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Abstract

Climate models have been making significant progress encompassing an increasing number of complex feedback mechanisms from natural ecosystems. Permafrost thaw and subsequent induced greenhouse gas emissions, however, remain a challenge for climate models at large. Deducing permafrost conditions and associated greenhouse gas emissions from parameters that are simulated in climate models would be a helpful step towards estimating emission budgets from permafrost regions. Here we use a regional climate model with a 5 km horizontal resolution to assess future potential methane (CH₄) emissions over presently unglaciated areas in Greenland under an RCP8.5 scenario. A simple frost index is applied to estimate permafrost conditions from the model output. CH₄ flux measurements from two stations in Greenland; Nuuk representing sub-Arctic and Zackenberg high-Arctic climate, are used to establish a relationship between emissions and near surface air temperature. Permafrost conditions in Greenland change drastically by the end of the 21st century in an RCP8.5 climate. Continuous permafrost remains stable only in North Greenland, the north-west coast, the northern tip of Disko Island, and Nuussuaq. Southern Greenland conditions only sustain sporadic permafrost conditions and largely at high elevations, whereas former permafrost in other regions thaws. The increasing thawed soil leads to increasing CH₄ emissions. Especially the area surrounding Kangerlussuaq, Scoresby Land, and the southern coast of Greenland exhibit potentially high emissions during the longer growing season. The constructed maps and budgets combining modelled permafrost conditions with observed CH₄ fluxes from CH₄ promoting sites represent a useful tool to identify areas in need of additional monitoring as they highlight potential CH₄ hot spots.

1. Introduction

Permafrost areas store large amounts of carbon within the frozen ground. This storage and the influence it can have on terrestrial-atmosphere carbon feedbacks in a warming climate is one of the least understood, but at the same time potentially one of the most significant climate feedbacks in this century (Schuur *et al* 2008, Tarnocai *et al* 2009, IPCC Intergovernmental Panel on Climate Change 2014). Natural carbon fluxes in and out of oceanic and terrestrial reservoirs are annually an order of magnitude larger than perturbation from fossil fuel and land-use change (Schuur *et al* 2008). Therefore, a temperature increase

can trigger a large positive feedback from land biomass and soils on the expected atmospheric carbon pool (Schneider von Deimling *et al* 2012). Permafrost is permanently frozen ground, or in more detail, sub-surface earth material with a soil temperature continuously at or below 0 °C for at least two consecutive years (Harris *et al* 1988). The global permafrost regions are estimated to cover an area of $22 \pm 3 \times 10^6$ km² (Gruber 2012), or about 25% of northern hemisphere land masses. Hence, permafrost is a very important part of the world's cold region climates and indeed the entire climate system. The overall existence of permafrost depends largely on the mean annual temperatures (Hollesen *et al* 2010). Naturally, permafrost can

be found at high latitudes and/or high altitudes. Furthermore, permafrost development is more likely in a continental climate, which has low precipitation. Snow precipitation and a snow layer on the ground limits the heat transfer between atmosphere and ground. This prevents the soil from freezing to great depth during winter (Stieglitz *et al* 2003). Permafrost areas are predominantly located in Alaska, northern Canada, Siberia and Greenland (e.g. Brown *et al* 1997). Generally, permafrost can be categorized into four groups: continuous permafrost being an area that is to more than 80%–90% underlain by frozen ground; discontinuous permafrost being between 50% and 90%; sporadic permafrost being 10%–50%; and isolated permafrost being less than 10% frozen ground (Harris *et al* 1988, Anisimov and Nelson 1997, Brown *et al* 1997).

The terrestrial landscapes of Greenland include environments varying from having presence to absence of permafrost both with respect to latitudinal and to altitudinal gradients. In the sub-Arctic southwest of Greenland, permafrost is only found at higher altitudes with the lowlands being permafrost-free. Due to the cold southward ocean current from the Arctic Ocean along the east coast, eastern Greenland experiences a colder climate than western Greenland. Therefore, in the more northern parts of Greenland and further south on the eastern coast relative to the western, continuous permafrost is found both in the lowlands and at higher altitudes. This renders Greenland a useful microcosm for analyzing within relative short geographical distance how permafrost in different forms may respond to climate change. Permafrost soils often have a high carbon content as low soil temperatures in Arctic regions reduce decomposition rates of organic matter and saturated, anoxic, poorly drained soil conditions amplify this effect (Hartley and Ineson 2008). In response to contemporary climate change, overall permafrost coverage is decreasing and is expected to decrease well into the future (Collins *et al* 2013, Schuur *et al* 2015, Romanovsky *et al* 2017). With permafrost thawing and increasing active layer thickness, former frozen organic matter reaches temperatures above 0 °C and becomes available to decay. The decomposition of organic matter produces greenhouse gases like carbon dioxide (CO₂) and methane (CH₄). In soils with high oxygen availability, decomposition is accompanied by CO₂ emissions. In oxygen-limited soils, CH₄ is released to the atmosphere. The focus of this study is on CH₄ emissions.

The representation of permafrost and CH₄ emission feedbacks in climate models is still a challenging task for various reasons. Multiple physical, biological, and chemical mechanisms are not sufficiently understood in the permafrost carbon cycle. Furthermore, climate models often lack a sufficiently high spatio-temporal resolution to adequately resolve the relevant processes. The lack of high horizontal and deep soil resolution in climate models lead to difficulties in

representing soil properties such as soil temperature, carbon content, and water table depth (Nicolsky *et al* 2007). A proper representation of changes in permafrost requires high resolution estimations of snow cover, precipitation, and vegetation evolution but these are not realistic on the scale of a typical general circulation model (GCM) grid. Moreover, the required simulations often covering millennia is only beginning to become feasible at a sufficient spatial resolution given modern computational resources (Stendel and Christensen 2012, Flato *et al* 2013, Eyring *et al* 2016).

