.ecmwf.int/datasets/data/interim-full-mnth. CARDAMOM 2001-2010 heterotrophic respiration outputs are available at datashare.is.ed.ac.uk/handle/10283/875; the complete 2001-2015 heterotrophic extensions outputs are included in the supplementary material. Inundation datasets were obtained from wetlands.jpl.nasa.gov. The GLWD dataset was obtained from gcmd.gsfc.nasa.gov. The GLOBCOVER dataset was obtained from due.esrin.esa.int. The WDCGG data was obtained from ds.data.jma.go.jp/gmd/wdogg. The Surface Water Microwave Product Series inundation dataset (described by Schroeder et al., 2015) was obtained from <http://wetlands.jpl.nasa.gov> (accessed on 5 June 2014); European Centre for Medium-Range Weather Forecasts reanalysis (ECMWF ERA-Interim)

[synoptic monthly means were downloaded from http://apps.ecmwf.int](http://apps.ecmwf.int). The code used to generate the FE and EE datasets is included in the supplementary material.

Appendix A: CARDAMOM extension

5

CARDAMOM heterotrophic respiration was derived from the Bloom et al., (2016) global terrestrial C cycle $1^\circ \times 1^\circ$ analysis. CARDAMOM retrieved C state and process variables for the period 2001-2010 were used to run the ecosystem carbon balance model DALEC2 (Bloom & Williams 2015) to span 2001-2015. The 2011-2015 ERA-interim meteorological drivers and MODIS burned area were obtained
10 as described by Bloom et al., (2016). The CARDAMOM output consists of 4000 heterotrophic respiration realisations at each monthly time-step: for each time-step, we use the median CARDAMOM heterotrophic respiration output. We downscale the data to a $0.5^\circ \times 0.5^\circ$ resolution using a nearest neighbour interpolation.

15 Appendix B: Error correlation structure

We derive the model ensembles' space-time $n \times n$ error correlation matrix \mathbf{M} as follows:

$$M_{ij} = \text{cor}(A_{i,*} | A_{j,*}) \quad (\text{A1})$$

20

where n corresponds to the number of space and time wetland CH_4 emission aggregations, and i, j span 1-to- n . $A_{(i,m)}$ and $A_{(j,m)}$ correspond to the total CH_4 flux for model m within the i th and j th space-time aggregations (i.e. total wetland CH_4 emissions within a given time & area); $A_{i,*}$ and $A_{j,*}$ are $1 \times N$ vectors, where N is the number of models within the ensemble. The “cor()” operator denotes the
25 Pearson's correlation coefficient between the two bracketed vectors. For Figure 7, we aggregated model wetland CH_4 emissions for each month across four zonal bands: Boreal & Arctic ($>55^\circ\text{N}$) Temperate ($23^\circ\text{N} - 55^\circ\text{N}$), Tropical ($23^\circ\text{S} - 23^\circ\text{N}$) and Southern Hemisphere ($<23^\circ\text{S}$). **Interpretation:** a perfect correlation between the i th and j th indices ($M_{ij} = 1$) indicates that models are consistently over- or under-

predicting CH₄ emissions at times-and-locations i and j relative to the ensemble mean; a perfect anti-correlation ($M_{ij} = -1$) indicates that models consistently over-predicting CH₄ emissions at time-and-location i consistently under-predict CH₄ emissions at time-and-location j (relative to the ensemble mean) and vice versa.

5

Appendix C: **Dominant** process uncertainty

We quantify the **dominant** process uncertainty of wetland CH₄ emission state variables ($s = 1-3$; 1. maximum emission month, 2. mean CH₄ emissions and 3. seasonal variability (standard deviation)) to wetland emission controls ($e = 1-3$; 1. model carbon decomposition, 2. CH₄:C temperature dependence and 3. wetland extent parameterization) at location x as follows:

10

$$R_{x,s,e} = \sum_{c=1}^N \frac{\max(\mathbf{M}_{x,s,m_c}) - \min(\mathbf{M}_{x,s,m_c})}{N} \quad (\text{A2})$$

15 where $R_{x,s,e}$ is the mean range of state variable s across the ensemble given a fixed emission control e ; $\mathbf{M}_{x,s,*}$ is a vector of all ensemble member state variables s at location x ; m_c denotes the indices of ensemble subset driven by c th emission control e ; N are the number of configurations for each e (the ensemble configuration details are show in Table 1). For example, $R_{100,3,1}$ is the mean range of seasonal CH₄ variability ($s = 3$) for a fixed carbon model configuration ($e = 1$) at the 100th gridcell ($x=100$). We
 20 attribute the zonal **dominant** uncertainty of state variable s to emission control e as:

$$P_{z,s,e} = \frac{\sum_{x_z} r_{x_z,s,e} F_{x_z}}{\sum_{x_z} F_{x_z}} \times 100\% \quad (\text{A3})$$

where x_z are the pixels x within 5° zonal band z , F_{x_z} is the mean 2009-2010 area-integrated CH₄ flux
 25 (Eq. 1 in main text). $r_{x_z,s,e} = 1$ if $R_{x_z,s,e} = \min(\mathbf{R}_{x_z,s,*})$ otherwise $r_{x_z,s,e} = 0$; the “min()” function denotes the minimum element of the bracketed vector; i.e. e is the largest source of uncertainty when

the mean range in state variable s is smallest for a fixed e . $P_{z,s,e}$ denotes the percentage of zonal band z where emission control e is the greatest source of uncertainty for each s .

