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Modeling Pan-Arctic Peatland Carbon Dynamics Under Alternative Warming Scenarios

Nitin Chaudhary[1,2], Wenxin Zhang[1,3], Shubhangi Lamba[4], and Sebastian Westermann[2]

[1]Department of Physical Geography and Ecosystem Science, Lund University, Lund, Sweden, [2]Department of Geosciences, University of Oslo, Oslo, Norway, [3]Department of Geosciences and Natural Resource Management, University of Copenhagen, Copenhagen, Denmark, [4]Department of Biological and Environmental Sciences, University of Gothenburg, Gothenburg, Sweden

Key Points:

- We modeled the effects of climate change on peatland carbon balance under different warming scenarios using peatland-vegetation model
- Peatlands will likely remain carbon sink until 2100 in low to moderate warming scenarios
- They are projected to shift from a carbon sink to carbon neutral in the strong warming scenario RCP8.5

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

N. Chaudhary,
nitin.chaudhary@nateko.lu.se

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Author Contributions:

Conceptualization: Nitin Chaudhary, Shubhangi Lamba, Sebastian Westermann
Formal analysis: Nitin Chaudhary
Funding acquisition: Nitin Chaudhary, Sebastian Westermann
Investigation: Nitin Chaudhary
Methodology: Nitin Chaudhary, Sebastian Westermann
Project Administration: Nitin Chaudhary
Validation: Nitin Chaudhary
Visualization: Nitin Chaudhary

Abstract Peatlands store large amounts of carbon in terrestrial ecosystems and they are vulnerable to recent warming. The ongoing warming may change their carbon sink capacity and could reduce their potential to sequester carbon. In this study, we simulated peatland carbon dynamics in distinct future climate conditions using the peatland-vegetation model (LPJ-GUESS). The study examined whether less pronounced warming could further enhance the peatland carbon sink capacity and buffer the effects of climate change. It also determined which trajectory peatland carbon balance would follow, what the main drivers were, and which one would dominate in the future. We found that peatlands will largely retain their carbon sink capacity under the climate scenario RCP2.6 to RCP6.0. They are projected to shift from a carbon sink to a carbon-neutral (5–10 gC m^{-2} yr^{-1}) in RCP8.5. Higher respiration rates will dominate the net productivity in a warmer world leading to a reduction in carbon sink capacity.

Plain Language Summary Peatlands are important components of the Earth climate system especially because they store large carbon stocks but continuous warming could reduce this carbon storage through enhanced soil decomposition that outweighs the increased net primary productivity of the ecosystem. In this study, we investigated how peatlands would behave in the distinct warmer conditions and whether less to moderate warming could increase their carbon sink capacity and reduce the effects of climate change. We found that peatlands will remain a major sink of carbon in the low and moderate warming conditions by the end of this century, although their carbon accumulation rates will somewhat decrease compared to present conditions. Conversely, their carbon sink capacity substantially reduces in an extremely warmer world and there is a risk that they become carbon neutral by 2100.

1. Introduction

Peatlands are considered one of the biggest carbon reserves in the terrestrial ecosystem, comprising 30% of the present-day soil organic carbon pool (Yu, 2012). They are also a major source of methane (CH_4), a potent greenhouse gas (Abdalla et al., 2016). They are transitional zones between upland mineral soils and wetland ecosystems (Loisel et al., 2017). High latitude peatlands constitute unique habitats with many special characteristics such as shallow water table depth, organic soils, distinct vegetation cover dominated by bryophytes, spatial heterogeneity, anaerobic biogeochemistry and permafrost spread in cold regions making these systems an important component in the global carbon cycle (Loisel et al., 2017; Yu, 2012). Recent observations have shown that the vegetation structure, hydrology, and carbon balance are rapidly changing in many peatlands (Johansson et al., 2006; Pinceloup et al., 2020). These ongoing changes will disturb the prevailing land-atmosphere carbon balance and trigger some pertinent climate-relevant feedbacks (Belyea, 2013; Zhu & Zhuang, 2016). Studies have indicated that peatlands will continue to act as carbon sinks in the next decades under different warming scenarios, but there is a possibility that they become carbon neutral or even a minor carbon source by the end of this century (Chaudhary et al., 2017b, 2020; Gallego-Sala et al., 2018; Qiu et al., 2020). To quantify and understand the overall effects of these rapid changes, various advanced peatland models have been employed, but often these models are forced with limited set of Representative Concentration Pathway (RCP) scenarios (Chaudhary et al., 2020; Müller & Joos, 2021; Qiu et al., 2020). It is a common trend to focus on two-three scenarios in modeling studies in order to obtain end-member estimates. All the climate scenarios are developed as a suite of complementary possibilities and the Intergovernmental Panel on Climate Change (IPCC) recommends that modeling studies should consider all the RCP scenarios for a complete understanding of system behavior in future conditions

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(IPCC, 2013a). Furthermore, Ritchie and Dowlatabadi (2017) recommend that the ultra-high warming scenario RCP8.5 should be used with caution for future scientific research or policy studies because the amount of coal that this scenario requires by major fossil fuel consuming countries assume to use in coming decades will likely exceed the estimates of readily available fossil resources. Experts believe that RCP4.5 and RCP6.0 are the more realistic scenarios (IPCC, 2013b; Ritchie & Dowlatabadi, 2017), yet these two scenarios are often omitted from modeling studies.

The purpose of this study is to simulate peatland carbon dynamics in the future climate conditions for four major future warming scenarios. The study examines whether less pronounced warming could further enhance the peatland carbon sink capacity and buffer the effects of climate change. It will also determine which trajectory peatland carbon balance will follow, what the main drivers are and which one will dominate in the future. This study is a follow-up of our previous study (Chaudhary et al., 2020), where we analyzed long-term carbon accumulation rates in the past and in the future, using only a limited number of model points (287 points) to simulate the observed peatland area under two extreme warming scenarios. In this study, we progress to perform simulations at one-degree resolution (around 3,900 points) within the observed peatland domain delineated by PEATMAP (Xu et al., 2018) with four different warming scenarios to obtain the overall picture of responses of peatlands in the coming century. Furthermore, we identify and highlight hotspot regions which are vulnerable to additional warming and likely switch its ecosystem functions between carbon sources or sinks according to our simulations. The carbon sink and source transition for the overall peatland ecosystem functioning is expected to more likely occur in the intermediate warming scenarios (i.e., RCP4.5 and RCP6.0 scenarios), which has not been touched upon by our previous study.

