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**Assessing the impact of climate change on permafrost and the terrestrial carbon cycle in the northern high latitudes**

**Abstract:** Permafrost contains large quantities of frozen organic carbon, which is vulnerable to decomposition and release into the atmosphere when it thaws. This is expected to exacerbate the rate of global warming in a process known as the permafrost carbon feedback (PCF). There are many uncertainties associated with permafrost carbon processes, and they are not well-represented in Earth System Models (ESMs). Here, output of the new Met Office ESM (UKESM1) is analysed to assess the impact of four different climate change scenarios on permafrost extent and terrestrial carbon cycle response in the northern high latitude (NHL) regions. Although the NHL regions are projected to warm rapidly and large areas of near-surface permafrost to thaw under even mild climate change, the region is projected to remain overall a carbon sink under all four scenarios analysed. However, aspects of the current UKESM1 configuration limit its ability to replicate permafrost carbon dynamics well, which results in a high degree of uncertainty to the magnitude of the NHL terrestrial carbon cycle response.

## 1 Introduction:

Permafrost underlies nearly a quarter of the land mass of the northern hemisphere (Zhang et al., 1999) and contains 60% of the global mass of soil carbon (Hugelius et al., 2014). Over 90% of the permafrost affected area lies in the northern high latitudes region (NHL; regions above 60°N), which is warming at twice the rate of the global average, leading to widespread permafrost thaw (Biskaborn et al., 2019). As permafrost soils thaw, the carbon they contain becomes vulnerable to decay and subsequent release into the atmosphere, potentially amplifying the rate of global warming in a process known as the permafrost carbon feedback (PCF) (Schaefer et al., 2014).

Earth System Models (ESMs) simulate the complex feedbacks between terrestrial biogeochemical processes and the oceans and atmosphere, and are a powerful tool for understanding the evolution of the global climate. However, few ESMs currently represent permafrost carbon dynamics in depth, owing to an incomplete understanding of the details of some feedbacks, and limited data with which to benchmark models (Schuur et al., 2015). This investigation will assess the impact of climate change on permafrost extent and the terrestrial carbon cycle in the NHL regions as represented by the UK Earth System Model (UKESM1) under four scenarios developed for the sixth phase of the Coupled-Model Intercomparison Project (CMIP6; Eyring et al., 2016).

*Permafrost and the carbon cycle:*

Carbon fluxes in the NHL depend on how the rate of organic carbon decay in the soil is balanced by carbon uptake in plant biomass (Lawrence et al., 2015). Most observations suggest that the NHL region is currently acting as a weak carbon sink (McGuire et al., 2012), which has been linked to a trend towards increased net primary productivity (NPP) over the 20$^{th}$ century (Yu et al., 2017). However, some recent studies of carbon fluxes suggest that the NHL is beginning to become a source (Natali et al., 2019; Graven et al., 2013). Future trends will depend on how warming temperatures affect the balance between these processes (McGuire et al., 2016).

Warmer temperatures, particularly in winter and spring, cause an increase in depth of the active layer of the soil (the layer which thaws for at least part of the year), making more carbon vulnerable to decomposition (Lawrence et al., 2015). This also results in a greater availability of soil nutrients, especially nitrogen, which can stimulate productivity as NHL plant growth tends to be nitrogen-limited (Zielke et al., 2005). NPP also rises with warmer temperatures an increased atmospheric carbon dioxide ($CO_2$), resulting in greater uptake of soil carbon into biomass, thus compensating for any increase in carbon release.

Biomass productivity is also limited by levels of soil moisture. Permafrost thaw can significantly affect local land cover and hydrology, potentially causing either increased soil saturation as slumping land fills to become lakes, or drying as newly-mobilised groundwater connects previously isolated wetlands to drainage networks (Connon et al., 2014). Overall, permafrost thaw tends to lead to a general drying of upper layers of the soil as water drains through the soil column, which limits the release of carbon as methane ($CH_4$) as this requires waterlogged anaerobic conditions (Lawrence et al., 2015).