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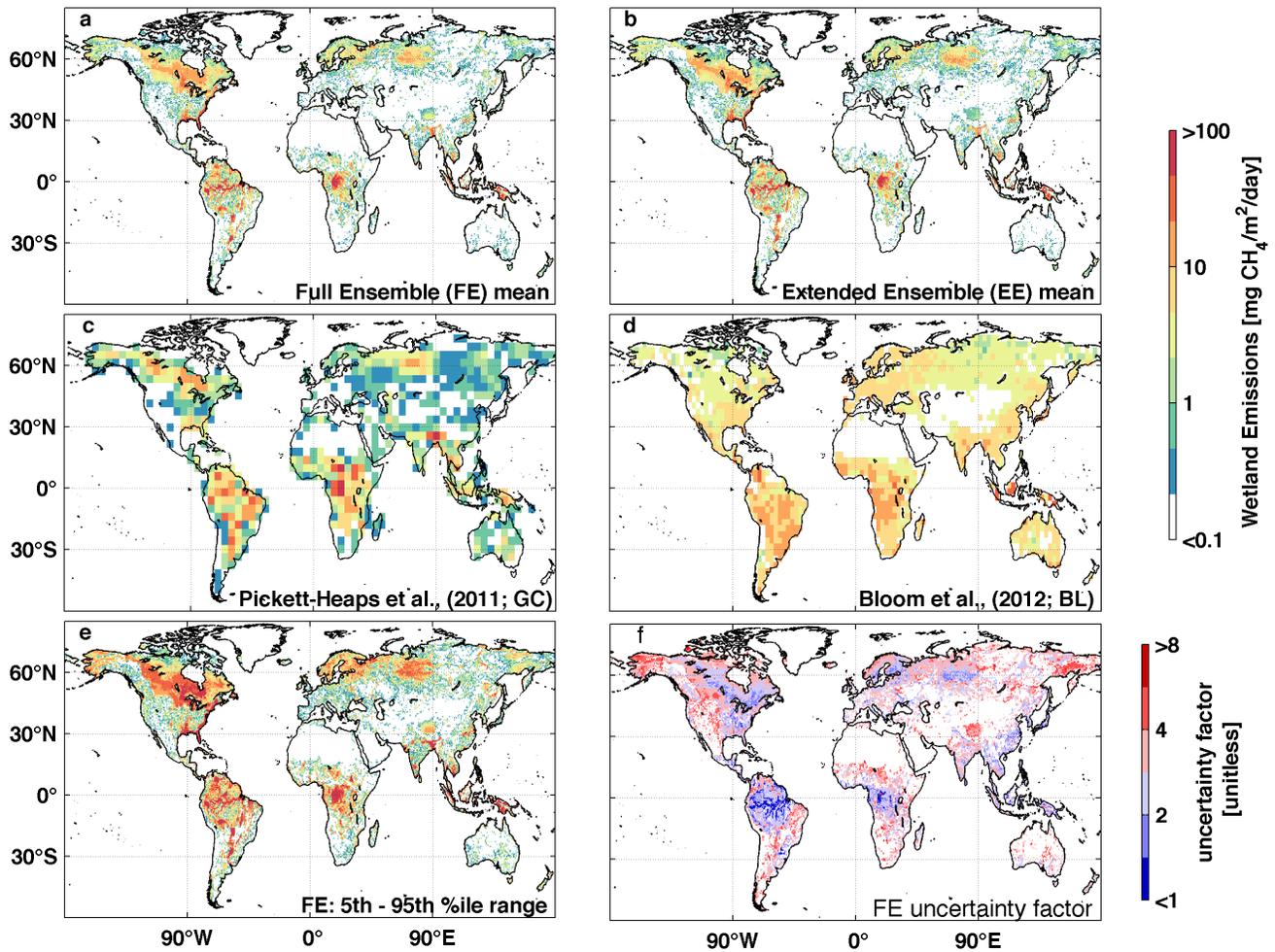


Figure 1. Top row: 2009-2010 full model ensemble (FE, left) and extended model ensemble (EE, right) mean wetland CH₄ emission. Middle row: 2009-2010 emissions from the GEOS-Chem wetland CH₄ emissions inventory (GC, left) model and satellite-constrained estimates by Bloom et al., (2012) (BL, right). Bottom row: Mean 2009-2010 FE 5th – 95th percentile range (left) and uncertainty factor (5th – 95th percentile range normalized by mean 2009-2010 emissions, right).