2. Methodology

2.1. LPJ-GUESS Peatland

LPJ-GUESS (Lund-Potsdam-Jena General Ecosystem Simulator; Smith et al., 2001; Smith et al., 2014) is a second-generation dynamic global vegetation model (DGVM) that is widely employed in global carbon cycle and vegetation dynamics studies (e.g., Saunois et al., 2020). LPJ-GUESS (without peatland) is included as a land surface scheme in the global Earth System Model (ESM) EC-Earth (Alessandri et al., 2017), and the regional ESM, such as RCA-GUESS (Wramneby et al., 2010; Zhang et al., 2014) and RCAO-GUESS (Zhang et al., 2020). LPJ-GUESS simulates vegetation structure and composition in response to a changing climate from local to global scales. It is a process-based model of vegetation dynamics which incorporates physiological changes and biogeochemistry of terrestrial ecosystems. It dynamically simulates water and carbon fluxes through coupled vegetation, soil, and hydrological interaction. Recently, new peatland and permafrost formulations with a unique representation of spatial heterogeneity were implemented in LPJ-GUESS (Chaudhary et al., 2017a). In particular, dynamic annual multi-layer peat accumulation, freezing-thawing cycles, lateral flow, and spatial heterogeneity in the framework of the dynamic vegetation model have for the first time been considered in the model (see Table S1 in Chaudhary et al. (2017a)), with applications from local to regional scales. Our previous studies have demonstrated that the mechanistic multi-layer peat accumulation scheme can simulate vegetation dynamics, permafrost, and peat distribution across the pan-Arctic region in a reasonably robust way. The current scheme consists of many important key mechanisms and interactions controlling the non-linear peatland dynamics (Chaudhary et al., 2018). These features allowed us to simulate major aspects of peatland dynamics, namely peat resilience due to peat compaction, recalcitrant characteristics of older peat layers and establishment of plants according to changes in water table. Phenomena such as the "hump-backed" relation between the average rate of peat formation and water table position, the cyclicity among micro-formations, internal eco-hydrological feedbacks and multi-directionality, which have been frequently observed in many peatland sites, can be simulated and explained using this detailed model scheme. In this study, we have employed the customized Arctic version of LPJ-GUESS that includes dynamic peat accumulation and decomposition functionalities with a freeze-thaw cycle. In the model, peat accumulates due to an imbalance between annual litter input and decomposition. The decomposition rate is controlled by the litter quality and thermo-hydrological conditions within the peat soil. The peat layers become more recalcitrant when sufficient labile peat material is decomposed over time. The current set up also features a unique individual- and patch-based representation of small–scale heterogeneity where the different vegetation units compete for resources, such as light and space. Over time, some patches gain height, while the surface elevation of others decreases or remains unaffected. The adjustment in the height of these dynamic

patches drives the water flow from elevated to low-lying patches and affects vegetation and biochemical properties of peatlands. For more information about the model and its functionalities, refer to Chaudhary et al. (2017a).

Using this model, we have performed experiments with four major RCP warming scenarios: RCP2.6, RCP4.5, RCP6.0, and RCP8.5. The future climate forcing for these RCP scenarios were obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5) runs with the IPSL-CM5 (Dufresne et al., 2013). The model is forced with daily temperature, precipitation, and cloudiness data which were constructed by interpolating monthly values. The peat initiation surface was constructed using peat basal age values (Chaudhary et al., 2020) and this surface determines the length of the simulated peat accumulation period. The climate data are divided in three different periods: Holocene climate, transient, and future runs. In the Holocene experiment, the model was run from prescribed basal ages in calendar years before present (cal. BP) until the year 1900. The basal age surface was constructed using 5,000 peat basal points from three published datasets (MacDonald et al., 2006; Gorham et al., 2007; Korhola et al., 2010). The details of the method of developing the basal age surface is given in Chaudhary et al., 2020. We used the delta-change method, that is, applying relative anomalies of temperature and precipitation, to develop the monthly climate forcing series. We extracted the climate anomaly data for the nearest global climate model gridcell corresponding to the modeled site location from the IPSL-CM5 and the linearly interpolated the climate anomalies values which were applied to the average monthly Climatic Research Unit gridded Time Series (CRU TS) 3.0 gridded climate data set (Mitchell & Jones, 2005) for that cell, from the period 1901–1930. This method conserves the interannual variability of temperature and precipitation from the baseline historical climate (1901–1930) throughout the simulation. In the transient run, the CRU TS 3.0 global gridded climate data set was used until the year 2005 and the future runs were performed from 2006 to 2100 using RCP warming scenarios. The model output variables examined for this study include recent and near-future pan-Arctic carbon accumulation rates, net primary productivity, decomposition rates, dominant plant cover and permafrost distribution. A detailed description of model structure, data requirement, and simulation protocol is available in Chaudhary et al. (2020) and references therein.

3. Results and Discussion

3.1. Peatland Carbon Accumulation Rates in the 21st Century

The modeled northern peatlands accumulated carbon at a rate of 20–35 g C m^{-2} yr^{-1} (0.05–0.15 PgC yr^{-1}) between 1901 and 2000 (Figures 1a and 1b) with an average of 25.3 g C m^{-2} yr^{-1} (0.08 PgC yr^{-1}). It was found that the carbon sink capacity of the peatlands remains almost stable for the low and intermediate scenarios and the carbon accumulation rates will largely remain in the range of average long-term Holocene carbon accumulation rates. On the other hand, the carbon accumulation rate sharply declines after 2050 under RCP8.5 and peatlands will become carbon neutral by the end of the 21st century. The rate of change in the net primary productivity and respiration rates remain almost identical leading to stabilization of carbon accumulation rates in the low and intermediate scenarios (Figures 1a and 3). However, the respiration rates override the gains of net productivity in RCP8.5 in the last few decades leading to the higher carbon release to the atmosphere (see Figure 3). It is interesting to note that there is virtually no difference between RCP2.6, RCP4.5, and RCP6.0, which indicates that peatlands are quite robust to future climate changes for a wide range of future warming trends (Figure 1). However, there is a clear temperature threshold to RCP8.5, beyond which the system starts behaving very differently, fully losing its capacity to sequester carbon by the end of this century.