Considering the uncertainties and challenges accompanying permafrost and greenhouse gas emission modelling, it would be helpful to be able to extract information about permafrost conditions from parameters that are normally included in comprehensive GCMs and/or regional climate models (RCMs). Deriving permafrost conditions could further enable us to draw a conclusion about greenhouse gas emission even if a model is not including a full carbon cycle as part of its basic formulation. The present work addresses the challenge in a simplified framework for the Greenland domain. Model simulations with a high spatial resolution of this area were available to us conducted with the Danish Meteorological Institute HIR-HAM5 model (Christensen *et al* 2006, Lucas-Picher *et al* 2012, Langen *et al* 2015, Boberg *et al* 2018). The high 0.05° resolution model version makes it possible to depict the complex topography, coast line and hence necessary landscape details of Greenland to capture the highly variable soil and permafrost conditions (e.g. Daanen *et al* 2011). A simple frost index (Nelson and Outcalt 1987; see section 3) will be used to identify permafrost conditions. Gas flux measurements from the Greenland Ecosystem Monitoring program are used to link permafrost and meteorological parameters with CH₄ fluxes (Christensen and Topp-Jørgensen 2017). It has to be kept in mind, however, that the spatial sub-grid variability is still large with respect to active methane production in soils and in the absence of a detailed vegetation map superimposed on the modelled predictions, these remain indicative of potential emission.

This work aims at defining a first-order link between measured greenhouse gas emissions to a simple climate model parameter. This relation can be used to estimate potential future CH₄ emissions from Greenland and could be generalized to other climate models and regions. In this paper, we have organized the analyses around the research questions:

- How will permafrost conditions on Greenland respond to a changing climate?
- What controls CH₄ emissions on Greenland and how will the emissions develop in a changing climate?

- Where can we expect to see the emergence of CH₄ emission hotspots?

To answer these questions, section 2 describes the data we have at our disposal for analysis. Section 3 combines climate model data to predict local permafrost conditions and observed CH₄ emission information to derive potential CH₄ emission maps for Greenland. Section 4 utilizes the aforementioned information to assess future CH₄ emissions in Greenland and identifies areas that are likely to become future CH₄ emission hotspots. Finally, section 5 discusses the findings, offers some concluding remarks of the analysis, and proposes avenues of future research.

2. Data

Since our aim is to upscale information from site specific measurements to the whole of Greenland using a RCM, we summarize the main features of the two independent dataset, we want to combine.

2.1. Model data

HIRHAM5 (Boberg *et al* 2018) is a regional atmospheric climate model that combines the dynamical core of the short-range weather prediction model HIRLAM7 (High-Resolution Limited Area Model; Undén *et al* 2002) with the physical parameterization package from the GCM ECHAM5 (Roeckner *et al* 2003). The horizontal resolution of HIRHAM in this study is 0.05° corresponding to about 5.5 km. So HIRHAM5 can be thought of as a high resolution limited area version of ECHAM5. The time stepping scheme is semi-Lagrangian instead of Eulerian, which allows longer time steps and makes high resolution simulations computationally realizable. Over Greenland, HIRHAM5 uses the topography of Bamber *et al* (2001) and a high resolution ice mask produced by Citterio and Ahlstrøm (2013) interpolated to the adopted model resolution of this study.

Due to the computationally expensive high resolution, a few time slices were chosen instead of using a full transient covering the 21st century: a time slice driven with ERA-Interim data produced by the ECMWF (Dee *et al* 2011) from 1981–2014 (split in two slices 1981–1990 and 1991–2014), a reference past time slice ‘HIST’ (1991–2010) and two future slices representing the middle (2031–2050) and the end (2081–2100) of the century driven with EC-Earth (Hazeleger *et al* 2010) boundaries. For each future time slice an RCP4.5 and RCP8.5 scenario simulation exists.

The model is updated every six hours with boundary data from the driving re-analysis. For the future scenarios and the reference past time slice HIRHAM is forced with EC-Earth. The EC-Earth global circulation model has a well-known cold bias (Koenigk *et al* 2013), which also influences the future and HIST

simulations used here. The HIRHAM5 model has been demonstrated to be able to simulate contemporary climate, including permafrost zonation, quite well (Christensen and Kuhry 2000). The uncertainties of such a computationally expensive RCM cannot be estimated by ensemble runs. Olesen *et al* (2018) tested the robustness of high resolution regional climate projections for Greenland via a method of uncertainty distillation using the corresponding temperature spread in a wider set of global climate models.

2.2. Temperature and surface flux observations

To connect model parameters to methane emissions and to validate the relevant parameters obtained from the model simulations, measurements from the Greenland Ecosystem Monitoring GEM (Christensen and Topp-Jørgensen 2017) data base are used. Near surface air temperature, heat and methane emission fluxes are available from the two main field stations in Nuuk and Zackenberg and temperature measurements were also available from Disko Island station (see location in figure 1). The Nuuk station is located in sub-Arctic west Greenland (64°07'N, 51°21'W, annual mean temperature 0.1 °C between 2008–2015). Zackenberg station represents high-Arctic conditions in central north-east Greenland (74°28'N, 20°34'W, annual mean temperature –9 °C between 1996–2015) and Disko Island represents low-Arctic conditions on an island in mid-south-west Greenland (69°15'N, 53°34'W, annual mean temperature –3.1 °C between 1991–2015). Temperature measurements were obtained from climate measurement masts, methane fluxes from automatic chamber (AC) measurements and latent and sensible heat fluxes from eddy covariance measurements from Nuuk and Zackenberg (Pirk *et al* 2017, Lund *et al* 2017). AC measurements are only available since 2006 and 2008 from Zackenberg and Nuuk respectively.