*Permafrost processes in ESMs:*

The complexities of these interactions, many of which take place on very local scales, make permafrost carbon dynamics difficult to capture in ESMs. While improvements have been made in modelling the processes associated with organic carbon decomposition, and the physics of freezing and thawing in the soil column, a large number of uncertainties remain (Schuur et al., 2015). Many of these relate to representation of terrestrial carbon cycle processes: the CMIP5 models showed a wide range of projections for trends in terrestrial carbon fluxes due to limitations in the modelling of key processes affecting carbon uptake and turnover (Todd-Brown et al., 2013). An additional challenge is the limited data available with which to benchmark models: permafrost is not straightforward to monitor, and the few datasets available are often dependent on observations that are unevenly distributed (Obu et al., 2019).

Key factors affecting the ability of ESMs to represent permafrost dynamics include the link between surface air temperature and ground temperature, which is dependent on the insulation of the soil column (Chadburn et al., 2015). In permafrost areas snow cover is the most important variable affecting this, and ESMs with the capacity to represent multiple layers of snow have been shown to represent insulation much more effectively (Wang et al., 2016). Soil column depth and discretisation affect the rate of change of temperature in the soil, and this varies considerably between models, with the CMIP6 ensemble having a range of between 2.0 and 65.6m, and between 4 and 25 layers (Burke et al., 2020). Many of the processes affecting permafrost thaw and carbon fluxes occur and the sub-cell scale, so parameterisation is important, particularly of hydrological processes (Swenson et al., 2012).

## 2 Method:

*Model description:*

The UK Earth System Model (UKESM1) consists of a core land-ocean-atmosphere model (HadGEM3-GC3.1; Williams et al., 2018) coupled with multiple component models representing different aspects of the Earth system (Sellar et al., 2019). In its low-resolution set-up the atmosphere and land are gridded at 1.25° x 1.875° resolution, while the ocean is gridded on a tripolar nominal 1° resolved grid. The atmosphere has 85 layers and the ocean 75 layers (Sellar et al., 2020). Couplings occur every three hours between the oceans and atmosphere, every hour between atmospheric components, every 45 minutes for oceans and sea ice, and every 20 minutes for land surface processes (Sellar et al., 2019).

Terrestrial biogeochemistry and land surface processes are represented by the land surface model JULES (Joint UK Land Environment Simulator; Best et al., 2011; Clark et al., 2011). Carbon fluxes on the land are driven by the dynamic vegetation model TRIFFID (Top-down Representation of Interactive Foliage and Flora Including Dynamics; Cox, 2001) linked with the RothC soil carbon model (Coleman and Jenkinson, 1999); carbon fluxes in the soil are limited by nitrogen availability (Sellar et al., 2019). Terrestrial carbon pools couple with the ocean and atmosphere. In its default configuration (JULES-ESM 1.0) the soil column is discretised into four layers, with depths of 0.1, 0.25, 0.65 and 2.0 m, for a total depth of 3.0 m. Thermal processes within the soil column, including the latent heat of freezing and thawing, are parameterised based on soil moisture (Chadburn et al., 2015).

*Approach:*

The data used for this investigation was derived from a single UKESM1 run using its default low-resolution setup. The run followed the historical setup from 1850-2014 (Eyring et al., 2016), and branched at 2015 into different scenarios for the years 2015-2100 based on shared socioeconomic pathways (SSPs) and climate outcomes for 2100 driven by prescribed radiative forcings (O'Neill et al., 2016). The scenarios investigated here are outlined in table 1 below.

| Scenario | Shared socio-economic pathway (SSP) | 2100 radiative forcing ($Wm^{-2}$) | Notes |
|---|---|---|---|
| SSP1-2.6 | SSP1 'Sustainability' | 2.6 | Sustainable development; limits warming to under 2°C |
| SSP2-4.5 | SSP2 'Middle of the road' | 4.5 | 'Middle of the road'; intermediate vulnerability and forcing |
| SSP3-7.0 | SSP3 'Regional rivalry' | 7.0 | High land-use change and emissions of $CH_4$ and tropospheric aerosols |
| SSP5-8.5 | SSP4 'Fossil-fuelled development' | 8.5 | Upper end of possible range |

