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LETTER

Subsea permafrost carbon stocks and climate change sensitivity estimated by expert assessment

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Abstract

The continental shelves of the Arctic Ocean and surrounding seas contain large stocks of organic matter (OM) and methane (CH_4), representing a potential ecosystem feedback to climate change not included in international climate agreements. We performed a structured expert assessment with 25 permafrost researchers to combine quantitative estimates of the stocks and sensitivity of organic carbon in the subsea permafrost domain (i.e. unglaciated portions of the continental shelves exposed during the last glacial period). Experts estimated that the subsea permafrost domain contains ~560 gigatons carbon (GtC; 170–740, 90% confidence interval) in OM and 45 GtC (10–110) in CH_4. Current fluxes of CH_4 and carbon dioxide (CO_2) to the water column were estimated at 18 (2–34) and 38 (13–110) megatons C yr^{-1}, respectively. Under Representative Concentration Pathway (RCP) RCP8.5, the subsea permafrost domain could release 43 Gt CO_2-equivalent (CO_2e) by 2100 (14–110) and 190 Gt CO_2e by 2300 (45–590), with ~30% fewer

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emissions under RCP2.6. The range of uncertainty demonstrates a serious knowledge gap but provides initial estimates of the magnitude and timing of the subsea permafrost climate feedback.

1. Introduction

Effective mitigation of climate change requires knowledge of human climate forcing and the ecosystem feedbacks that could amplify or stabilize the response of the Earth system (Lenton *et al* 2008, 2019). Due to complexity and limited data, quantitative estimates of some ecosystem feedbacks are not available and will not be available in the foreseeable future (Schuur *et al* 2013, Abbott *et al* 2016, Steffen *et al* 2018). This creates potentially severe knowledge gaps, where known but unquantified ecosystem feedbacks may be disregarded during the selection of climate targets and regulatory policies (Barrett and Dannenberg 2012, Turetsky *et al* 2020). One example of such an ecosystem uncertainty is the climate sensitivity of organic matter (OM) stored in permanently frozen ground, or permafrost, which is widely distributed in Arctic, Boreal, alpine, and subsea environments (Lindgren *et al* 2018, Biskaborn *et al* 2019, Martens *et al* 2019, Yang *et al* 2019). Recent research has improved understanding of the terrestrial climate feedback from permafrost (Schuur *et al* 2015, Mcguire *et al* 2018, Natali *et al* 2019, Turetsky *et al* 2020), but potential emissions from the subsea permafrost domain (figure 1) remain unknown because of limited observational data and modeling estimates (Schuur *et al* 2015, Shakhova *et al* 2017, Martens *et al* 2019). Consequently, this ecosystem feedback is virtually absent from climate policy discussions (table S1 available online at https://stacks.iop.org/ERL/15/124075/mmedia).

During the last glacial period (∼115 000–11 700 years BP), permafrost formed on exposed portions of the continental shelves surrounding the Arctic Ocean (Osterkamp *et al* 1989, Lindgren *et al* 2016). Unglaciated portions of the exposed continental shelves accumulated billions of tons of undecomposed plant material in frozen sediment (figures 1(a) and (c); Clark *et al* 2009, Tesi *et al* 2016, Lindgren *et al* 2018). Methane (CH_4) from biogenic and thermogenic sources accumulated within and below permafrost deposits, potentially in gas hydrate form (Frederick and Buffett 2014, Thornton and Crill 2015, Ruppel and Kessler 2017). After the Last Glacial Maximum (LGM, ∼26 500 BP), climate warming melted ice sheets and glaciers, which increased global sea level by ∼134 m on average (Clark *et al* 2009, Lambeck *et al* 2014), inundating more than 3 million km^2 of terrestrial permafrost (figure 1(a); Lindgren *et al* 2018, Overduin *et al* 2019). This marine transgression changed the thermal conditions of inundated permafrost, initiating warming and thawing of subsea permafrost that continue today (Hubberten and Romanovskii 2001, Shakhova *et al* 2009, Ruppel *et al* 2016). Because neither the amount nor climate sensitivity of subsea carbon stocks is known, the subsea permafrost domain remains one of the least-constrained ecosystem feedbacks in the Earth's climate system (Vonk *et al* 2012, Schuur *et al* 2015, Thornton and Crill 2015).