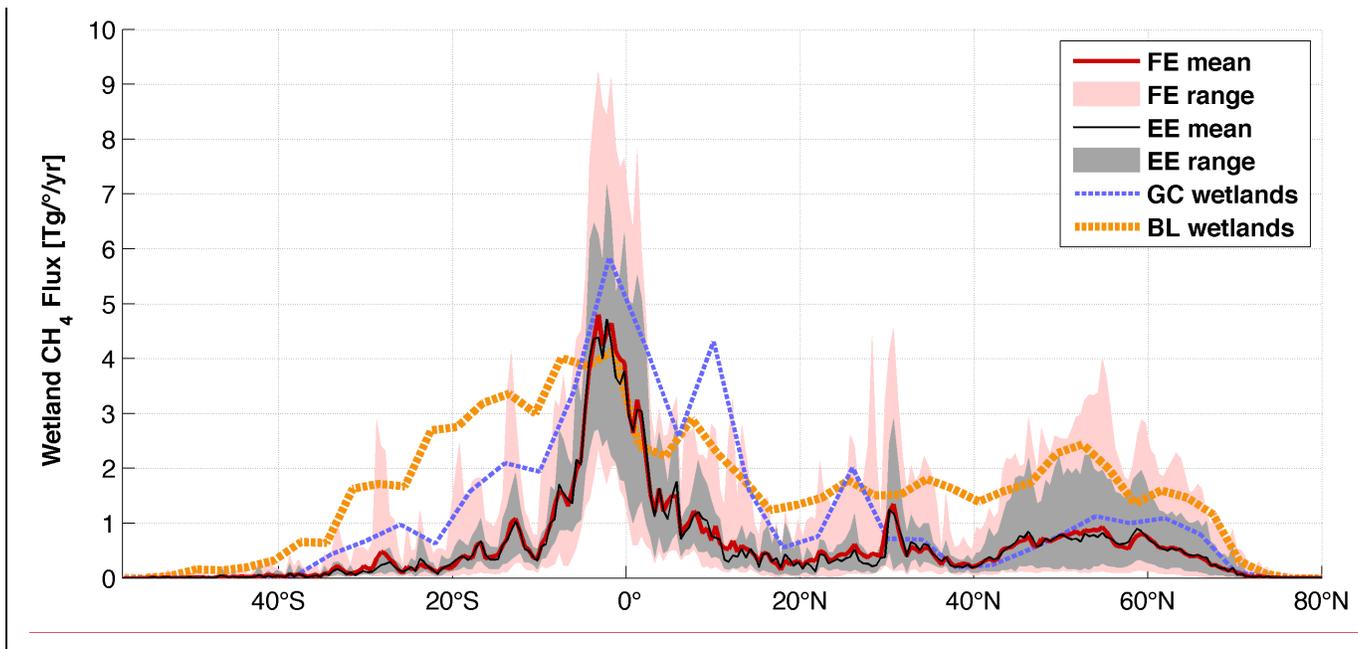
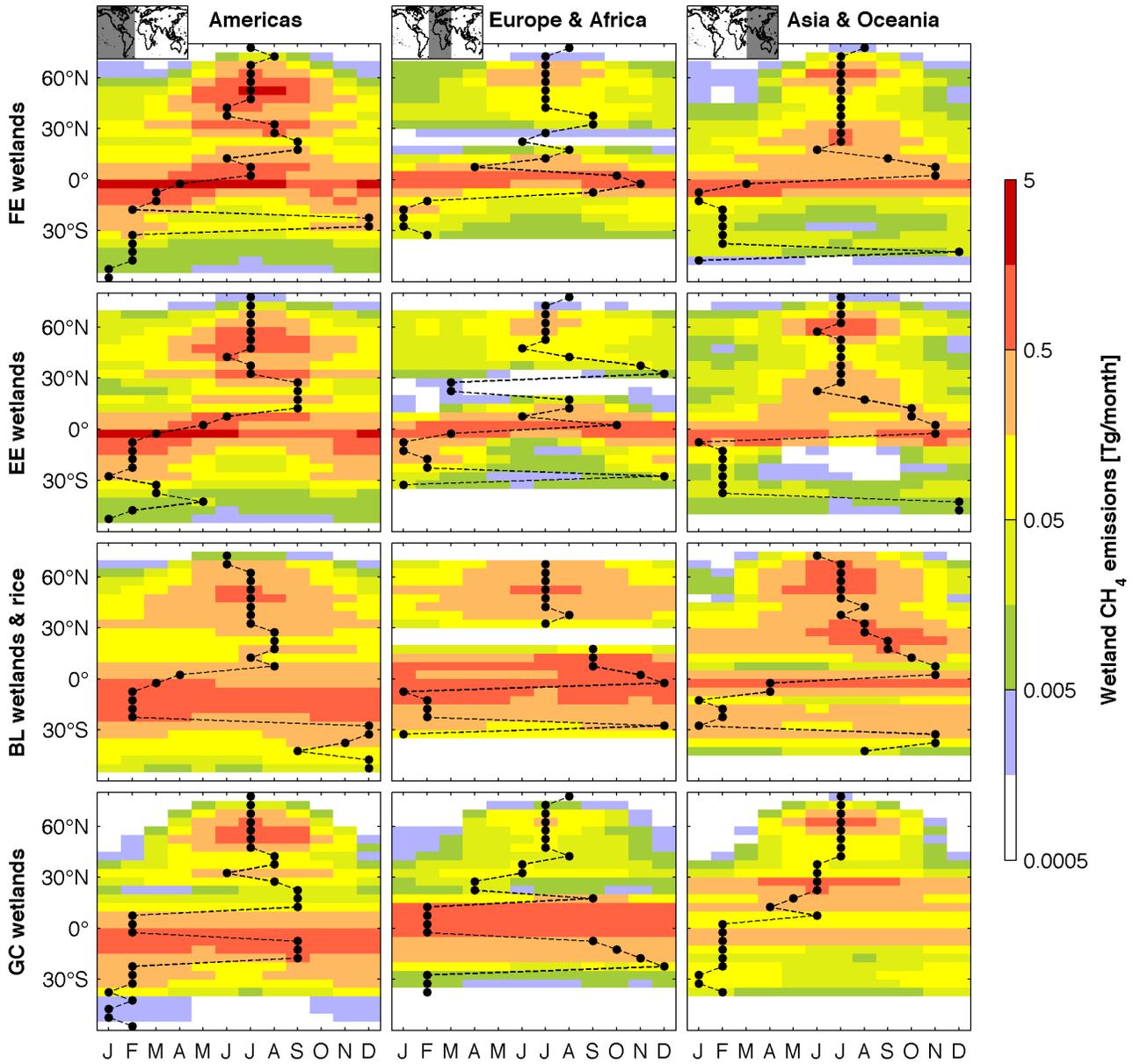