Overall, it is projected that peatlands will reduce their carbon sink capacity and become carbon neutral by the end of this century in RCP8.5, while peatland carbon accumulation rates remain within the range of long-term Holocene carbon accumulation rates under the low and moderate warming experiments. The Siberian Lowlands, Hudson Bay and Eastern Russian peatlands sites are modeled the major carbon stock hotspot regions (Figure 1c). The total modeled northern peatland carbon stocks is around 516 PgC by the year 2000 which increases in the range of 531–533 PgC under the future warming scenarios (see Figure S1 in Supporting Information S1). This shows that peatlands will continue accumulating carbon and remain a major carbon sink by the end of the 21st century. However, their carbon sink capacity will be relatively reduced in extremely warming conditions.

If we look at the spatial distribution of peatland carbon accumulation rates, the majority of peatlands showed an increase in their carbon accumulation rates from the 19th to 20th century (Figure 2b). The mean carbon accumulation rates at the beginning of the 20th century were predicted to be around 25 g C m^{-2} yr^{-1} that steadily

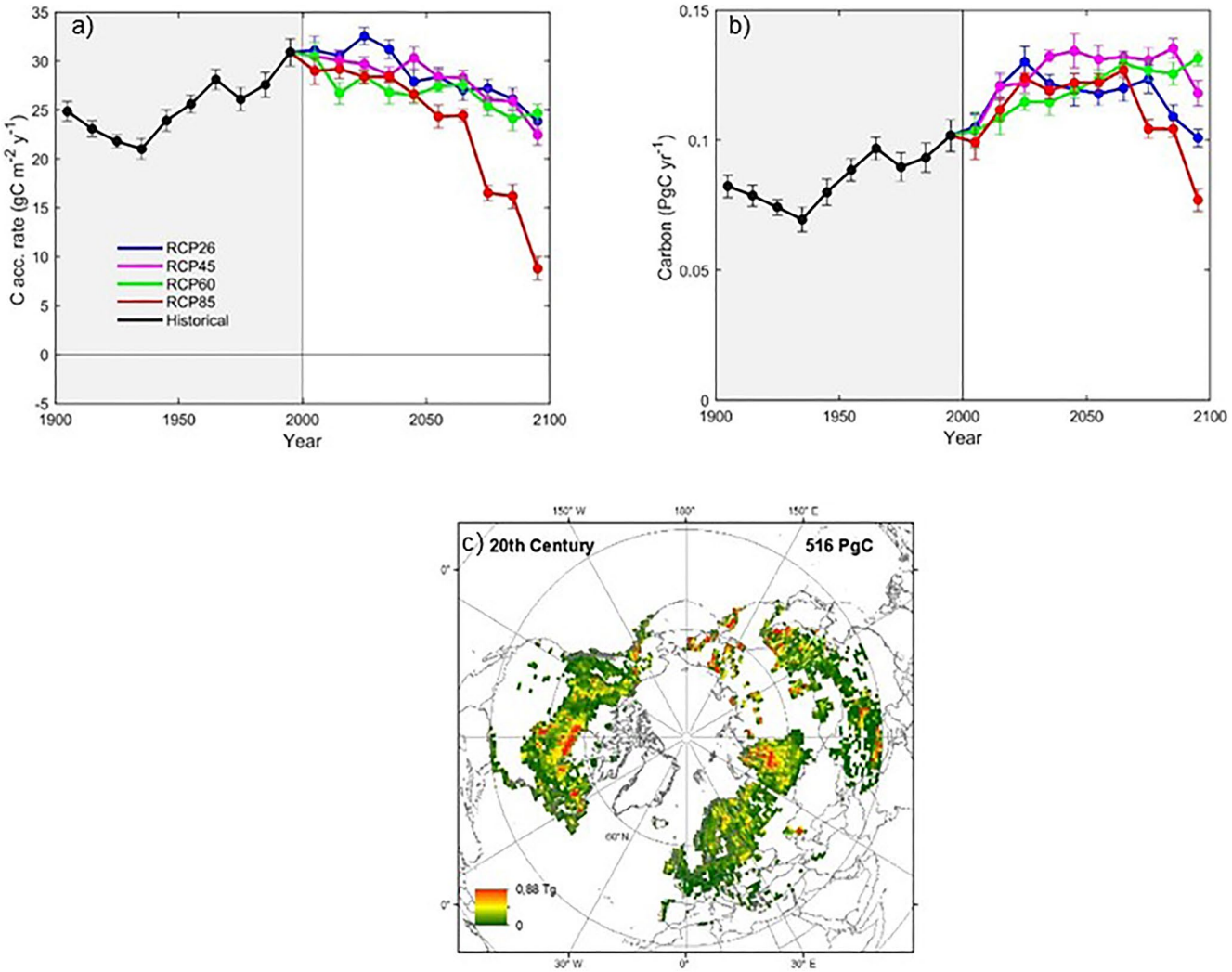

Figure 1. (a) Modeled carbon accumulation (decadal mean with standard error) rates for different Representative Concentration Pathway (RCP) scenarios, (b) modeled peat carbon accumulation (decadal mean in PgC yr^{-1}) and (c) distribution of peat carbon (in PgC) across the northern latitudes.

increased to 30–32 g C m^{-2} yr^{-1} by the end of the 20th century. Peatlands located in central and Eastern Europe, northeastern US, southeastern Canada and along the Russian-Chinese border were found to be most vulnerable to additional climate warming and predicted to become a strong source of carbon, as the climate becomes progressively warmer. Conversely, peatlands in Siberia, the Hudson Bay Lowlands and western Canada strengthen their carbon sink capacity. In short, low latitude peatlands are predicted to become a greater source of carbon, but other regions enhance their carbon sink capacity and counteract those losses in the model (Figures 2c–2j). The moderate warming since the 19th and 20th century benefited the overall peatland carbon accumulation rates, but this gain will be rapidly compensated by a warming-driven increase in decomposition rates in the last few decades of this century in extremely warm climates (RCP8.5) (Figures 1, 3 and S2 in Supporting Information S1). However, to better understand the differences between the scenarios, longer runs beyond 2100 are required to get a clearer picture of whether the rates stabilize or continue to decrease, in which case peatlands could eventually become a strong source of carbon.