In this context, we used structured expert assessment (Schuur *et al* 2013, Morgan 2014, Sutherland and Burgman 2015, Abbott *et al* 2016) to explore how climate change could impact carbon dynamics of the complex and data-limited subsea permafrost domain. Expert assessment is an interdisciplinary approach often used for risk assessment and decision making in the face of uncertainty (Bamber and Aspinall 2013, Morgan 2014, Oppenheimer *et al* 2019). Using a quantitative questionnaire (supplementary information), we documented the understanding of 25 permafrost-zone researchers about carbon stocks in the subsea permafrost domain, defined as the unglaciated continental shelf areas exposed during the LGM that are currently inundated (figure 1). Our goals were to: (a). generate first-order estimates of OM and CH_4 stocks on the continental shelves, (b). assess risk of carbon dioxide (CO_2) and CH_4 release, (c). provide a long-term perspective on vulnerability of carbon currently being thawed from terrestrial permafrost, and (d). improve consideration of this Earth system feedback in climate policy circles. These goals have been identified as critical research priorities (Lenton *et al* 2008, Shakhova *et al* 2010, Thornton and Crill 2015, Lindgren *et al* 2018, Martens *et al* 2019), but given the scarcity of data and complexity of subsea permafrost, precise empirical or model-based estimates of the factors driving subsea permafrost dynamics are unlikely to be available in the near future. Consequently, we sought to combine the best available information on the subsea permafrost domain to inform policy and future research activities (Bamber and Aspinall 2013, Sutherland and Burgman 2015, Oppenheimer *et al* 2019).

2. Methods

Expert assessment has long been used to synthesize the best available information to inform policy and decision making (Joly *et al* 2010, Sutherland and Burgman 2015). It is particularly useful when the published scientific knowledge is not adequate for making decisions and the necessary research cannot be done before the decision must be made (Singh *et al* 2017, Oppenheimer *et al* 2019). While it does not generate definitive answers of system state