*Table 1: Summary of the scenarios analysed in this investigation. Adapted from O'Neill et al. (2016)*

For each scenario, UKESM1 output was analysed to identify the seasonal temperature anomaly for the NHL, the global area of permafrost, and changes to the terrestrial carbon pool. The variables analysed to assess regional climate and permafrost distribution were monthly surface air temperature (at 1.5 m) and soil temperature (at a depth of 2.0 m). To assess changes in the terrestrial carbon pool, variables analysed were soil carbon, vegetation carbon, total land carbon, and net primary productivity. The regional focus was the northern permafrost zone, consisting of latitudes greater than 60°N.

Permafrost areas were identified following the criteria of Slater and Lawrence ( 2013) as cells where the annual mean soil temperature at a depth of 2.0 m remained below 0°C for at least two consecutive years. Since this is likely to prove an underestimate of areas of discontinuous permafrost, the isotherm of mean annual surface temperature of 0°C and -4.3°C were also calculated, as these closely define areas where there is respectively >1% and >50% likelihood of finding permafrost (Chadburn et al., 2017). The surface area was calculated based on the cell areas, taking into account the percentage of the cell filled by land. Anomalies in mean annual surface temperatures and mean carbon content in soil and vegetation were calculated relative to a baseline period of 1850-1900 calculated from the historical simulation.

**3 Results:**

The NHL are projected to warm at a dramatically faster rate than the global average under all scenarios, and this is trend is especially pronounced in the winter months, with average warming of up to 14°C compared to the 1850-1900 baseline projected for the Arctic winter even under SSP1-2.6. Under SSP5-8.5 the winter temperature anomaly approaches 25°C in the Arctic by the end of the century (figure 1).

As the temperatures in the NHL regions rise, the permafrost area is projected to shrink by 2100 under all scenarios.  Even under SSP1-2.6, much of the permafrost is projected to be lost in Siberia; under SSP5-8.5, it remains only in the furthest northern areas of Canada and Greenland (excluding the ice sheet). The reduction in size of the 0°C mean annual temperature isotherm indicates that large areas of discontinuous permafrost  will also be lost (figure 2).

| Scenario | Mean permafrost area 2090-2100 (million km$^2$) | Total area of permafrost lost compared to 1850-1900 baseline (million km$^2$) |
|---|---|---|
| SSP1-2.6 | 20.7 | 9.8 |
| SSP2-4.5 | 17.5 | 13.0 |
| SSP3-7.0 | 16.5 | 13.9 |
| SSP5-8.5 | 16.3 | 14.1 |

*Table 2: Permafrost area 2090-2100 and total area lost relative to the baseline, calculated based on the mean soil temperature at 2 m in depth (after Slater and Lawrence, 2013).*

NPP is projected to increase relative to the baseline across almost all of the NHL (figure 3). Carbon mass in the terrestrial carbon pools will also rise relative to the baseline in this region, although interestingly at the global level, vegetation carbon will decrease under SSP1-2.6, while soil carbon will decrease under the higher warming scenarios (figure 4).