3. Potential permafrost and methane distribution

3.1. Frost index

The frost index we use here, was first derived by Nelson and Outcalt (1987). It is a dimensionless ratio of freezing and thawing degree-day sums. The index can be used to define an unambiguous latitudinal zonation of permafrost continuity (Nelson and Outcalt 1987) and has been found to correlate relatively well with observed permafrost conditions at larger scales (Anisimov and Nelson 1997). The normalized frost index, F used here is defined as follows:

$$F = \frac{\sqrt{DDF}}{\sqrt{DDF} + \sqrt{DDT}},$$

where DDF and DDT are the annual degree-days of freezing and thawing, respectively. Degree-days are calculated as the sum of mean monthly temperatures

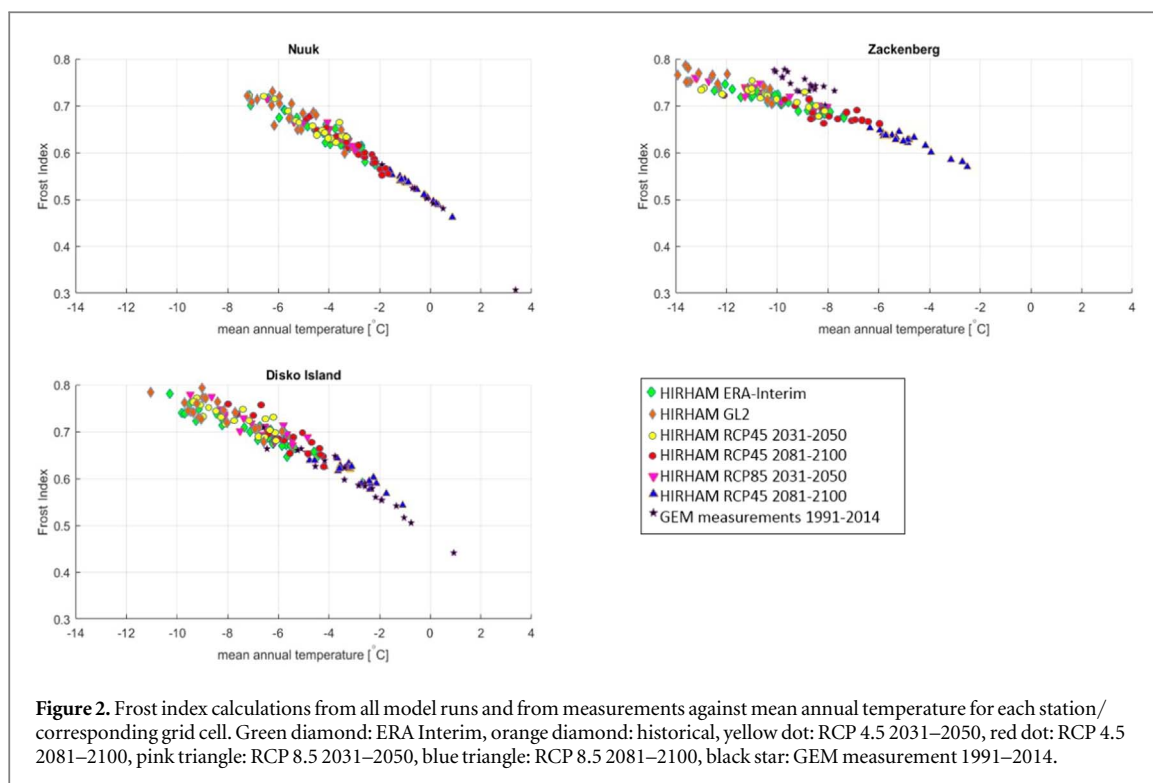


in degrees Celsius above or below the threshold of 0°C . A higher than monthly temporal resolution only has minor implications (Christensen and Kuhry 2000). Permafrost should be expected for F values above 0.5 (Nelson and Outcalt 1987).

By its definition, the frost index ' F ' depends on the ratio of degree-days of freezing to all days of the year. This means a high number of months with a mean temperature below zero and/or extremely low mean monthly temperatures are needed for a high index. The annual mean temperature can reflect these two criteria combined. To validate the behavior of the frost index calculated from model output and measurements, scatter plots show the index against the mean annual temperature for all model runs and measurements for each station (figure 2).

As one could expect, there is a clear negative correlation between F and the mean annual temperature. The lower the temperature the higher the index. The modelled F -values do not increase linearly with decreasing temperature but rather parabolically,

adapting to one for very low temperatures. For the stations Nuuk and Disko Island the measured values fit very well into the bulk of modelled values. The Zackenberg grid cell shows a different behavior. Here the measured values are off the second order fit, but also a linear fit is not able to represent all values. However, calculating F of the model grid cell just east of the actual Zackenberg station cell shows the expected behavior, where the modelled and measured data fit well together (see supplementary material, figure S1, at: stacks.iop.org/ERL/14/035001/mmedia). A possible explanation for this behavior is the relatively complex topography along the coast in this part of Greenland. Not even the high resolution of 5.5 km of the model can catch the characteristics of this high frequency landscape, meaning that issues related to both topography and land/sea contrast influence the individual grid cells. This will impact the quality of our upscaling. Our model resolution is not sufficient enough to represent exactly each grid cell but it should at least represent the region reasonably well.