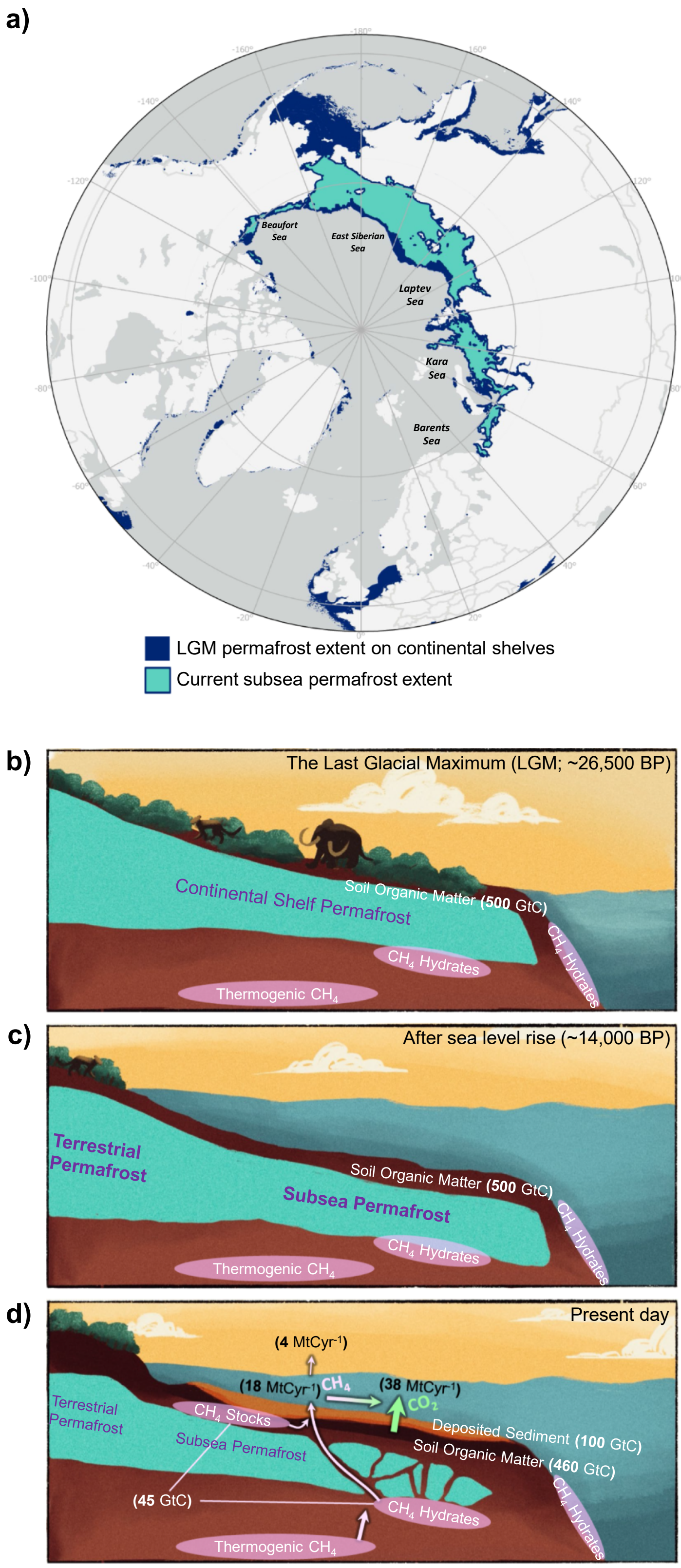

Figure 1. Extent and carbon dynamics of the subsea permafrost domain. We define the subsea permafrost domain as the unglaciated continental shelf areas exposed during the Last Glacial Maximum (LGM) that are currently inundated. (a) Extent of continental shelf permafrost at the LGM (data from Lindgren *et al* (2016)) and current subsea permafrost extent (data from Overduin *et al* (2019)). (b)–(d) Conceptual drawings of the thermal, physical, and biogeochemical changes initiated in the subsea permafrost domain by deglaciation and sea level rise. Major stocks are shown in white text and major fluxes are shown in black text. Soil organic matter (SOM) refers to the SOM that accumulated on the exposed continental shelf in tundra and steppe ecosystems prior to sea level rise (Lindgren *et al* 2018). *Deposited Sediment* refers to the sediment and associated organic matter eroded from coastal and terrestrial environments that was deposited on top of subsea permafrost during and after sea level rise (Vonk *et al* 2012, Tesi *et al* 2016). *CH_4 Stocks* and *CH_4 Hydrates* refer to methane trapped in the subsurface in free, dissolved, or clathrate states (Ruppel and Kessler 2017). Thermogenic CH_4 refers to methane formed abiotically in deeper geological processes (Thornton *et al* 2016a, Ruppel and Kessler 2017). The quantitative estimates of carbon pools (white) and fluxes (black) are the median values from this study (see text for uncertainty ranges).

or behavior, expert assessment provides subjective and holistic estimates that integrate a broad suite of information extending beyond well-established knowledge, including professional opinion, subjective confidence in published results, and proprietary information (e.g. industry knowledge) (Joly *et al* 2010, Morgan 2014).

Starting in December of 2018, we compiled all available articles and reports on subsea permafrost in a literature review of 92 articles published between 1949 and 2019. These studies included empirical (53%) and modeling (47%) approaches. We integrated findings from these studies into a background document distributed to all participants (supplementary information: Methods) to limit the effects of availability bias, where relevant information that is difficult to access may be unconsciously discounted (Morgan 2014). Based on this information and best practices from expert elicitation and assessment studies (Schuur *et al* 2013, Bamber and Aspinall 2013, Morgan 2014, Sutherland and Burgman 2015), we developed a structured questionnaire to collect central estimates and 90% confidence intervals of current, past, and future subsea permafrost carbon stocks and fluxes.

After testing with an initial group of 'lead experts,' we distributed the final questionnaire to a list of ∼120 permafrost researchers, including all co-authors of papers identified in the background literature review and referrals from invitees. Following several rounds of invitations, we received estimates from 25 experts (table 1), representing a 21% response rate, which is typical for this kind of assessment (Abbott *et al* 2016). Participants had experience with all major areas in the subsea permafrost domain, came from a variety of field and modeling backgrounds, and together represented over 180 cumulative years of research in subsea permafrost. In addition to quantitative estimates, respondents identified sources of uncertainty and provided self-ratings of their confidence and expertise. The number of responses per question ranged from 9 to 24, with a mean of 14 (table S2).

In addition to their central, 'best' estimate, we asked experts to provide a 90% confidence interval for each question. This process of considering the 'lower' and 'upper' plausible bounds—respectively defined as a 95% likelihood that the actual value is greater or lesser than this estimate—can help counteract expert tendency toward overconfidence, providing a more reliable measure of uncertainty (Aarstad 2010, Aspinall 2010, Koksalmis and Kabak 2019). To consider all expert input while not overemphasizing extreme values, we calculated the among-expert medians for the lower, best, and upper estimates. We performed calculations and created visualizations with the R software enfigurevironment for statistical computing (Core Team 2013). Detailed methods and descriptions of each calculation are provided in tables S3 and S4.

2.1. Results

2.2. Past and present subsea permafrost degradation and carbon dynamics

The median estimate by the group of experts for the area of formerly subaerial permafrost inundated after the LGM was 3.5 million km^2 (2.5–4.4; range is the 90% confidence interval), which agrees closely with estimates from the literature (Lindgren *et al* 2016, Overduin *et al* 2019). This estimate suggests the subsea permafrost domain is ∼1/5 the size of the terrestrial permafrost domain, which includes ∼18 million km^2 in the Northern Hemisphere (Hugelius *et al* 2014, Schuur *et al* 2015). Experts estimated that the current extent of subsea permafrost was ∼2 million km^2 (1–2.7; figure 2(a)), indicating a 42% decrease in subsea permafrost extent since the LGM (figure 2(a)). When calculated for each expert individually, the median decline in permafrost extent since the LGM was 47% (figure S3(a)).