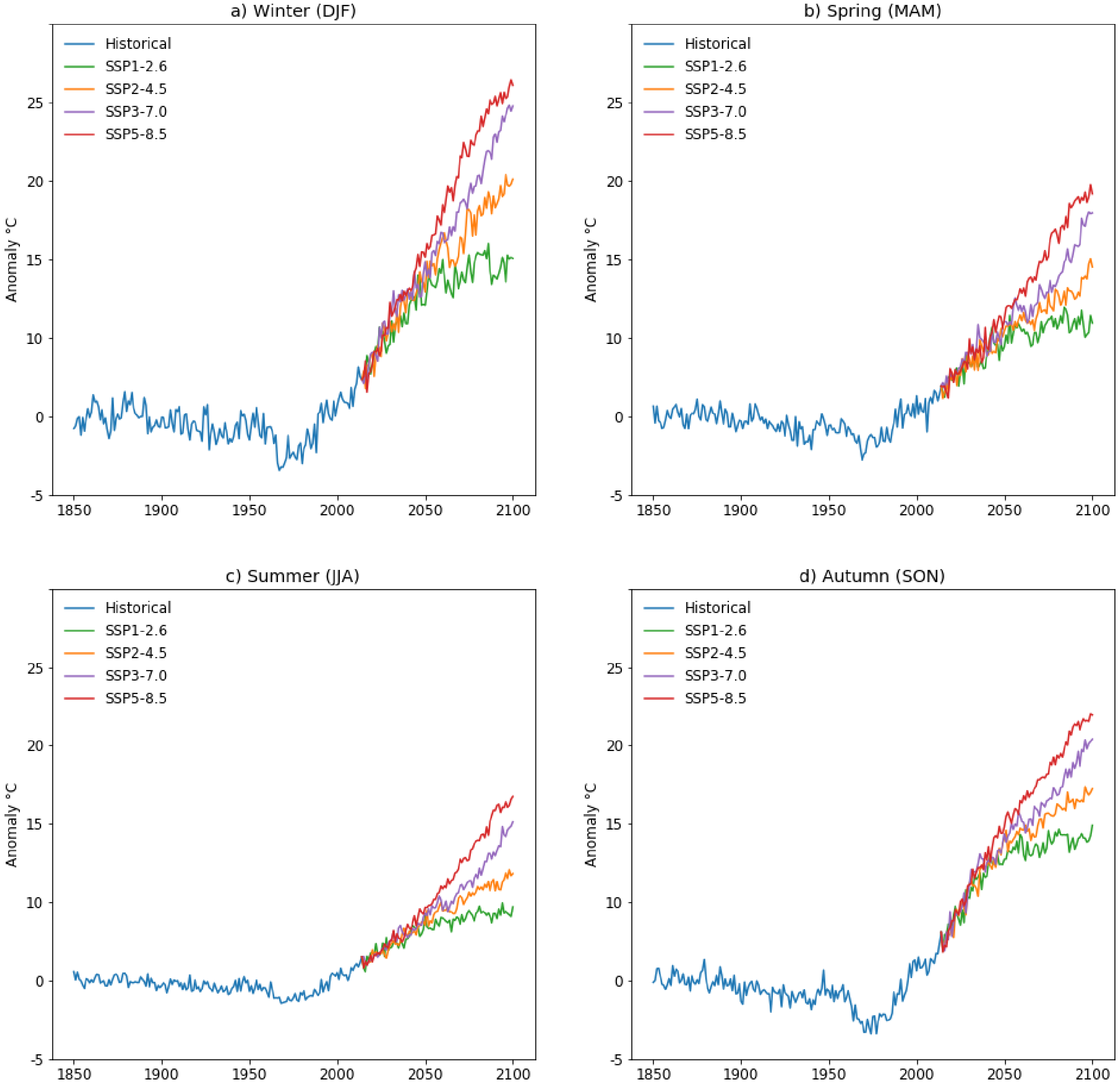


*Figure 1: Projected change in the mean seasonal temperature for the northern high latitude regions under different climate change scenarios. Anomaly is relative to a baseline of 1850-1900.*