Figure 2. Top: Zonal profile of full ensemble (FE, red) extended ensemble (EE, black dashed line) and mean wetland CH₄ emissions from 108 ensemble members (grey). **Bottom:** mean FE (red), mean EE (black dashed line) and 90% FE confidence range (pink), GEOS-Chem wetland emission inventory (GC) and the Bloom et al., (2012) emissions (BL).



5 **Figure 3.** Seasonally averaged 2009-2010 wetland CH₄ emissions for this study (full ensemble: FE; extended ensemble: EE) Bloom et al., (2012) wetland emissions (BL) and GEOS-Chem wetland emissions inventory (GC) across North & South America (left column; 180°W – 35°W); Europe & Africa (center column; 35°W – 55°E) and Asia & Oceania (right column; 55°E – 180°E); emission for

each region are reported as total monthly fluxes across 5° latitude bins. The black dotted line denotes the maximum emissions month within each 5° latitude bin.

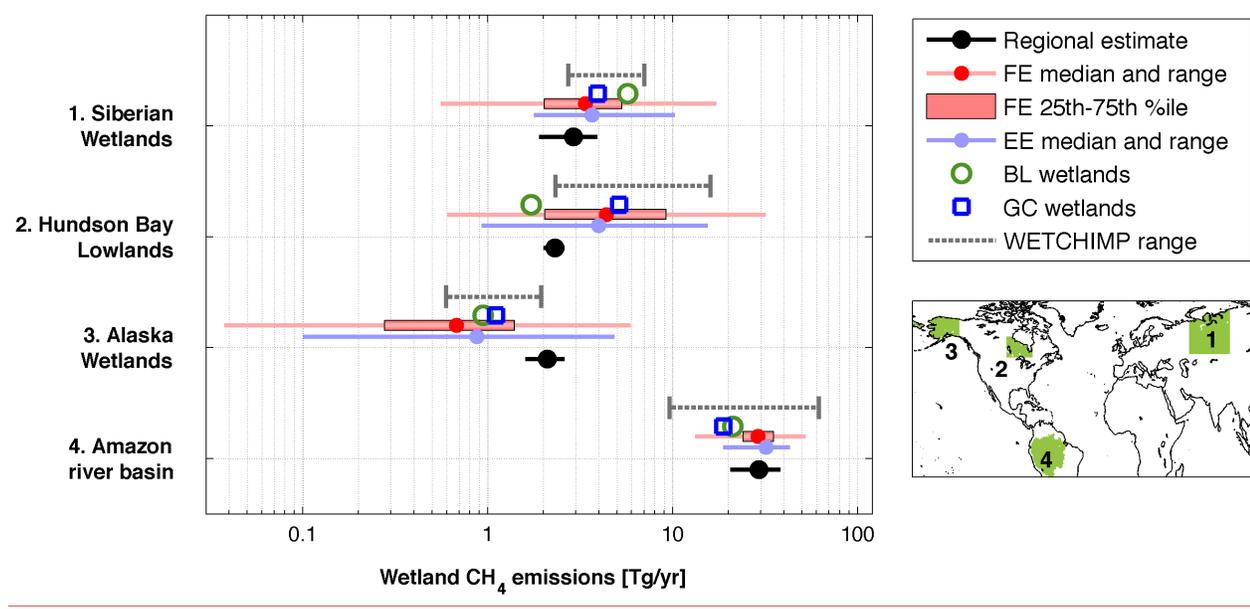


Figure 4. Comparison between mean annual regional wetland CH₄ emission estimates (1. Glagolev et al., 2011; 2. Picket Heaps et al., 2011; 3. Chang et al., 2014; 4. Melack et al., 2004) and global wetland emission datasets by Bloom et al., 2012 emissions (BL), the GEOS-Chem wetland CH₄ emission inventory (GC); this study (full ensemble: FE; extended ensemble: EE), and the range of WETCHIMP models (Melton et al., 2013). Wetland emissions (horizontal axis) correspond to mean annual totals within the regions shown in the inset map.

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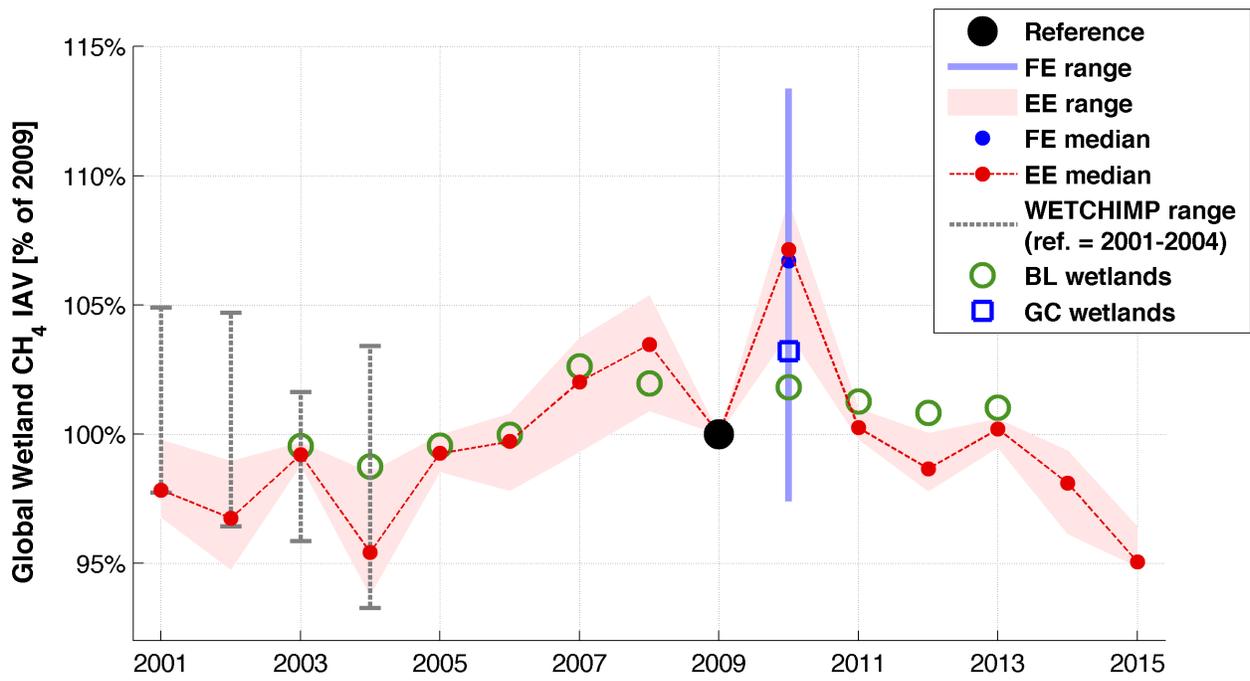
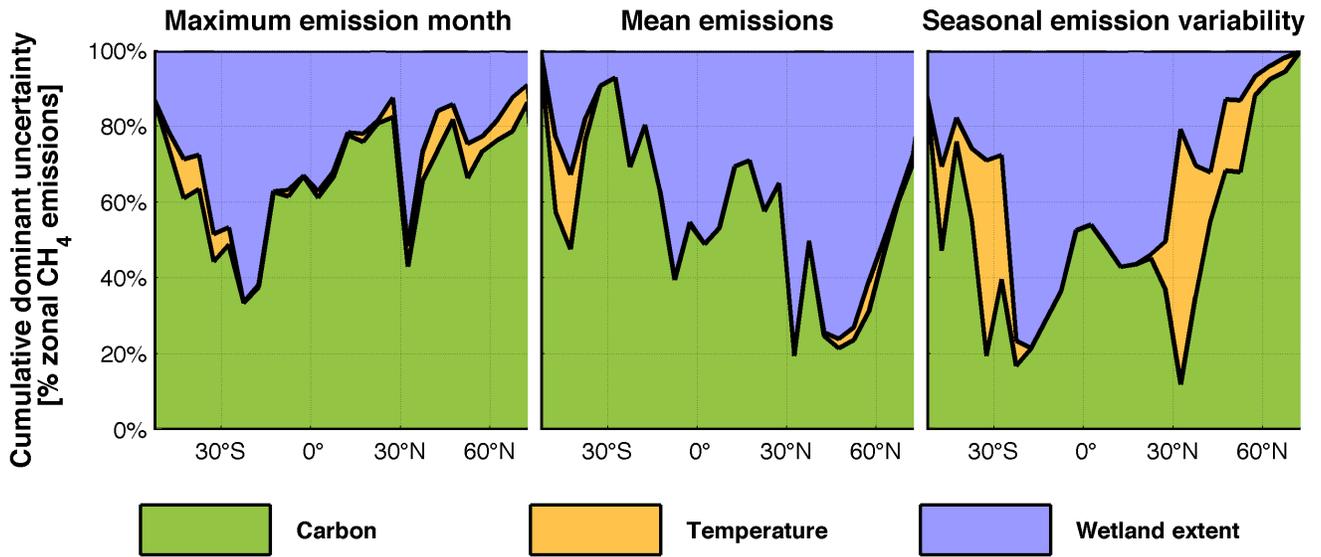