3.2. Controls of Vegetation Productivity and Decomposition Rates on Peat Accumulation

The main uncertainties in quantifying the peatland carbon balance in the coming century arise from future trajectories of primary productivity and respiration rates. Some studies note that net primary productivity will

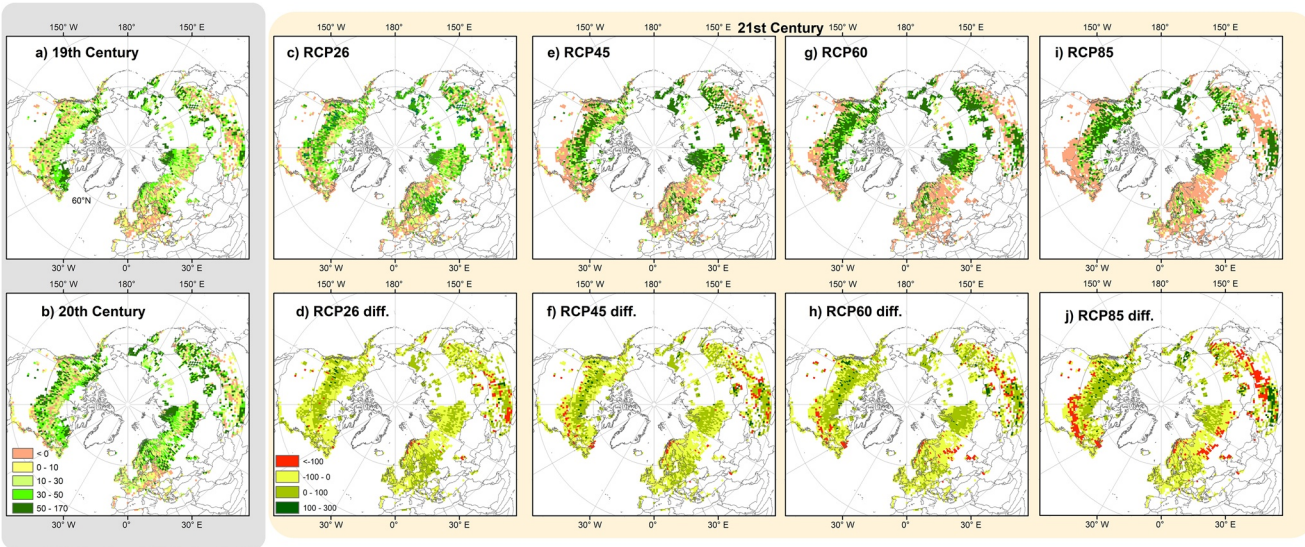

Figure 2. Modeled mean carbon accumulation rates (in g C m^{-2}) (a) 1891–1900, (b) 1991–2000, and (c–f) 2091–2100 across pan-Arctic under different Representative Concentration Pathway (RCP) warming scenarios.

override decomposition rates and accelerate the carbon accumulation (Wilson et al., 2017; Zhang, Gallego-Sala, et al., 2018), while others argue that the respiration rates remain high and gains in the net primary productivity do not catch up to temperature-driven microbial decomposition (Hugelius et al., 2020). Our results suggest that the soil respiration will override the increases in net primary productivity in the RCP8.5 experiment (Figures 3 and S3 in Supporting Information S1), while soil respiration and net primary productivity change by more similar magnitudes in the other scenarios, so that the overall carbon accumulation does not change strongly.

The main mechanism behind the higher productivity in the model is a temperature-dependent spring onset of photosynthesis which leads to a longer growing season in a warmer climate. This results in plants allocating additional production to the canopy, leading to increased leaf area and canopy growth, which further intercepts light and increases production. The increase in the modeled primary productivity is similar to the one observed in tundra warming experiments and satellite data (Berner et al., 2020; Olsrud et al., 2010). On the other hand, decomposition is exponentially related to soil temperature in the model, so temperature increases can substantially amplify the respiration rates. From Figures 3 and 4, it can be seen that the net primary productivity increases as the temperature gets warmer particularly in mid- and low-latitude regions, but the increase in net primary productivity is compensated by an increase in soil respiration rates. The respiration rates are higher in low-latitude regions and remain moderate in mid and high latitudes. In the low and intermediate scenarios, we see that the carbon accumulation rates remain stable and show some decrease in the last two decades. In RCP8.5, peatlands reduce their carbon sink capacity and become near neutral by the end of this century as ecosystem respiration will be equivalent to the net primary productivity.

The dominant plant type was determined by weighting the carbon mass of each plant type in the grid cell. Our results suggest that low latitude areas will be dominated by tall shrubs, while higher latitudes feature mosses, graminoids, and dwarf shrubs, collectively characterized as tundra vegetation (Figures 5a and 5b). As the climate gets warmer, high latitude plant types will lose their ecological niche in many areas. While areas with high moisture content maintain their plant cover assemblage of mosses and graminoids, some areas show encroachment by tall shrubs (Figures 5c–5f). The net primary productivity in these regions is projected to increase, leading to increased carbon accumulation in the soil. The underlying mechanism is longer growing season and increases in temperature that interacted with competition for light to allow taller shrubs to out-compete shorter ground vegetation. Shrub expansion and densification due to recent warming trends have been documented in many studies (Liljedahl et al., 2020; Rundqvist et al., 2011) which is in line with our findings.