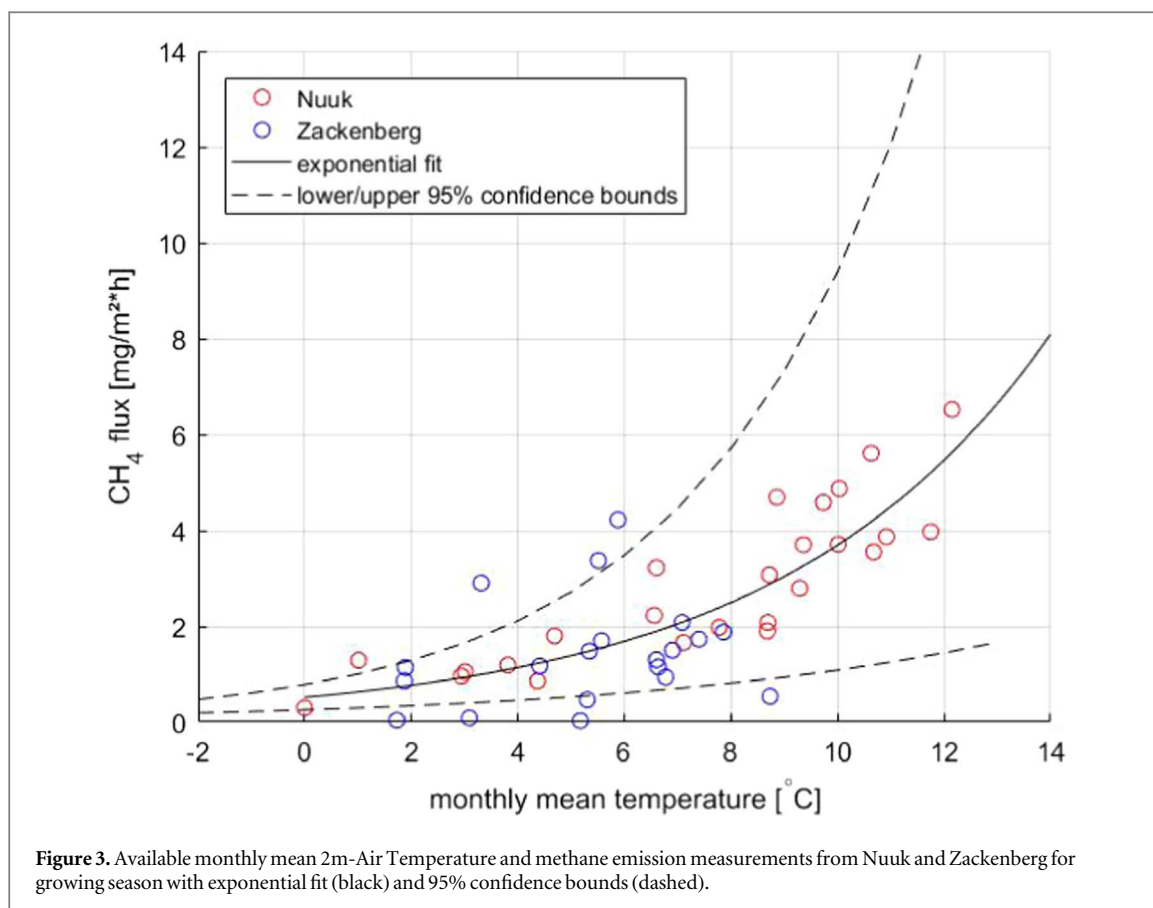
The cold bias of the EC-Earth driven simulations compared to the ERA-Interim run is apparent in that the annual mean temperatures in the HIST run are clearly lower than in the ERA driven run. Among the EC-Earth driven simulations, a decreasing F with increasing temperatures for the simulations representing the future is apparent. It has to be kept in mind that the frost index only relies on temperature and is therefore unable to take into account other factors such as relic permafrost and snow cover.

3.2. Methane emissions in the growing season

To be able to upscale measured methane emissions, a link between the methane flux and a meteorological parameter that is described in the climate model has to be identified. Three parameters were chosen to test correlations with the methane emissions based on conceptual models: temperature, sensible and latent heat flux. Air temperature shows the best relation with combined methane measurements from Nuuk and Zackenberg in terms of plausibility of a real correlation and of smallest sum of error squares (compared to relationships between methane and heat flux). A rise in air temperature will cause the soil temperature near the surface to rise (Bartlett *et al* 2005, Chudinova *et al* 2006), and should lead to an increased microbiological activity. Disregarding the potential effects on the microbial oxidation this will lead to a higher decomposition rate of organic matter, an increasing methane gross production and likely also a net positive flux. There is evidence from observations that temperature is the main driver of CH_4 emissions (e.g. Christensen *et al* 2003, Tagesson *et al* 2012). Gedney *et al* (2004) also found in a model experiment that the dominant

driving force for CH_4 emissions was increasing temperature.

AC measurements are not active all year round, therefore we concentrate on emissions during the growing season only. The growing season in this case is defined from the last day of the first continuous four-day period with daily mean temperature at 2 m above 2°C to the last day of the last four-day period with those conditions. This mainly includes the months May, June, July, August and September. While Nuuk shows a clear relation between methane emission and temperature, the Zackenberg signal is weaker, partly because the dynamical range is smaller. The few available autumn measurements (past September) from Zackenberg show high CH_4 emission ‘bursts’. Due to their high variability and the few years that include late season measurements, these are not included here and we concentrate on the growing season only. This leads to an underestimation of arctic CH_4 emissions. The phenomena of autumn emissions will be discussed in section 5. Considering a wider body of data including multiple sites’ and years’ temperature remain the best overall predictor of growing season methane emissions (Christensen *et al* 2003). Therefore, Nuuk and Zackenberg CH_4 emissions are combined in the current context. An exponential relation between temperatures and CH_4 fluxes during growing season gives the best fit (figure 3, see also Christensen *et al* 2003, Tagesson *et al* 2012, Mastepanov *et al* 2013). A linear fit result in negative emission for temperatures below 0.7°C which is not realistic, as an uptake of CH_4 by the soil should not be expected. A second order polynomial fit give an increasing emission for temperatures below 1.5°C , which is not reasonable either.