Figure 5. Global wetland CH₄ emission inter-annual variability range of the FE (2009-2010) and EE (2001-2015) emission models, normalized relative to 2009 emissions; the WETCHIMP (Melton et al., 2013) model ensemble inter-annual variability is normalized relative to 2001-2004 mean emissions.

5



5 **Figure 6** Dominant uncertainty attribution of maximum CH₄ emissions month (left), magnitude (center) and seasonal variability (right), to carbon decomposition, temperature CH₄:C dependence (q_{10}) and wetland extent parameterization, within 5° latitude bins. The derivation of dominant uncertainties is described in Appendix C.

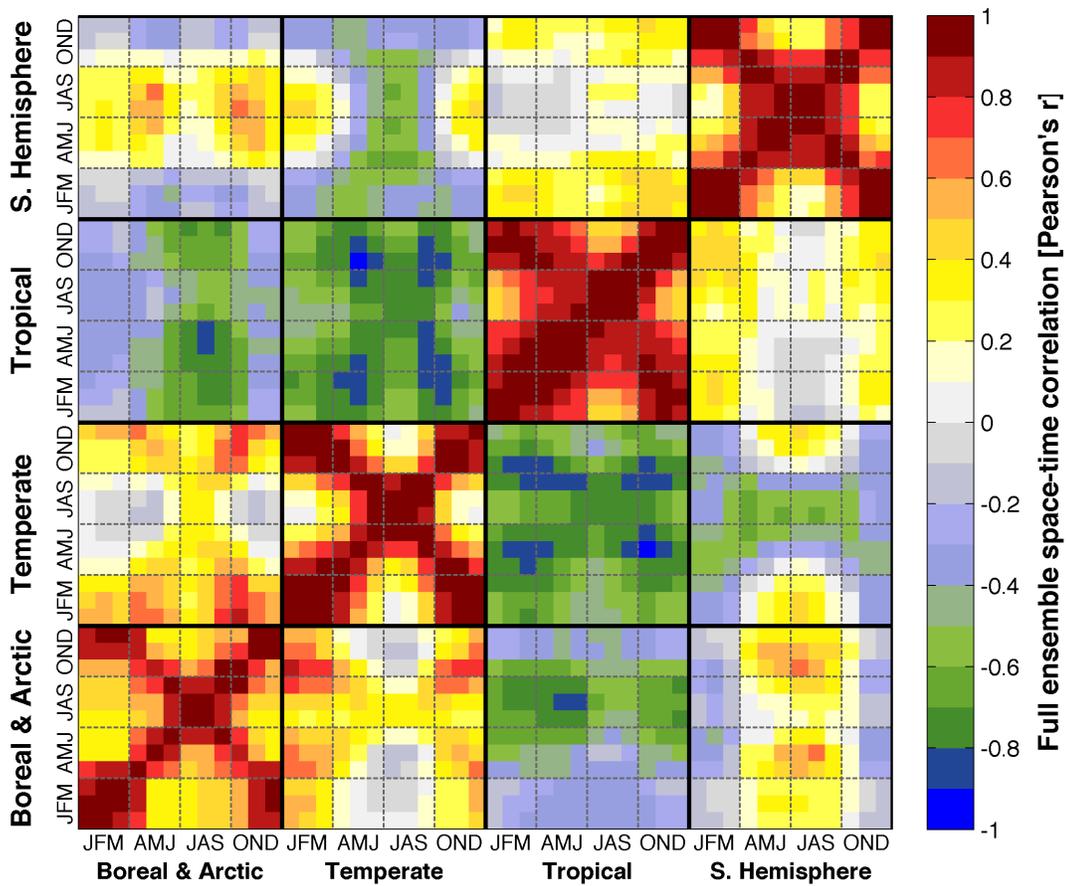


Figure 7. Full ensemble (FE) spatial and temporal error covariance, summarized as monthly error correlation across boreal & arctic ($>55^{\circ}\text{N}$) temperate ($23^{\circ}\text{N} - 55^{\circ}\text{N}$), tropical ($23^{\circ}\text{S} - 23^{\circ}\text{N}$) and southern hemisphere ($<23^{\circ}\text{S}$) latitudes. A correlation between two location-and-time indices indicates the degree to which models consistently over- or under-predict wetland CH_4 