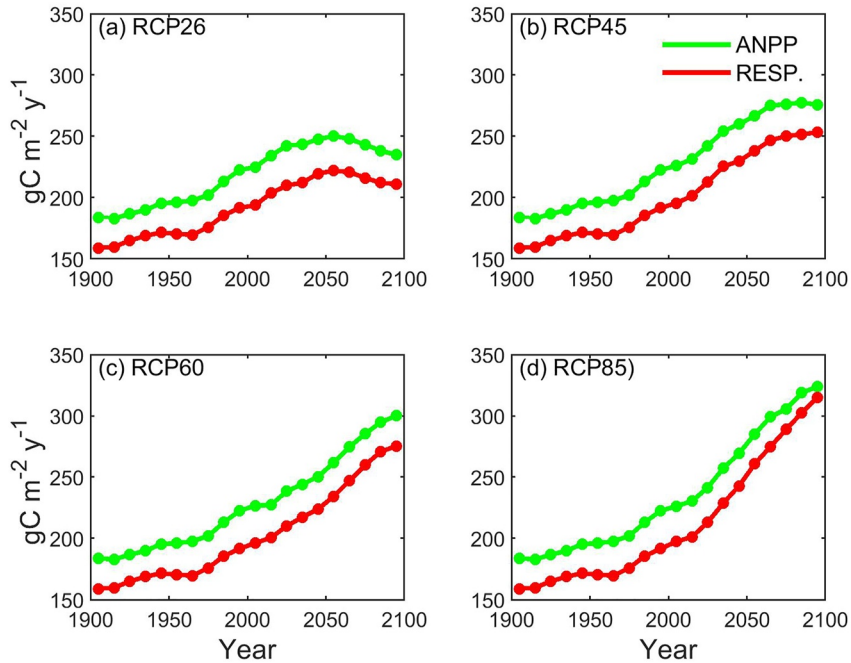

Figure 3. Modeled net primary productivity and respiration rates across pan-Arctic under different warming scenarios (ANPP—Annual net primary production and RESP—Annual heterotrophic respiration).

3.3. Permafrost Distribution

We found that almost 63% of peatlands were underlined by permafrost in beginning of the 20th century which reduced to 61% by the end of it. Hugelius et al. (2020) also found that that almost half of the peatlands are underlain by permafrost which affects their biogeochemistry and carbon cycle. Permafrost peatlands are characterized by ice-rich conditions and observations show that these ice-rich peatlands have been continuously thawing, which changes net primary productivity and carbon accumulation rates. Our simulation results suggest that today's permafrost peatlands start to thaw under all future warming scenarios, resulting in deeper active layer depths (Figures 6a and 6b), while the rate of permafrost loss is dependent on the warming scenario. In line with recent

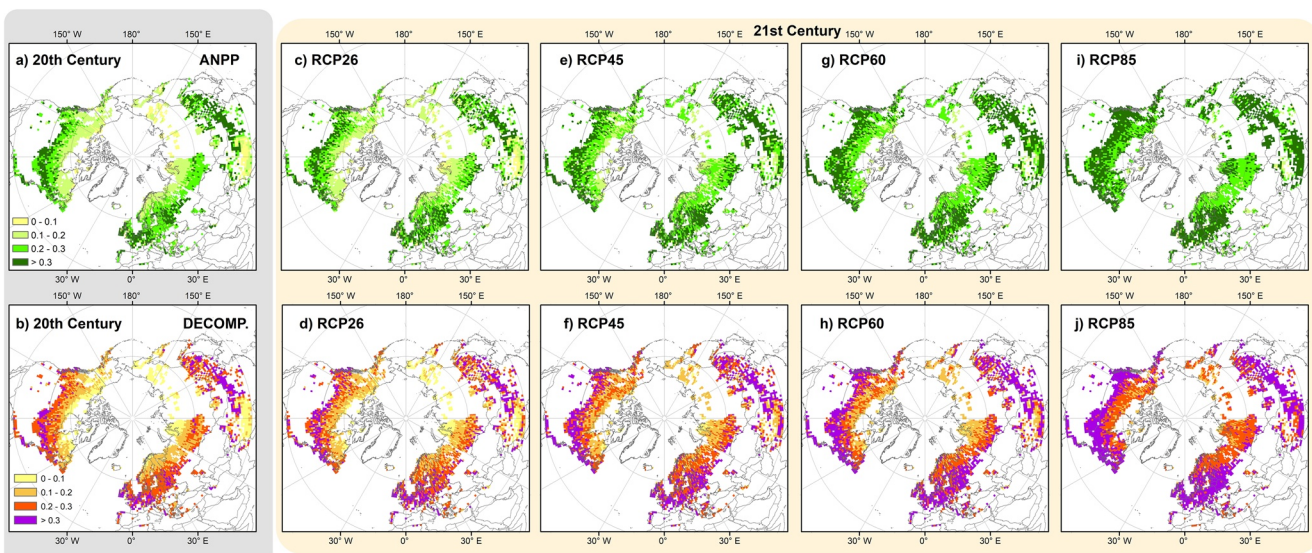

Figure 4. Modeled net primary productivity and peat decomposition rates (in kg C m^{-2}) (a and b) 1991–2000 and (c–j) 2091–2100 in northern peatland sites for different Representative Concentration Pathway (RCP) scenarios.