Experts estimated that 500 gigatons carbon (GtC) (250–750) in soil organic matter (SOM) was stored in and on the continental shelves at the LGM (figure 2(b)). Expressed on an areal basis (i.e. 140 kg C m^{-2}), these estimates of SOM from the continental shelves are similar to carbon densities in the continuous permafrost zone (70–200 kg C m^{-2}), where SOM is often deposited many meters below the surface by periglacial processes (Hugelius *et al* 2014, Shmelev *et al* 2017, Lindgren *et al* 2018). Current SOM stocks were estimated at 460 GtC (150–540; figure 2(b)), indicating a median decrease of 10% of the SOM present at the LGM, based on the two unpaired distributions. However, when calculated for each expert individually, median SOM decreases were 33%–40%, suggesting substantial mineralization since the LGM (figure S3(b)). In their comments, experts attributed this decrease in SOM to microbial decomposition of OM to CH_4 and CO_2 after permafrost thaw (Thornton *et al* 2016a, Winkel *et al* 2018). Current stocks of OM in sediment deposited following the marine transgression were estimated at 100 GtC (23–200; figures 1(d) and 2(b)). Together, these estimates suggest that 560 GtC (170–740) of OM is currently stored in surface sediment and paleosols of the subsea permafrost domain (figure 1(d)).

Experts estimated a wide range of current CH_4 stocks with a median of 45 GtC (14–110; figure 2(c)). Based on expert comments, the main reason for this uncertainty was the extremely patchy spatial coverage of observations of CH_4 deposits, primarily hydrates, but also dissolved and free gas in sediment (figure 1(d)). Experts highlighted that estimating organic carbon content of surface sediments across the vast subsea permafrost domain is already chal-

Table 1. Composition and characteristics of expert respondents.

Survey section	Past and current extent	Past and current carbon stocks and fluxes	Future carbon stocks and fluxes
Average response per question	22	17	14
Primary region of study			
North America	11	8	10
Europe	2	2	2
Asia	8	7	8
Circumpolar	7	3	6
Average modeling/field self-rating[a]	2.5	2.4	2.5
Combined years of experience	183	130	121
Ratio male:female	17:8	11:7	13:6

[a] 1 was defined as exclusively field research and 5 as exclusively modeling research.