emissions relative to the ensemble mean. The non-zero off-diagonal correlation patterns emerge as a function of varying biogeochemical commonalities across ensemble members, such as wetland CH_4 dependencies on temperature, carbon availability and wetland extent. Negative correlations between tropical and northern hemisphere extratropical (i.e. temperate, boreal and arctic) wetlands emerge as a function of a global constraint on wetland CH_4 emissions ($166 \text{ Tg CH}_4 \text{ yr}^{-1} \pm 25\%$).

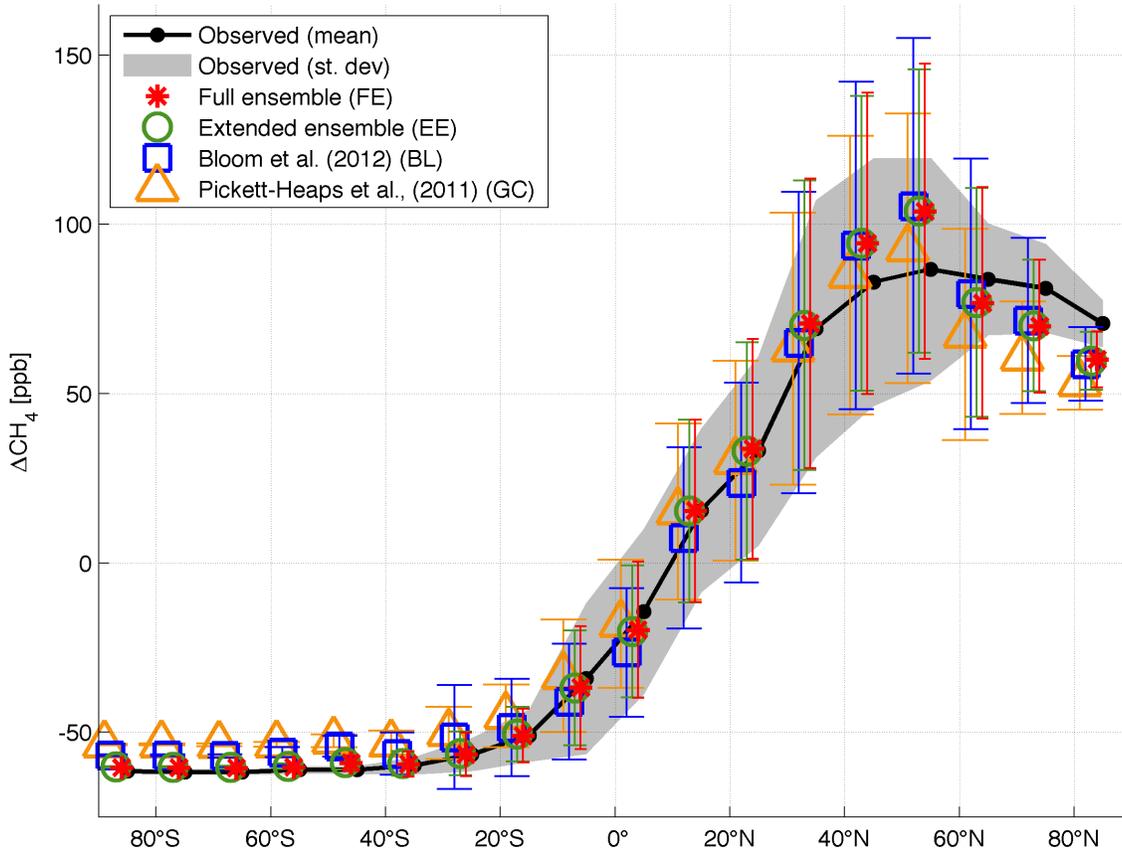


Figure 8. Mean 2009-2010 CH₄ measurements and model CH₄ zonal anomalies (ΔCH_4), relative to the mean 2009-2010 global CH₄ concentration. The black dots denote mean WDCGG network observed CH₄ concentrations within 5° latitude bins; the grey envelope denotes the mean 2009-2010 standard deviation across all sites within 5° latitude bins. The coloured symbols and error bars denote the GEOS-Chem equivalent model concentrations statistics based on the FE and EE ensembles (this study), Bloom et al., (2012) (BL) and the GEOS-Chem emission inventory (GC) wetland CH₄ emissions datasets.