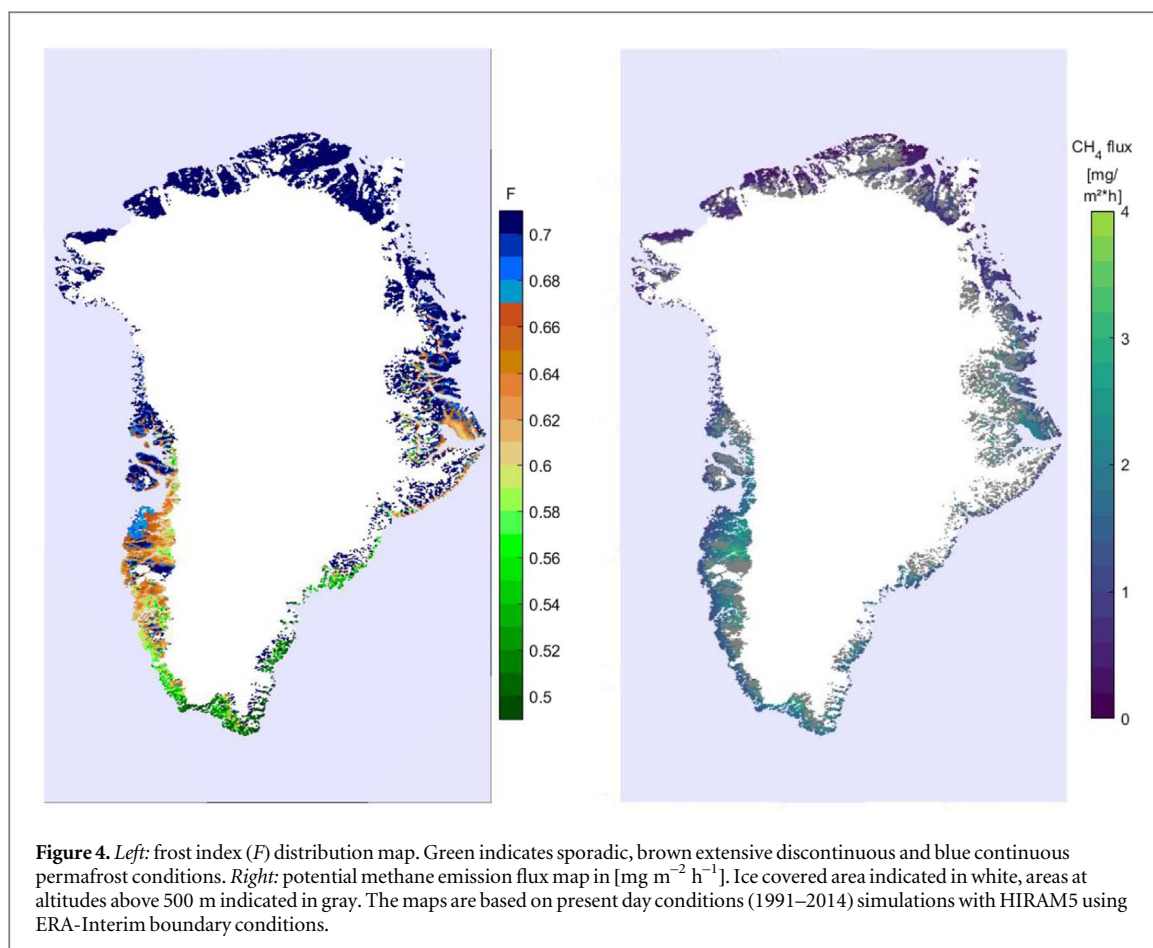
An exponential fit seems as a pragmatic option. The relationship between CH_4 emission and temperature can now be used as a simple tool to upscale the potential methane fluxes for all of Greenland with the modelled temperature. This is based on the crude assumption that all of Greenland behaves like the two measurement stations available to us. The best-fitting exponential relationship is: $C = 0.5206 \cdot \exp(0.1960 \cdot T)$ with T monthly mean temperature and C CH_4 emission flux.

4. Projected changes

Figures 4 and 5 display frost index and potential methane emission maps for ERA-Interim and EC-Earth driven simulations respectively. F is calculated yearly and then averaged over the time slice. For the methane map the exponential relationship found in section 3.2 is implemented on mean growing season temperature over the time slice. Note the different F color bars for the two different boundary condition simulations. The ERA-I F map in figure 4 uses the original thresholds for transitions from one permafrost classification to another suggested by Nelson and Outcalt, where sporadic permafrost conditions start at frost index values of 0.5, the transition from sporadic discontinuous to extensive discontinuous permafrost is at 0.6 and from extensive discontinuous to continuous at 0.67. Considering the cold bias of the driving

model EC-Earth, the adjusted F color bars in figure 5 were adapted following Christensen *et al* (2015). Thus, sporadic permafrost zones are defined by values from 0.52 to 0.63, extensive discontinuous permafrost zones from 0.63 to 0.70 and continuous permafrost zones above 0.70. The emission scales have not been adapted to the cold bias. Therefore, the future emission scenario needs to be seen in comparison to the HIST simulation. One should also note that the frost index is an indicator for permafrost conditions but considers a climate in equilibrium. It cannot take transient changes in climate into account. Therefore, the index can tell if and where a change in permafrost conditions will take place but not when it will take place. The result is simulated permafrost in equilibrium with climate, which is not always the case, in particular when considering different time-scales. The frost index map for an RCP 8.5 future in figure 5 is based on the climate in this certain time period. However, the adaption of permafrost to this climate will most likely take longer and will not already be seen in the time period for which it is calculated.