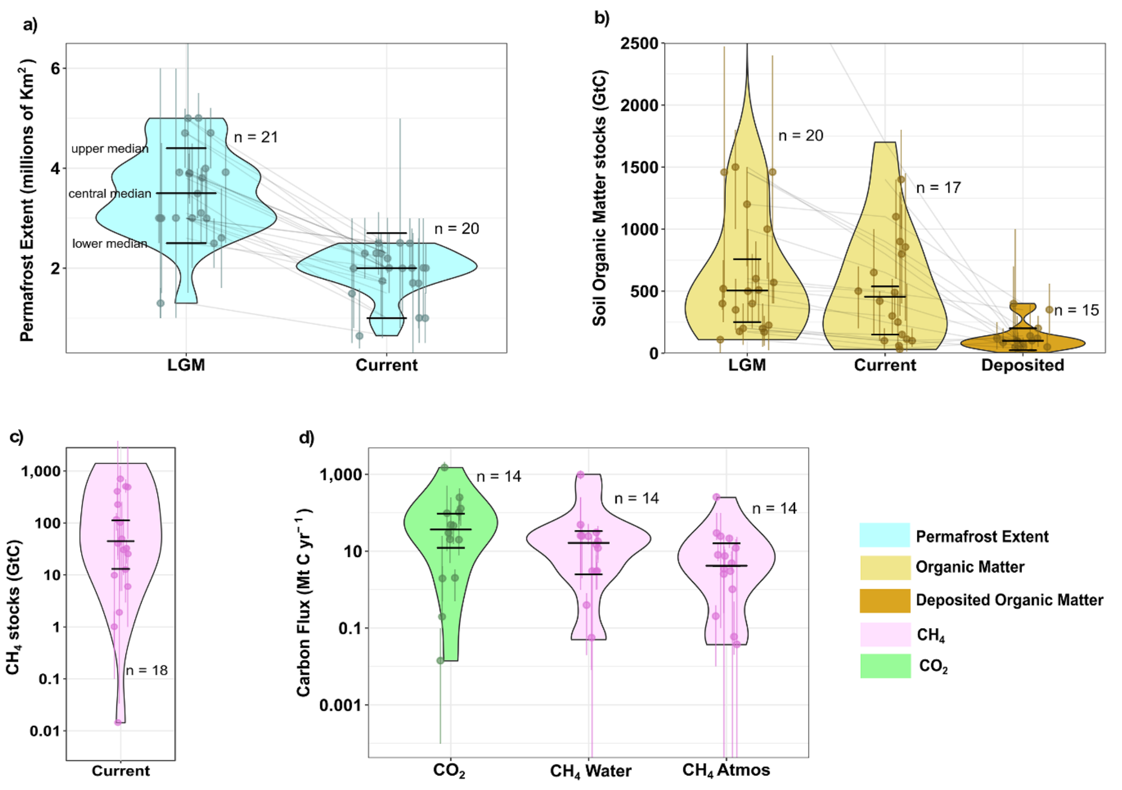

Figure 2. Violin plots showing carbon stocks and fluxes for the subsea permafrost domain. (a) and (b) Expert estimates of subsea permafrost extent and carbon stocks at the Last Glacial Maximum (LGM) and present. (b) Organic matter stocks including soil organic matter (SOM) at the LGM and present (Current), and sediment deposited since the LGM (deposited; figure 1). (c) Current methane (CH_4) stocks, including hydrates, dissolved, and free gas. (d) Carbon flux from sediment to the water column and from the water column to the atmosphere (for CH_4). For each parameter, experts were asked to give lower, central, and upper estimates, representing a subjective 90% confidence interval around a central value. For all panels, the individual expert estimates are represented as dots (central) and error bars (lower and upper), while the violin plots show the among-expert distribution of the central estimates (width indicates number of estimates in that range). The horizontal black lines indicate the among-expert medians of lower, central, and upper estimates. The faint grey lines in a and b group individual experts to emphasize pairwise differences among parameters. Number of respondents is indicated on or next to each violin plot (for questions that had several parts, the minimum n is shown). Detailed data and calculations shown in table S3.

lenging (Martens *et al* 2019), and quantifying CH_4 deposits requires more expensive and complicated drilling beneath the seafloor (Frederick and Buffett 2014, Ruppel and Kessler 2017). Experts mentioned that the scarcity of CH_4 observations is exacerbated by reluctance or legal prohibition of sharing data generated during research expeditions, energy exploration by private companies, and national security activities.

2.3. Present and future fluxes of CO_2 and CH_4

We asked experts to estimate potential changes in CO_2 and CH_4 flux for three climate scenarios from the IPCC Fifth Assessment Report (Moss *et al* 2010). The selected RCPs were RCP2.6, which has a peak concentration of ∼490 ppm CO_2-equivalent (CO_2e) reached before 2100, RCP4.5 with a peak of ∼650 ppm CO_2e at 2100, and RCP8.5 with a peak of ∼1400 ppm CO_2e at 2100 (Moss *et al* 2010, Koenigk *et al* 2013). There