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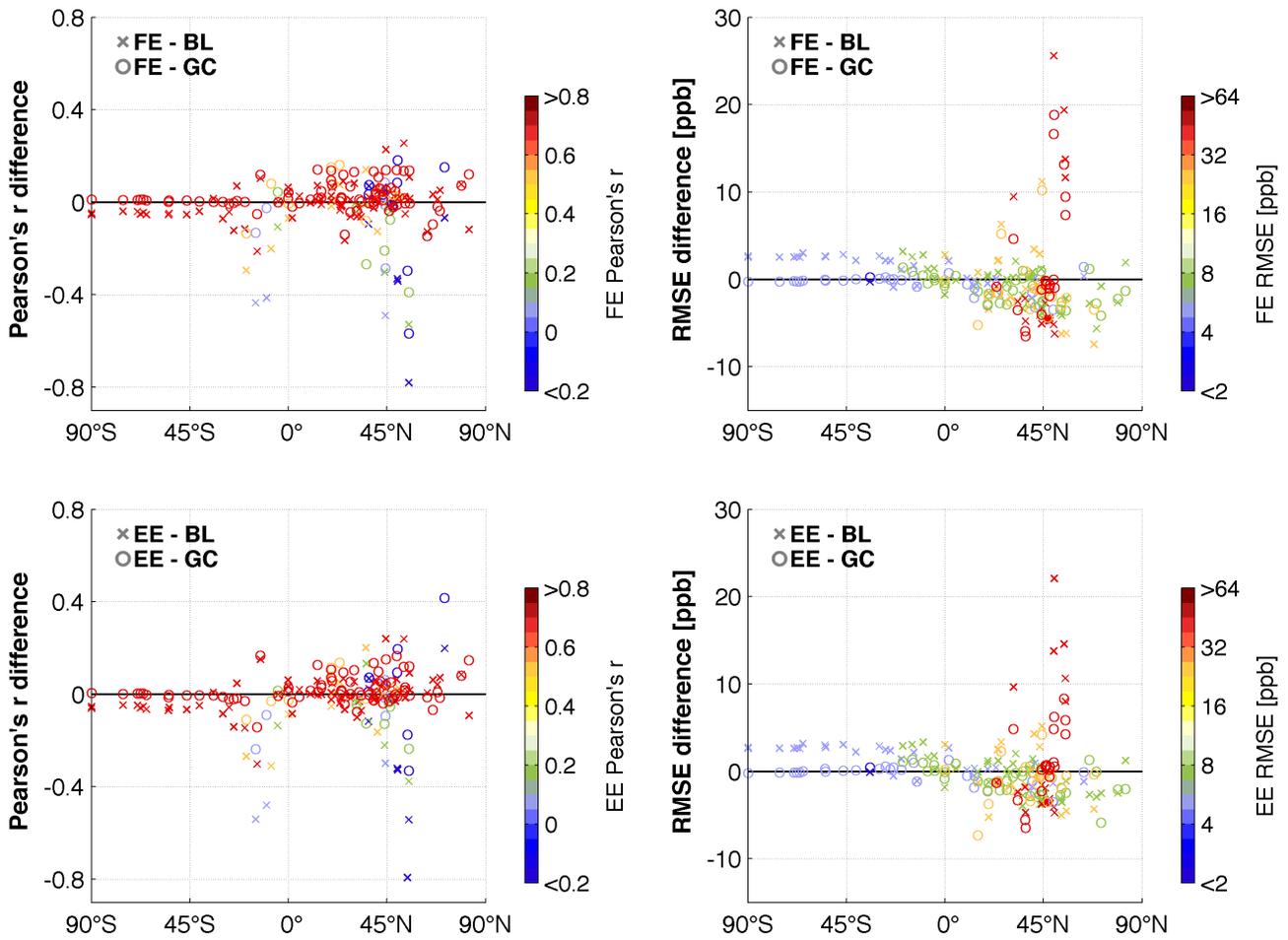


Figure 9. Symbol colours denote the monthly de-trended CH₄ model-observation Pearson's r correlation (left column) and RMSE (right column) for the FE (top-row) and EE (bottom-row) wetland CH₄ emissions (monthly CH₄ observations are from the WDCGG measurement site network). The y-axis denotes the difference between FE/EE and model runs with Bloom et al., (2012) wetland CH₄ emissions (BL) and the GEOS-Chem wetland CH₄ emissions inventory (GC).

Tables

5 **Table 1:** Wetland CH₄ model ensemble configurations

Parameter	Description		Ensemble configurations
s	<u>Global scaling factor</u>		<u>3 configurations: emissions are scaled such that 2009-2010 emissions amount to 124.5, 166 or 207.5 Tg CH₄ yr⁻¹</u>
A	Wetland extent	<i>Spatial Extent</i>	2 spatial extent parameterization (scaled using GLOBCOVER and GLWD)
		<i>Temporal Variability</i>	SWAMPS inundation extent ^(*)
			ERA-interim precipitation
R	Heterotrophic respiration		8 MsTMIP terrestrial C models ^(*)
			CARDAMOM terrestrial C cycle analysis
$q_{10(c)}$	Temperature-dependent CH ₄ respiration fraction.		3 CH ₄ :C temperature parameterizations: $q_{10(c)} = [1, 2, 3]$

^(*) These datasets are only used in the 2009-2010 “Full Ensemble” (FE).