A precondition for CH_4 emission is the existence of soil with an active microbiology. This requires moisture availability, which could also change under general warming conditions. In order to assess whether the general moist conditions are altered in a negative way, we show the projected change in both annual and JJA mean effective precipitation (simulated precipitation minus evaporation) in figure 6. It is evident



that a.e. the annual mean effective precipitation change is positive, while for JJA there is only minor changes, but in general no sign of a drying trend.

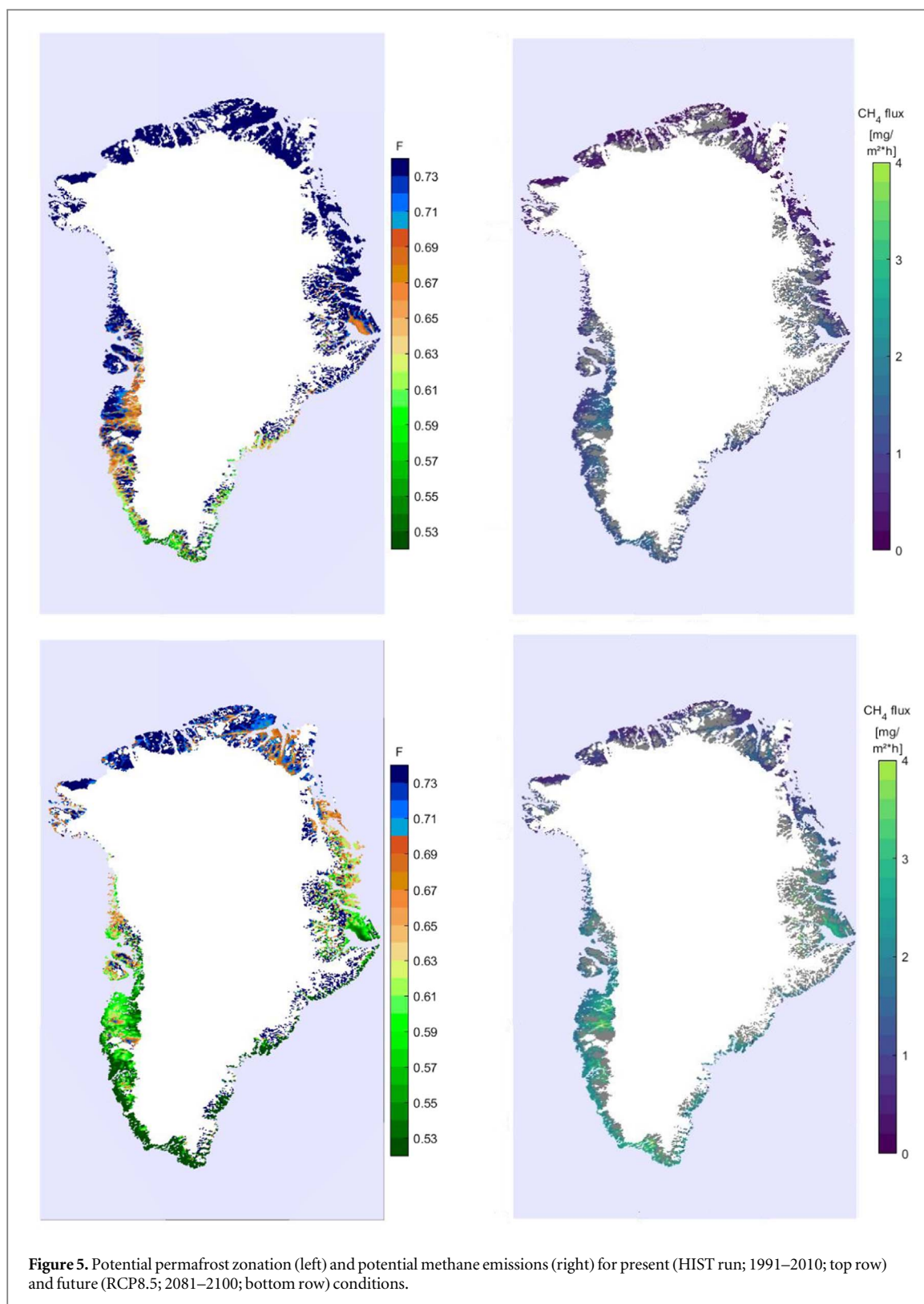
Further to this, we note that for an upper bound potential methane emission estimate, all grid cells not covered by glacier and with an altitude below 500 m are considered to contain soil and vegetation and therefore to contribute to methane emission. Areas at altitudes above 500 m are ignored and colored gray in the methane maps as no soil with sufficient material of organic origin to contribute to methane emissions can be expected there. Even with these grid cells excluded, the maps will show an upper end potential emission during growing season (keeping in mind also that this method still ignores emissions outside the growing season). Both AC measurements from Nuuk and Zackenberg are from fen areas, which is an ecosystem that is likely to produce CH_4 , while other common vegetation types like heathlands and bare ground will not (to the same extent).