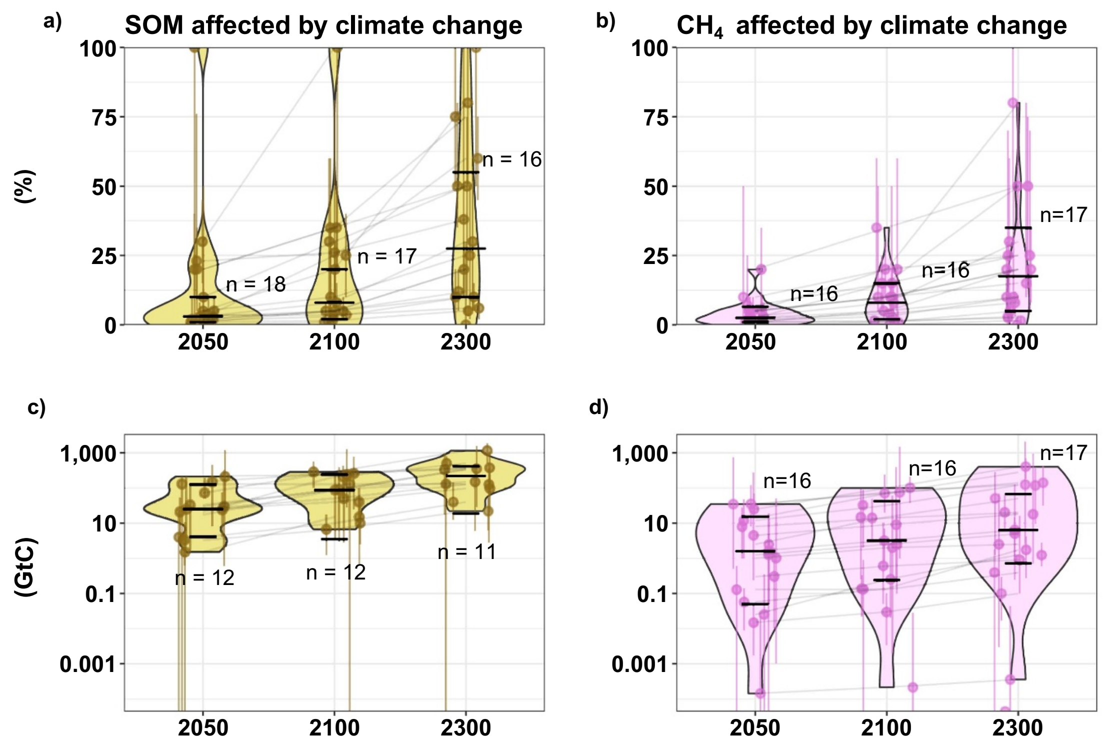

Figure 3. Expert estimates of organic matter (OM) and CH_4 stocks potentially affected by climate change. (a) and (c) OM and (b) and (d) CH_4 deposits that could experience a shift in thermal or chemical state because of anthropogenic climate change. Estimates expressed as percentage of the total stock affected in the top panels and affected mass in gigatons of carbon (GtC) based on the percentages and current estimates in the bottom panels. Symbology is the same as figure 2. Detailed data and calculations in table S4.

are many potential controls on greenhouse gas production and consumption in the subsea permafrost domain, including changes in temperature, microbial activity, sea level, altered chemistry in the Arctic Ocean, and changes in photosynthesis associated with loss of sea ice or changes in nutrient availability (supplementary information). Because of this complexity, we first asked experts to estimate the percentage of the subsea OM (including relict SOM and sediment deposited since the LGM) and CH_4 stocks that could be affected thermally or biogeochemically by any of the RCP scenarios.

For OM in 2050, 2100, and 2300, experts estimated that 3% (1–10), 8% (2–20), and 28% (10–55), respectively (figure 3(a)), could be influenced by climate change. This suggests that a globally-relevant store of OM may experience changes in physical or biogeochemical state due to anthropogenic climate change by 2100 (3.3–240 GtC) and 2300 (18–420 GtC; figure 3(c)). Experts estimated that a smaller percentage of CH_4 stocks would be affected by anthropogenic climate change, with median estimates of 2.5% (1–6.5), 8% (2–15), and 18% (5–35) by 2050, 2100, and 2300 (figure 3(b)). When combined with current estimates of CH_4 stocks (figure 2(c)), these percentages translate into highly uncertain but still substantial quantities of affected CH_4 by 2100 (0.2–42 GtC) and 2300 (0.6–64 GtC; figure 3(d)). Together, these estimates suggest that CH_4 in the forms of hydrates, dissolved, and free gas may be less sensitive to climate change than OM stored in the continental shelves. Experts suggested this could be due to the depth of some hydrate deposits and the combined effects of water pressure, temperature, and hydrate composition, which together determine the zone of hydrate stability (Frederick and Buffett 2014, Ruppel and Kessler 2017). These findings of relatively insensitive CH_4 deposits support the growing evidence from paleoclimate studies that subsea hydrates contributed minimally to the abrupt climate change and correspondingly abrupt increase in CH_4 at the beginning of the Holocene (Fischer *et al* 2008, Sowers 2010, Petrenko *et al* 2017, Dyonisius *et al* 2020) and during previous paleoclimate perturbations (Jurikova *et al* 2020).

The central estimates of present and future fluxes of CO_2 and CH_4 were highly dispersed, varying by a factor of 30, based on average range of lower and upper values for each expert (figures 2(d) and 4(a), (b)). For present conditions, the net CO_2 flux to the water column was estimated at 38 MtC yr^{-1} (13–110), though two high estimates were two orders of magnitude above that (figure 2(d)). We only asked for CO_2 flux estimates to the water column to avoid complexities associated with marine primary production, which is already included in Earth system models (Laufkötter *et al* 2015). For the current net flux of CH_4 to the water column, experts estimated 18 MtC yr^{-1} (2.3–34) and for the release to the atmosphere, they estimated 4.3 MtC yr^{-1} (3–16), indicating that ~75% of CH_4 released from sediment is oxidized before reaching the atmosphere (figure 2(d); Thornton *et al* 2016a). The experts projected that the amount of CH_4 flux to the atmosphere would have a net increase of 2% (0–3), 5% (1–8), and 4.5% (0.5–15) for RCP2.6 by 2050, 2100, and 2300, respectively; 5% (0.4–10), 10% (4.5–23), and 15% (5–60) for RCP4.5; and 10% (2.5–25), 25% (13–55), and 49% (16–80) for RCP8.5 on the same time steps (figure 4(b)). The estimates paired by expert indicated a 75% (72–79) decrease in added CO_2 emissions for RCP2.6 versus RCP8.5 and a 73% (70–89) decrease in added CH_4 emissions (figure S4).