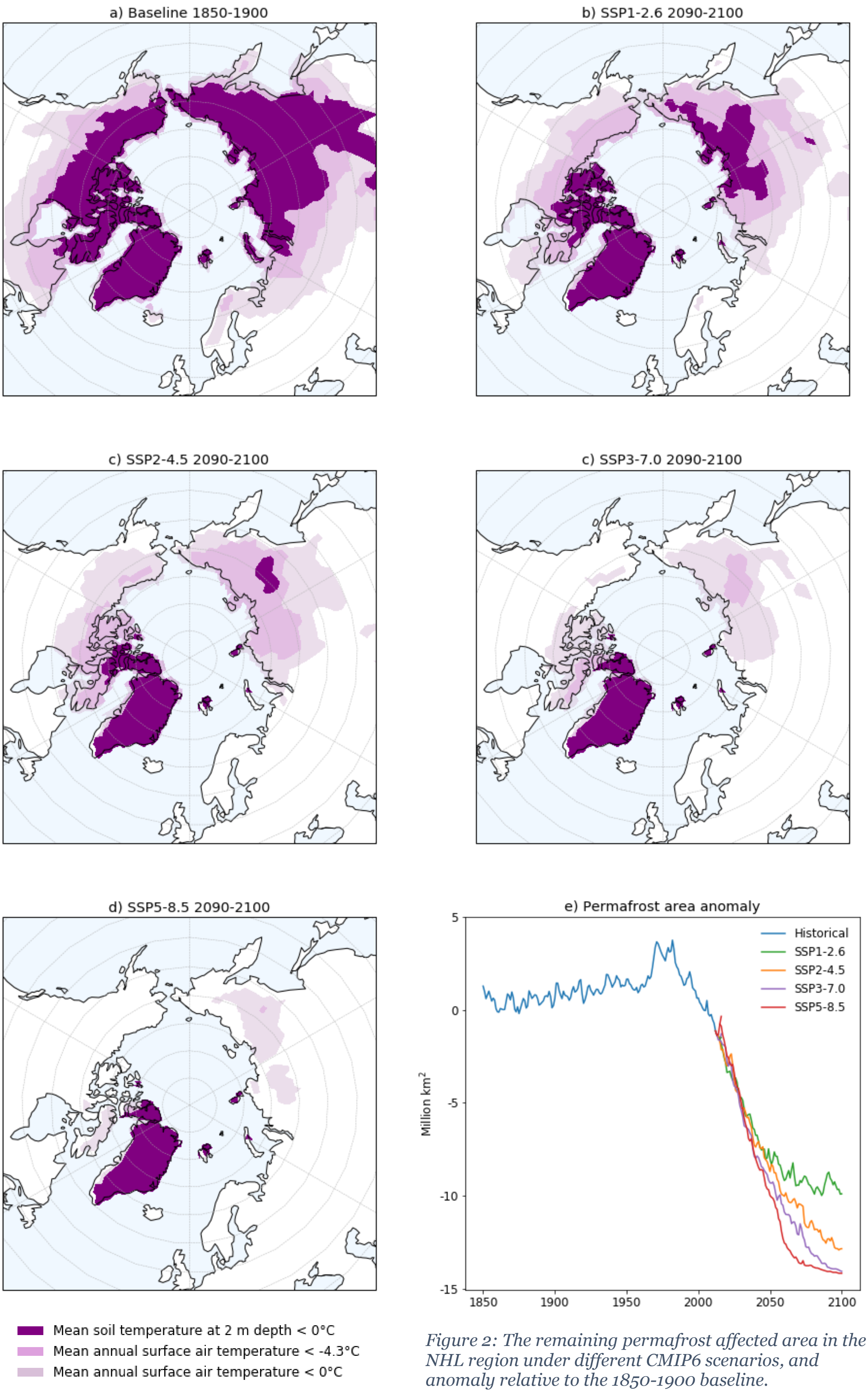


*Figure 2: The remaining permafrost affected area in the NHL region under different CMIP6 scenarios, and anomaly relative to the 1850-1900 baseline.*