The permafrost conditions derived from monthly mean temperatures by the frost index depend on the number of months below or above the threshold 0°C , and on the maximum or minimum mean temperatures. The EC-Earth driven HIRHAM simulations show that the number of months below zero decreases in the future. The temperatures increase in general, but especially the winters become warmer (see figure S2). These two factors lead to a declining frost index,

indicating a destabilization and consequently thawing of permafrost.

Present day climatic conditions are not favorable for permafrost in lower lying areas in Greenland south of Kangerlussuaq in west and Tasiilaq on the eastern coast, which is in agreement with observationally based estimates (Christiansen and Humlum 2000). Hence, only sporadic permafrost is present and predominantly at higher elevated areas. Under RCP8.5 end of century climate conditions only the northern most part of Greenland still predominantly will favor wide spread continuous permafrost conditions. The southern half of Greenland will mostly not favor permafrost conditions and only allow for sporadic permafrost to be sustained at particularly highly elevated areas.

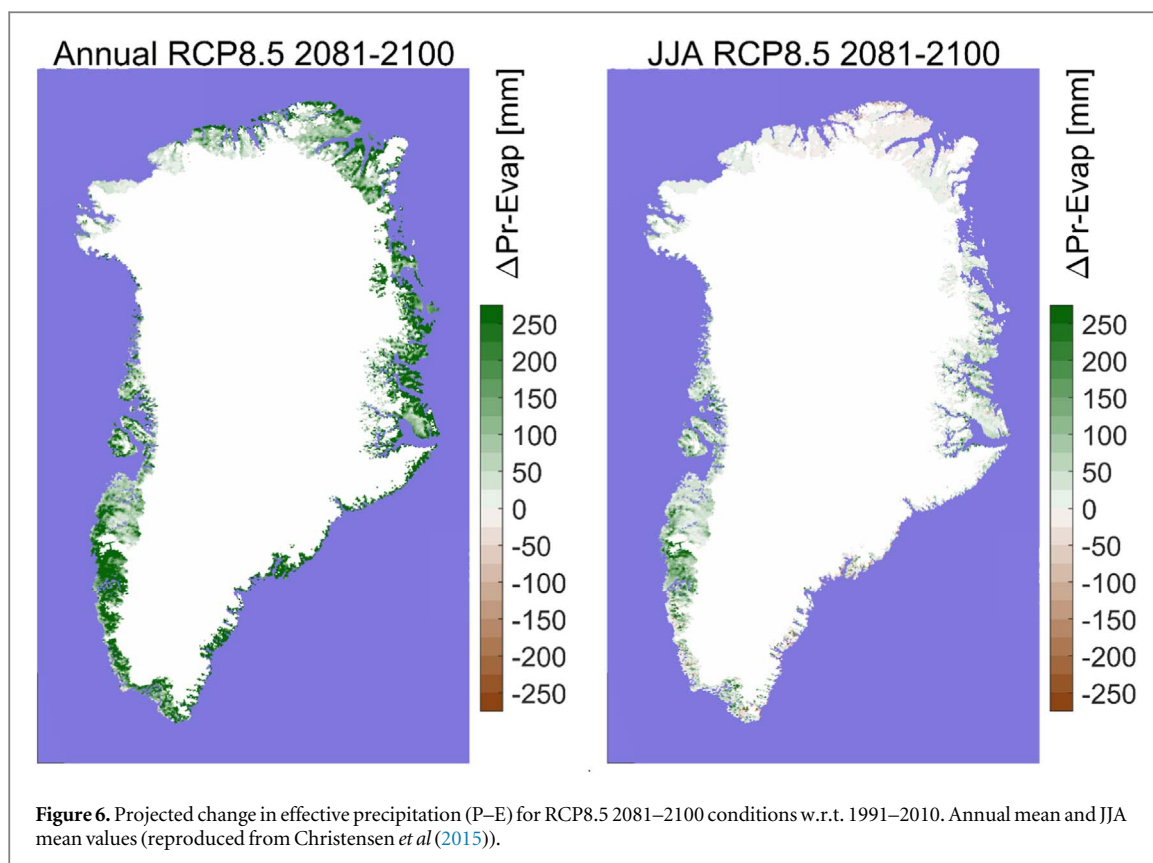
In Zackenberg, the mean growing season CH_4 emission measured is about $1.42 \text{ mg m}^{-2} \text{ h}^{-1}$, which corresponds well to the methane emission of $1.20 \text{ mg m}^{-2} \text{ h}^{-1}$ obtained using the exponential relationship for the ERA-I driven HIRHAM simulation and the corresponding grid cell. As the model seems to underestimate Nuuk temperatures and therefore predicts a higher frost index than actually measured, the CH_4 emissions show this cold bias as well. In the growing season 2008–2015, mean CH_4 flux was recorded as $2.86 \text{ mg m}^{-2} \text{ h}^{-1}$ at the station while HIRHAM ERA-I predicts $1.34 \text{ mg m}^{-2} \text{ h}^{-1}$. Comparing this to the ECHAM driven historical simulations shows the overall cold bias: For Nuuk a CH_4 emission of



$1.00 \text{ mg m}^{-2} \text{ h}^{-1}$ and for Zackenberg of $0.77 \text{ mg m}^{-2} \text{ h}^{-1}$ is calculated. Therefore, the future potential CH_4 emission need to be seen as a change from historical to future conditions rather than considering the actual values.

We see increasing CH_4 emissions all over Greenland for RCP8.5. Methane emissions are highest in the southern half of Greenland where permafrost

conditions turn into sporadic permafrost or into seasonally frozen ground. The most outstanding areas of CH_4 emission hot spots are seen around Kangerlussuaq and Scoresby Land. The area around Kangerlussuaq is widely covered with moist grasslands and shrubs, which makes a high biological activity in the soil and high CH_4 emissions likely (CAVM



Team 2003). The permafrost conditions in the 1990s for this area are discontinuous but already showing an increase in soil temperatures and hence an expected decrease in frost index towards sporadic permafrost conditions during the last 24 years (e.g. Daanen *et al* 2011).