To compare the overall climate forcing from the subsea permafrost domain, we converted CH_4 emissions into CO_2e, using the 100 year conversion factor of 28 from the IPCC Fifth Assessment Report (Schuur *et al* 2013, Abbott *et al* 2016). After conversion (table S5), CH_4 contributed more than half of the overall climate forcing, accounting for a mean of 65%, 67%, and 72% of the cumulative CO_2e releases for RCP2.6, RCP4.5, and RCP8.5, respectively (figure 5). Experts estimated substantially different responses depending on warming scenario, with the smallest increases associated with RCP2.6 and the largest with RCP8.5 (figure 4(a)). By 2050, 2100, and 2300, experts projected a change of 2% (0.1–3), 5% (1–10), and 4.5% (2–8) for RCP2.6; a change of 5% (0.5–10), 10% (3.5–30), and 28% (10–50) for RCP4.5; and a change of 10% (2.5–20), 20% (11–45), and 53% (20–100) for RCP8.5 (figure 4(a)).

When summed to estimate total climate forcing in CO_2e, the cumulative greenhouse gas release from the subsea permafrost domain under RCP2.6 was 11 Gt CO_2e (4–30) by 2050, 35 (10–83) by 2100, and 130 (34–270) by 2300. Under RCP4.5, cumulative greenhouse gas emissions were similar to RCP2.6 for 2050 and 2100—12 (5–32) and 38 Gt CO_2e (14–96), respectively—but higher for 2300: 150 Gt CO_2e (49–380). For RCP8.5, emissions were substantially higher across 2050, 2100, and 2300, with 13 (5–36), 43 (14–110), and 190 Gt CO_2e (45–590) released, respectively. Experts estimated substantially elevated emissions under all scenarios relative to current rates, with 35%–45% higher emissions by 2050, 50%–80% higher emissions by 2100, and 60%–135% higher emissions by 2300 (figure 5). Together, these results highlight how the permafrost domain continues to respond to past warming (i.e. after the LGM) yet is still sensitive to the degree of anthropogenic warming in the future.

3. Discussion

3.1. Slow but substantial climate forcing from subsea permafrost

Evaluating how much subsea permafrost has degraded and how much SOM has been decomposed since sea levels rose ~14 000 years ago (Church *et al* 2010) can provide perspective on the current permafrost climate feedback. If the expert range of estimates of 30%–50% decline in area and 33%–40% decline in OM stocks are reliable (figure S3(b)), this suggests that the subsea permafrost system responds relatively slowly (i.e. millennial timescales) to climate change, and that anthropogenically-driven changes may only substantially alter subsea permafrost dynamics several hundreds or thousands of years from now. However, if the expert estimates of current carbon fluxes are reliable, the subsea permafrost domain is already contributing regionally and globally relevant quantities of greenhouse gases to the Arctic Ocean and atmosphere in response to paleoclimate changes since the LGM. Our results suggest the ocean-atmosphere flux of CH_4 from the subsea permafrost domain equals 10%–40% of CH_4 release from the five-fold larger terrestrial permafrost zone (Mcguire *et al* 2009). This range is bracketed by low (Thornton *et al* 2016a) and high (Shakhova *et al* 2013, Thornton *et al* 2016b) field estimates from the East Siberian shelf. Furthermore, our estimates suggest that subsea CO_2 flux could already be offsetting 10%–20% of the terrestrial permafrost carbon sink (Mcguire *et al* 2009).

Considering future emissions scenarios, the net ecosystem carbon balance of the subsea permafrost domain was projected to be negative under all scenarios (i.e. net loss to the atmosphere) in our study. This contrasts with estimates of future carbon balance in the terrestrial permafrost zone, where both positive and negative projections are considered plausible (Mcguire *et al* 2018). Under RCP4.5, the multimodel median of terrestrial permafrost carbon balance projects net removal of 140 and 94 Gt CO_2 from the atmosphere by 2100 and 2300, respectively (Mcguire *et al* 2018). Our central estimates suggest that the subsea permafrost zone could offset 27% of that uptake by 2100 and 160% of that uptake by 2300, i.e. releasing substantially more greenhouse gas than the terrestrial permafrost zone removes. Under RCP8.5, the terrestrial permafrost zone is expected to release 16 GtC by 2100 and 220 GtC by 2300 (Mcguire *et al* 2018). Our central results suggest that subsea carbon release could augment this terrestrial release by 32% in 2100 and 8% in 2300. Considering the upper estimates from our study, the subsea permafrost domain could augment terrestrial release by 100% in 2100 and 34% in 2300. These simplified comparisons suggest that the subsea permafrost domain may play an outsized role in determining the overall carbon balance