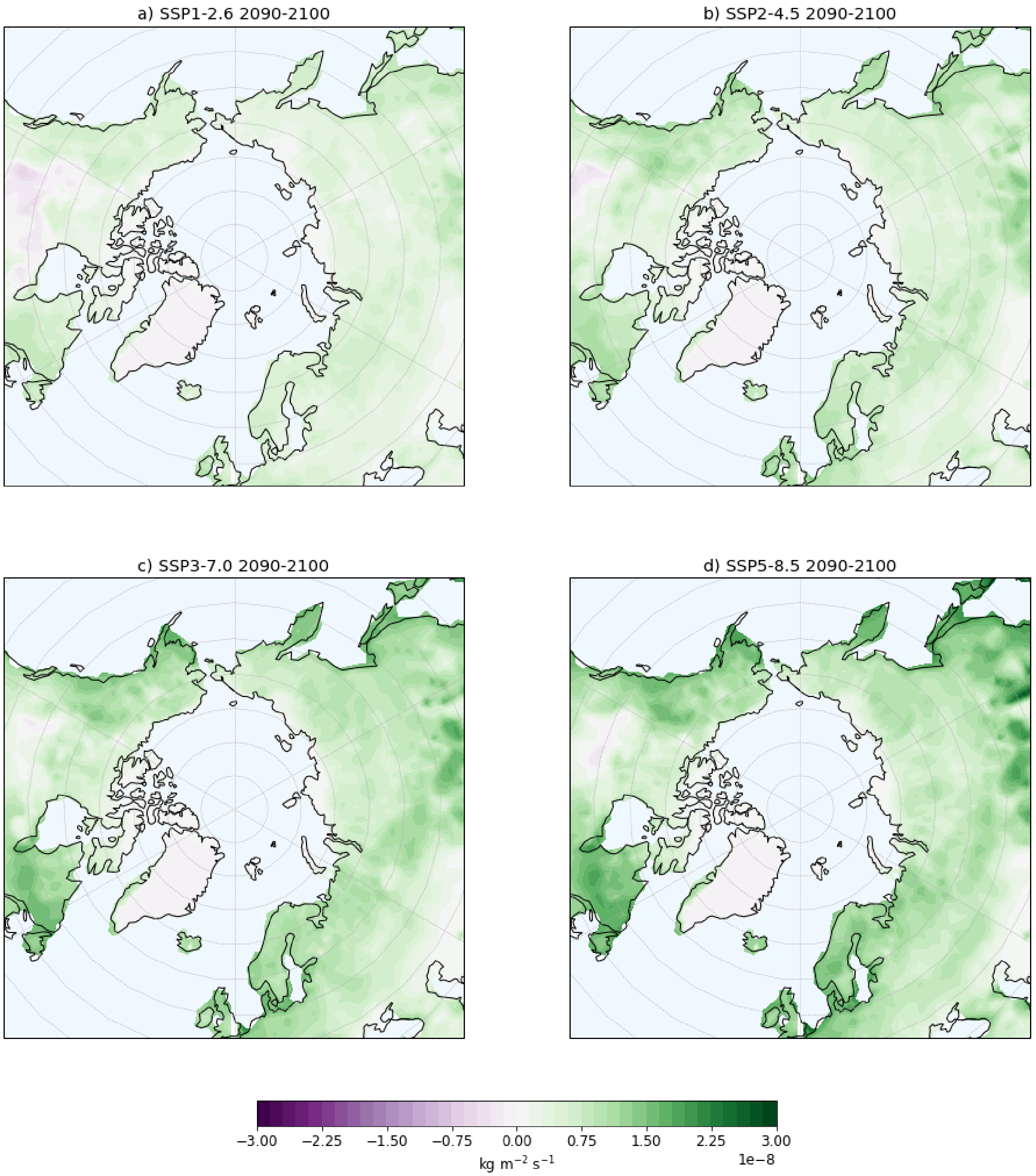


*Figure 3: Changes to the net primary productivity in the NHL regions relative to the 1850-1900 baseline.*