The coastal area of southern Scoresby Land contains cliff with bedrock not contributing to methane emissions. However, the permafrost conditions would enable high emissions in any fen areas in this region.

5. Discussion and conclusion

The frost index has shown to be a reasonable tool to assess permafrost conditions in former work (e.g. Anisimov and Nelson 1997, Christensen and Kuhry 2000). The 5 km resolution enables us to reasonably handle the complex topography of Greenland and to zoom in to the three stations where we have permafrost observations to compare the model simulation and frost index calculations. Our ERA-Interim HIRHAM simulations indicate a present-day frost index of 0.6 for Nuuk, indicating discontinuous permafrost, while the area around Nuuk is dominated by sporadic permafrost. This can be explained by noting that even at a grid point resolution of 5 km, the topographical features in the area results in grid point altitudes at higher elevations than local sites where on-site permafrost assessment has been carried out. For the grid cells of Zackenberg and Disko Island the modelled frost index is 0.7 indicating continuous

permafrost. This agrees well with observed permafrost conditions. Therefore, we conclude HIRHAM represents permafrost conditions across Greenland with a reliability that is sufficient to assess the changes in permafrost conditions under warming conditions. These results are in agreement with previous findings which were conducted at a lower spatial resolution (Daanen *et al* 2011). Therefore, we propose that HIRHAM is fit for purpose to address the question ‘How will Permafrost conditions on Greenland respond to a changing climate?’.

By an end of century RCP8.5 scenario, only northern Greenland can sustain continuous permafrost conditions while southern Greenland permafrost areas only contain sporadic permafrost or seasonally frozen ground.

As noted above, an exponential increase of methane emissions with increasing temperature is found to be in agreement with the observed relation. This allows us to interpret climate model simulations at a sufficiently high spatial resolution and provides an up-scaled estimate of an all Greenland potential CH_4 flux. Using time slice experiments with HIRHAM then allows us to estimate how the emissions potentially will develop in a changing climate under a given emission scenario.

One has to keep in mind that this fit in some southerly areas is extrapolated to the projected higher temperatures and this potentially may result in implausible high emissions. For the simulations and temperature ranges used here, we propose that the

exponential fit is still reasonably in agreement with the observational evidence, particularly in regions currently underlain by permafrost.

Combining the information about potential future changes in permafrost zonation and moisture availability from HIRHAM with the temperature—CH₄ flux relationship enables us to identify hot spot zones all over Greenland, where the risk of permafrost degradation and the resulting potential release of methane are the greatest. This is a useful tool to identify areas that need additional monitoring, like the potential hot spots in the area around Kangerlussuaq and Scoresby Land.

Our estimate of CH₄ emission has one main source of uncertainty: the correlation used to upscale the flux measurements is only based on two stations and could not be validated with more independent data. When measurements from Disko Island become accessible, this would possibly help to bridge the gap between sub and high-Arctic climate and ecosystems in Greenland. But we note that Christensen *et al* (2003) showed a similar simple relationship to work across several sites from central Siberia to Zackenberg. Furthermore, it is of course a simplified view, to link the greenhouse gas emissions with only one parameter. CH₄ emissions depend to first-order on temperatures but there are likely dependencies to the water table depth, soil properties, as well as specific plant functional relationships (e.g. Ström *et al* 2012) which are to be explored in future work.

Year-round measurements could further improve our knowledge of CH₄ emissions in Greenland. For the few years during which the AC stations recorded beyond the growing season, an interesting pattern was found in Zackenberg. While CH₄ flux measurements from Nuuk show an expected increase towards summer and a decrease in CH₄ emissions towards autumn (not shown), the measurements from Zackenberg exhibit a bimodal behavior with a first maximum in summer and a highly variable second maximum in late autumn (not shown). Mastepanov *et al* (2008, 2013) explain the bimodal distribution by a gradual freezing of the active layer in autumn that squeezes the remaining methane out of the soil as there is a permafrost layer present below that prevents methane from diffusing downwards. The autumn month emissions are highly variable and can be larger than the summer month emissions that we considered in this work.

Jørgensen *et al* (2014) found that the dry to moist tundra landscapes (with less than 55 vol% soil moisture) in the Zackenberg area act as sinks of atmospheric methane through oxidation in the upper 35–40 cm of the soil. Methane uptake is positively correlated to increasing temperature (although not as sensitive as methane production) and negatively to soil moisture. The HIRHAM simulations show that while the temperature is increasing for future scenarios, the soil moisture is expected to increase or not to change. Therefore we do not expect the methane sink behavior to significantly increase in the future.


Another remaining problem is the insufficiently detailed knowledge of the ground conditions on Greenland. Schuur *et al* (2008) finds that permafrost regions are highly heterogeneous considering their carbon content and upscaling from local measurements is difficult. Here, all grid cells are considered to contribute to emissions along the same exponential trend established by Nuuk and Zackenberg. The measurements are specifically from sites that promote methane emissions. Possibly a lot of the grid cells on Greenland do not contribute to greenhouse gas emissions at all (because they are composed of largely bare ground or only have a very shallow organic layer on top of the bedrock) or simply contribute less (because of lower carbon content). However, the relative future change in potential emissions from productive areas may still be evaluated using the presented modeling approach. A further next step in this work will then be to overlay a high resolution digitized map of vegetation composition in Greenland but such is unfortunately not available to date.

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