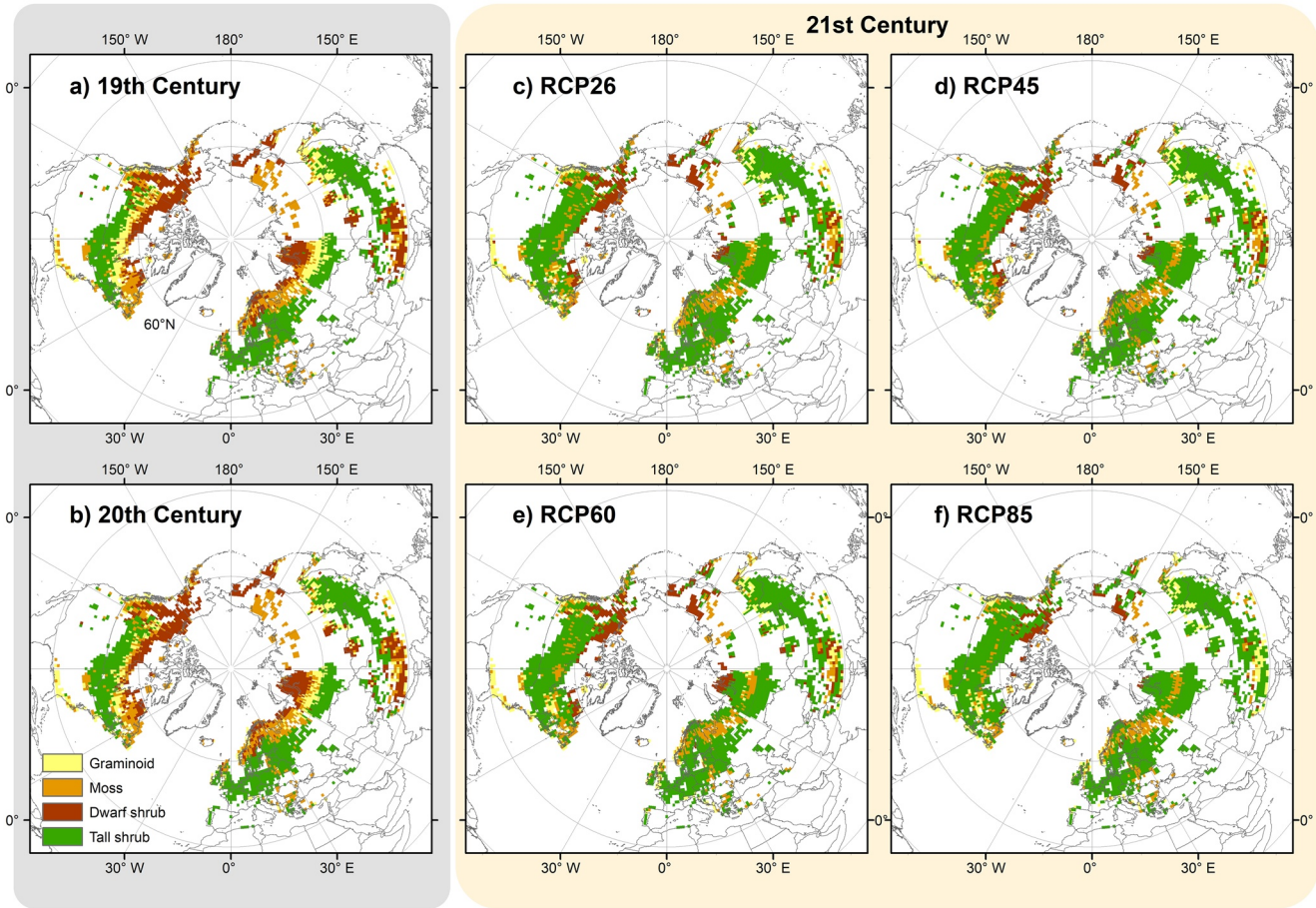

Figure 5. Modeled dominant plant types (a) 1891–1900, (b) 1991–2000 and (c–f) 2091–2100 in northern peatland sites under different Representative Concentration Pathway (RCP) scenarios.

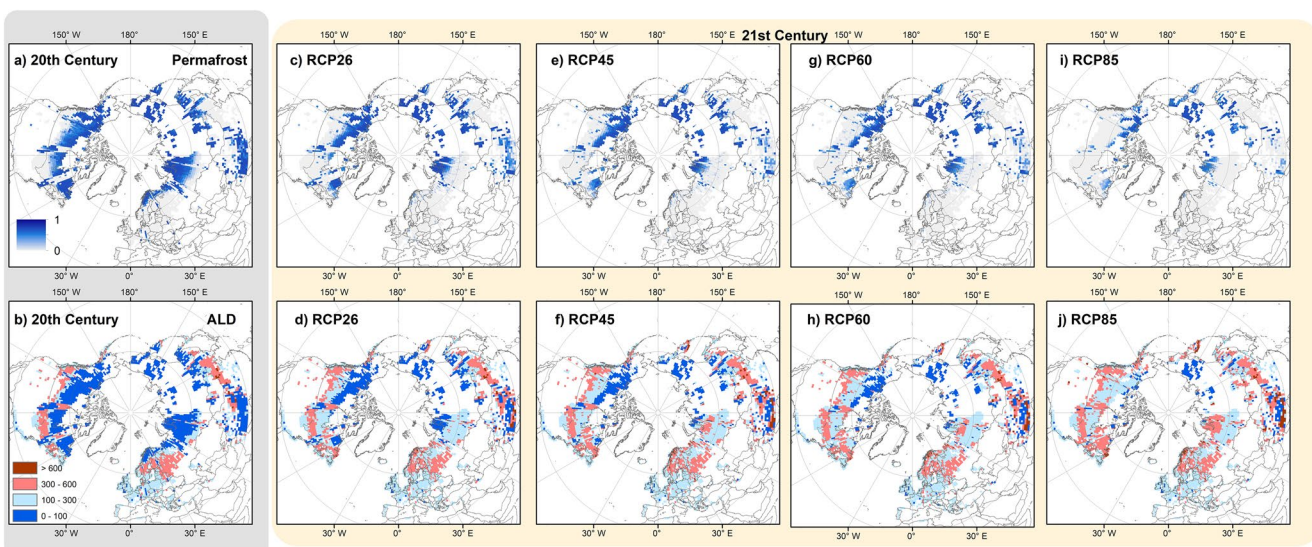

Figure 6. Modeled permafrost distribution (in fraction 0–1) and active layer depth (ALD in cm); (a and b) 1991–2000 and (c–j) 2091–2100 in northern peatland sites for different Representative Concentration Pathway (RCP) scenarios.

studies (Hugelius et al., 2020; Turetsky et al., 2019; Zhang, Piilo, et al., 2018), the permafrost extent starts shrinking from the southern limit in our simulations, creating space for new vegetation assemblages, which in turn modifies the carbon accumulation rates in those regions. During the permafrost thawing process, the vegetation can access water from the thawed soil leading to increase in plant productivity and accumulation rates. Permafrost-peatlands are predicted to completely disappear from many regions within a few decades, underlining their vulnerability to ongoing warming. According to our simulations, permafrost peatland fractions are predicted to reduce to 41%, 35.8%, 35.7%, and 28% under RCP2.6, RCP4.5, RCP6.0, and RCP8.5 respectively.