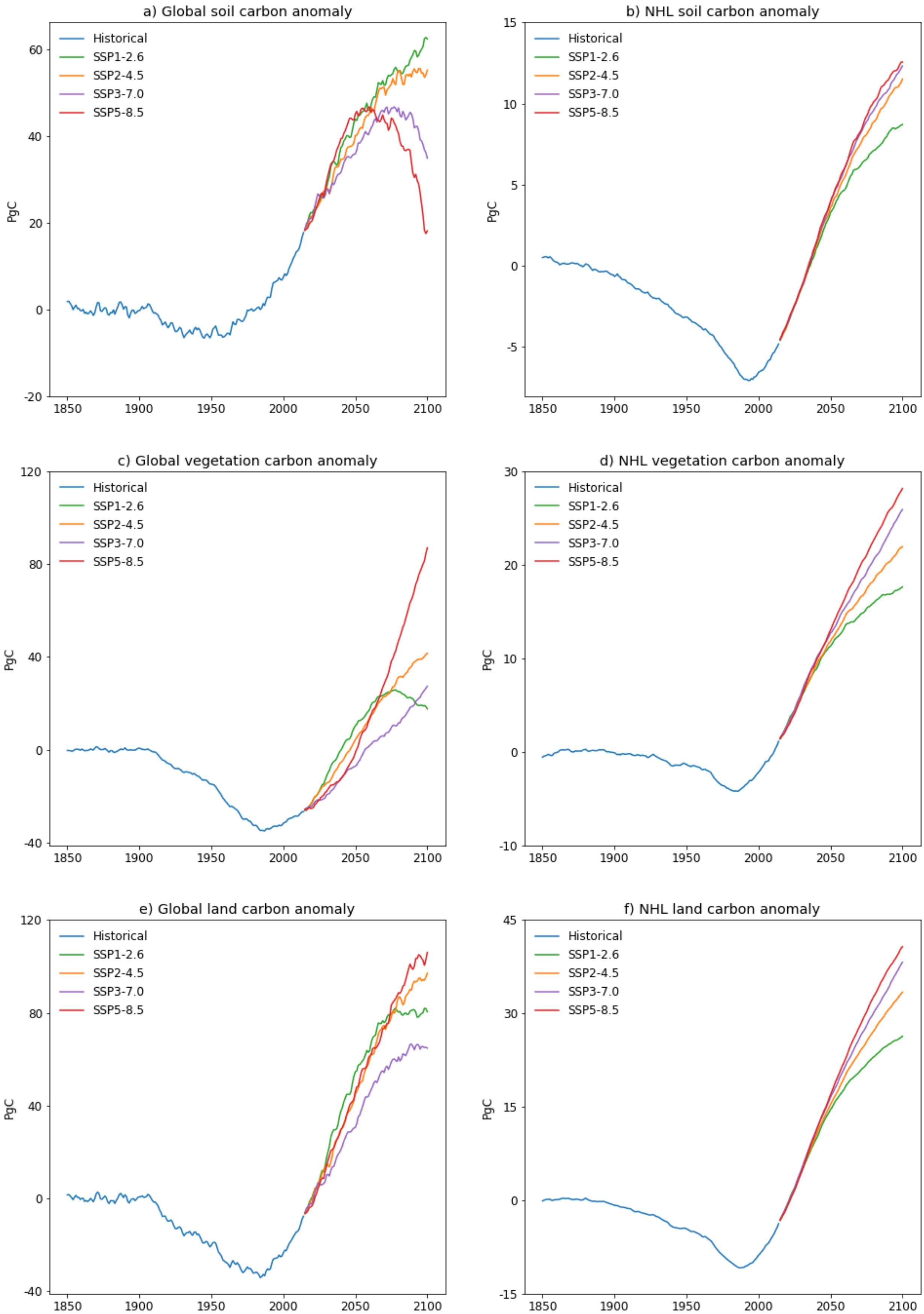


*Figure 4: Projected changes to terrestrial carbon pools under different CMIP6 scenarios. Anomalies are calculated relative to an 1850-1900 baseline.*

**4 Discussion:**

Extreme rises in temperatures in the Arctic is one of the most widely projected consequences of the rise in global mean temperatures (Taylor et al., 2013), largely due to surface albedo and temperature feedbacks (Pithan and Mauritsen, 2014). The high rates of warming in the winter and spring months are likely to lead to an overall increase in active layer thickness, and larger amounts of soil carbon at risk of decomposition.

This is in line with the large reductions in the permafrost-affected area projected under all scenarios. The decrease in area of the 0°C isotherm indicates a large loss in sporadic and discontinuous permafrost, which tends to thaw more quickly than deeper, colder deposits. The absolute permafrost areas calculated using the soil temperature diagnostic method are rather high (table 2), likely due to a failure to mask out areas of permanent ice such as the Greenland ice sheet; nonetheless the rate of change relative to the selected baseline is likely to be indicative, and is in line with projections from other models (Burke et al., 2020; McGuire et al., 2018).