4. Conclusion

Peatlands are an important long-term carbon sink in the global climate system and the ongoing warming trend has the potential to modify the peatland carbon balance by the end of this century. In this study, we used a state-of-the-art peatland-vegetation model to simulate the peatland carbon balance in mid- and high-latitude regions of the Northern Hemisphere. We found that peatlands can largely retain their carbon sink capacity for the climate change scenario RCP2.6 to RCP6.0, but are projected to shift from a carbon sink to carbon neutral (~5–10 g C m^{-2} yr^{-1} and 0.04–0.06 PgC yr^{-1} in the strong warming scenario RCP8.5. While the past warming in the 19th and 20th century has increased the carbon accumulation rates across the pan-Arctic, those gains will be reversed by strong warming. Temperature driven higher respiration is the primary cause of larger CO_2 release from the peat soil in RCP8.5. Increase in CO_2 level in the atmosphere will further accelerate climate warming and will give rise to important climate-relevant feedbacks.

Data Availability Statement

Model output data can be downloaded from https://doi.org/10.5281/zenodo.6519772.

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References

Abdalla, M., Hastings, A., Truu, J., Espenberg, M., Mander, U., & Smith, P. (2016). Emissions of methane from northern peatlands: A review of management impacts and implications for future management options. *Ecology and Evolution*, *6*(19), 7080–7102. https://doi.org/10.1002/ece3.2469

Alessandri, A., Catalano, F., De Felice, M., Van Den Hurk, B., Doblas Reyes, F., Boussetta, S., et al. (2017). Multi-scale enhancement of climate prediction over land by increasing the model sensitivity to vegetation variability in EC-Earth. *Climate Dynamics*, *49*(4), 1215–1237. https://doi.org/10.1007/s00382-016-3372-4

Belyea, L. R. (2013). Nonlinear dynamics of peatlands and potential feedbacks on the climate system. In *Carbon cycling in northern peatlands*, (pp. 5–18). American Geophysical Union.

Berner, L. T., Massey, R., Jantz, P., Forbes, B. C., Macias-Fauria, M., Myers-Smith, I., et al. (2020). Summer warming explains widespread but not uniform greening in the Arctic tundra biome. *Nature Communications*, *11*(1), 4621. https://doi.org/10.1038/s41467-020-18479-5

Chaudhary, N., Miller, P. A., & Smith, B. (2017a). Modelling Holocene peatland dynamics with an individual-based dynamic vegetation model. *Biogeosciences*, *14*(10), 2571–2596. https://doi.org/10.5194/bg-14-2571-2017

Chaudhary, N., Miller, P. A., & Smith, B. (2017b). Modelling past, present and future peatland carbon accumulation across the pan-Arctic region. *Biogeosciences*, *14*(18), 4023–4044. https://doi.org/10.5194/bg-14-4023-2017

Chaudhary, N., Miller, P. A., & Smith, B. (2018). Biotic and abiotic drivers of peatland growth and microtopography: A model demonstration. *Ecosystems*, *21*(6), 1196–1214. https://doi.org/10.1007/s10021-017-0213-1

Chaudhary, N., Westermann, S., Lamba, S., Shurpali, N., Sannel, B. K., Schurgers, G., et al. (2020). Modelling past and future peatland carbon dynamics across the pan-Arctic. *Global Change Biology*, *26*(7), 4119–4133. https://doi.org/10.1111/gcb.15099

Dufresne, J. L., Foujols, M. A., Denvil, S., Caubel, A., Marti, O., Aumont, O., et al. (2013). Climate change projections using the IPSL-CM5 Earth System Model: From CMIP3 to CMIP5. *Climate Dynamics*, *40*(9–10), 2123–2165. https://doi.org/10.1007/s00382-012-1636-1

Gallego-Sala, A. V., Charman, D. J., Brewer, S., Page, S. E., Prentice, I. C., Friedlingstein, P., et al. (2018). Latitudinal limits to the predicted increase of the peatland carbon sink with warming. *Nature Climate Change*, *8*(10), 907–913. https://doi.org/10.1038/s41558-018-0271-1

Gorham, E., Lehman, C., Dyke, A., Janssens, J., & Dyke, L. (2007). Temporal and spatial aspects of peatland initiation following deglaciation in North America. *Quaternary Science Reviews*, *26*(3–4), 300–311. https://doi.org/10.1016/j.quascirev.2006.08.008

Hugelius, G., Loisel, J., Chadburn, S., Jackson, R. B., Jones, M., MacDonald, G., et al. (2020). Large stocks of peatland carbon and nitrogen are vulnerable to permafrost thaw. *Proceedings of the National Academy of Sciences*, *117*(34), 20438–20446. https://doi.org/10.1073/pnas.1916387117

IPCC. (2013a). Climate Change 2013: The physical science basis. *Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge University Press.

IPCC. (2013b). Summary for policymakers. In T. F. Stocker, D. Qin, G.-K. Plattner, et al. (Eds.), *Climate Change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change*, (pp. 1–30). Cambridge University Press.

Johansson, T., Malmer, N., Crill, P. M., Friborg, T., Akerman, J. H., Mastepanov, M., & Christensen, T. R. (2006). Decadal vegetation changes in a northern peatland, greenhouse gas fluxes and net radiative forcing. *Global Change Biology*, *12*, 2352–2369. https://doi.org/10.1111/j.1365-2486.2006.01267.x

Korhola, A., Ruppel, M., Seppa, H., Valiranta, M., Virtanen, T., & Weckstrom, J. (2010). The importance of northern peatland expansion to the late-Holocene rise of atmospheric methane. *Quaternary Science Reviews*, *29*(5–6), 611–617. https://doi.org/10.1016/j.quascirev.2009.12.010

Liljedahl, A. K., Timling, I., Frost, G. V., & Daanen, R. P. (2020). Arctic riparian shrub expansion indicates a shift from streams gaining water to those that lose flow. *Communications Earth & Environment*, *1*, 50. https://doi.org/10.1038/s43247-020-00050-1

Loisel, J., van Bellen, S., Pelletier, L., Talbot, J., Hugelius, G., Karran, D., et al. (2017). Insights and issues with estimating northern peatland carbon stocks and fluxes since the Last Glacial Maximum. *Earth-Science Reviews*, *165*, 59–80. https://doi.org/10.1016/j.earscirev.2016.12.001

MacDonald, G. M., Beilman, D. W., Kremenetski, K. V., Sheng, Y., Smith, L. C., & Velichko, A. A. (2006). Rapid early development of circumarctic peatlands and atmospheric CH_4 and CO_2 variations. *Science*, *314*(5797), 285–288. https://doi.org/10.1126/science.1131722

Mitchell, T. D., & Jones, P. D. (2005). An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *International Journal of Climatology*, *25*(6), 693–712. https://doi.org/10.1002/joc.1181

Müller, J., & Joos, F. (2021). Committed and projected future changes in global peatlands—continued transient model simulations since the Last Glacial Maximum. *Biogeosciences*, *18*(12), 3657–3687. https://doi.org/10.5194/bg-18-3657-2021

Olsrud, M., Carlsson, B. Å., Svensson, B. M., Michelsen, A., & Melillo, J. M. (2010). Responses of fungal root colonization, plant cover and leaf nutrients to long-term exposure to elevated atmospheric CO2 and warming in a subarctic birch forest understory. *Global Change Biology*, *16*(6), 1820–1829. https://doi.org/10.1111/j.1365-2486.2009.02079.x

Pinceloup, N., Poulin, M., Brice, M.-H., & Pellerin, S. (2020). Vegetation changes in temperate ombrotrophic peatlands over a 35 year period. *PLoS One*, *15*(2), e0229146. https://doi.org/10.1371/journal.pone.0229146

Qiu, C., Zhu, D., Ciais, P., Guenet, B., & Peng, S. (2020). The role of northern peatlands in the global carbon cycle for the 21st century. *Global Ecology and Biogeography*, *29*(5), 956–973. https://doi.org/10.1111/geb.13081

Ritchie, J., & Dowlatabadi, H. (2017). Why do climate change scenarios return to coal? *Energy*, *140*, 1276–1291. https://doi.org/10.1016/j.energy.2017.08.083

Rundqvist, S., Hedenås, H., Sandström, A., Emanuelsson, U., Eriksson, H., Jonasson, C., & Callaghan, T. V. (2011). Tree and shrub expansion over the past 34 years at the tree-line near Abisko, Sweden. *Ambio*, *40*(6), 683–692. https://doi.org/10.1007/s13280-011-0174-0

Saunois, M., Stavert, A. R., Poulter, B., Bousquet, P., Canadell, J. G., Jackson, R. B., et al. (2020). The global methane budget 2000–2017. *Earth System Science Data*, *12*, 1561–1623.

Smith, B., Prentice, I. C., & Sykes, M. T. (2001). Representation of vegetation dynamics in the modelling of terrestrial ecosystems: Comparing two contrasting approaches within European climate space. *Global Ecology and Biogeography*, *10*(6), 621–637. https://doi.org/10.1046/j.1466-822x.2001.t01-1-00256.x

Smith, B., Warlind, D., Arneth, A., Hickler, T., Leadley, P., Siltberg, J., & Zaehle, S. (2014). Implications of incorporating N cycling and N limitations on primary production in an individual-based dynamic vegetation model. *Biogeosciences*, *11*(7), 2027–2054. https://doi.org/10.5194/bg-11-2027-2014

Turetsky, M. R., Abbott, B. W., Jones, M. C., Anthony, K. W., Olefeldt, D., Schuur, E. A. G., et al. (2019). Permafrost collapse is accelerating carbon release. *Nature*, *569*(7754), 32–34. https://doi.org/10.1038/d41586-019-01313-4

Wilson, R. M., Fitzhugh, L., Whiting, G. J., Frolking, S., Harrison, M. D., Dimova, N., et al. (2017). Greenhouse gas balance over thaw-freeze cycles in discontinuous zone permafrost. *Journal of Geophysical Research: Biogeosciences*, *122*(2), 387–404. https://doi.org/10.1002/2016jg003600

Wramneby, A., Smith, B., & Samuelsson, P. (2010). Hot spots of vegetation-climate feedbacks under future greenhouse forcing in Europe. *Journal of Geophysical Research*, *115*(D21), D21119. https://doi.org/10.1029/2010jd014307

Xu, J. R., Morris, P. J., Liu, J. G., & Holden, J. (2018). PEATMAP: Refining estimates of global peatland distribution based on a meta-analysis. *Catena*, *160*, 134–140. https://doi.org/10.1016/j.catena.2017.09.010

Yu, Z. C. (2012). Northern peatland carbon stocks and dynamics: A review. *Biogeosciences*, *9*(10), 4071–4085. https://doi.org/10.5194/bg-9-4071-2012

Zhang, H., Gallego-Sala, A. V., Amesbury, M. J., Charman, D. J., Piilo, S. R., & Valiranta, M. M. (2018). Inconsistent response of arctic permafrost peatland carbon accumulation to warm climate phases. *Global Biogeochemical Cycles*, *32*(10), 1605–1620. https://doi.org/10.1029/2018gb005980

Zhang, H., Piilo, S. R., Amesbury, M. J., Charman, D. J., Gallego-Sala, A. V., & Valiranta, M. M. (2018). The role of climate change in regulating Arctic permafrost peatland hydrological and vegetation change over the last millennium. *Quaternary Science Reviews*, *182*, 121–130. https://doi.org/10.1016/j.quascirev.2018.01.003

Zhang, W., Döscher, R., Koenigk, T., Miller, P. A., Jansson, C., Samuelsson, P., et al. (2020). The interplay of recent vegetation and sea ice dynamics—results from a regional Earth system model over the Arctic. *Geophysical Research Letters*, *47*(6), e2019GL085982. https://doi.org/10.1029/2019gl085982

Zhang, W., Jansson, C., Miller, P. A., Smith, B., & Samuelsson, P. (2014). Biogeophysical feedbacks enhance the Arctic terrestrial carbon sink in regional Earth system dynamics. *Biogeosciences*, *11*(19), 5503–5519. https://doi.org/10.5194/bg-11-5503-2014

Zhu, X., & Zhuang, Q. (2016). Relative importance between biogeochemical and biogeophysical effects in regulating terrestrial ecosystem-climate feedback in northern high latitudes. *Journal of Geophysical Research: Atmospheres*, *121*(10), 5736–5748. https://doi.org/10.1002/2016jd024814