Interestingly, the rate of permafrost loss does not appear to differ significantly between scenarios until 2050, will all four projecting a steep decline relative to the baseline (figure 2f). The sensitivity of permafrost response to changes in climate in the subject of some uncertainty; permafrost landscapes have been shown to decay extremely rapidly through thermokarst processes, even in areas that are extremely deeply frozen, (Olefeldt et al., 2016; Farquharson et al., 2019). Wildfires, projected to increase in many NHL regions, can destabilise permafrost deposits and exacerbate this kind of rapid thaw (Genet et al., 2013; Jafarov et al., 2013). This kind of abrupt thaw may mobilise as much as half of all carbon currently frozen in permafrost (Turetsky et al., 2020), but such rapid rates of decay are unlikely to be sustained once the most fragile sources have been exhausted (Schuur et al., 2015). Representing this in ESMs will be important for thoroughly exploring the effects of the PCF.

The continued uptake of carbon for all terrestrial sources in the NHL under climate change show that this region will continue to act as a carbon sink until 2100, in line with projections from previous CMIP phases (Qian et al., 2010). This is likely to be due to the increased NPP as a result of temperature rises in the spring and summer, higher rates of atmospheric $CO_2$ and increased nutrient availability, as evidenced by the increase in vegetation carbon uptake in the NHL and globally under all scenarios. This compensates even for the drop in global soil carbon under more extreme warming scenarios.

Soil carbon anomalies projected here may actually be a slight underestimate: UKESM1 does not explicitly represent permafrost carbon and as a result under-represents NHL soil carbon mass (Sellar et al., 2019). The nitrogen cycle representation within JULES is also likely to act to limit the uptake of soil carbon projected; the CMIP5 models tended to overestimate carbon uptake by the soil due to the lack of nitrogen limitation (Zaehle et al., 2014), and the JULES carbon-nitrogen coupling was explicitly tuned to avoid this (Sellar et al., 2019).

Even were UKESM1 to contain a more comprehensive representation of permafrost carbon, most impacts of the PCF are more likely to be felt after 2100 (Schaefer et al., 2014), so it is unsurprising that there is no obvious signal of an NHL carbon source in the UKESM data. Nevertheless, there are limitations to the current set-up of UKESM1 model which make modelling of permafrost carbon dynamics difficult . At 3 m deep, the soil column is too shallow to accurately represent changes in the active layer thickness (Chadburn et al., 2015), while the lack of vertical resolution of carbon in the soil column limits the ability to represent turnover times through the terrestrial carbon cycle (Koven et al., 2017). However, there do exist configurations of JULES where some of these issues are addressed (Burke et al., 2017), which may be included in future versions of the UKESM. Although this particular model run was driven by the prescribed forcings required under the scenarios, UKESM1 can be emissions driven, and there remain many possibilities for future experiments to explore carbon feedbacks from NHL ecosystems.

## 5 Conclusion:

The UKESM1 projections show enhanced warming in the NHL regions compared to the global average, and subsequent decline of permafrost affected areas under all scenarios. NPP increases in the NHL regions under all scenarios, and global terrestrial carbon uptake remains positive until the end of this century. However, there are still many uncertainties surrounding the modelling of the NHL response to climate change; the lack of explicit representation of permafrost carbon in UKESM is probably the most crucial.

Improving the representation of permafrost dynamics in ESMs is a matter of some urgency, given that additional warming due to the PCF may add to the already significant political and technical challenges linked to global attempts to keep global warming below 2°C in the longer term (Burke et al., 2018). The continued uptake of carbon into terrestrial pools until 2100 does suggest that there is significant potential to limit the PCF magnitude by taking action to reduce global greenhouse gas emissions, a fact that will be important to communicate to policy-makers (McGuire et al., 2016).

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