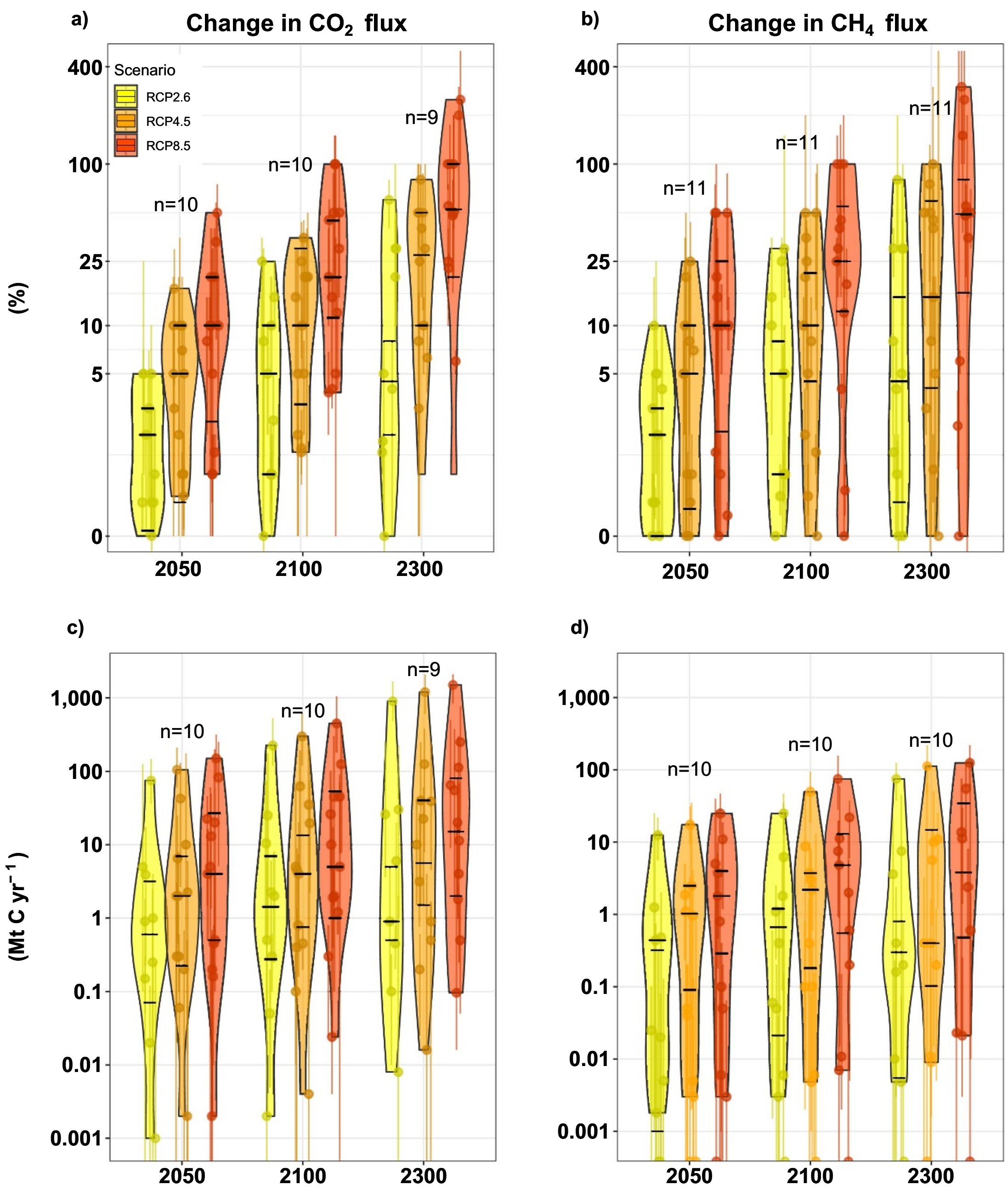

Figure 4. Expert estimates of changes in CO_2 flux to the water column and CH_4 flux to the atmosphere in response to climate scenarios RCP2.6, RCP4.5, and RCP8.5. Upper panels represent percentage of change directly asked by experts (hyperbolic sine function is used for y axis scale for ease of visualization). Bottom panels represent the net flux change in Mt C yr^{-1} which was calculated using the current estimates and the percentage of changes. Symbology is the same as figure 2. Detailed data and calculations in table S5.

of high latitude ecosystems. More generally, the carbon stocks and current and future emissions from the subsea permafrost domain are large relative to the geographical size of this region: ∼0.4% of the Earth's surface area but up to 2% of global CH_4 release and 31% of oceanic surface sediment carbon (Saunois *et al* 2016, Friedlingstein *et al* 2019). This suggests that the subsea permafrost domain is already a hot spot of carbon storage and greenhouse gas release, justifying increased ecological research and monitoring.

The expert estimates from this study suggest that contemporary CO_2 and CH_4 emissions from the subsea permafrost domain are sensitive to anthropogenic climate change on decadal timescales. However, compound uncertainties surrounding the terrestrial and subsea permafrost climate feedbacks mean that the relative importance of these environments in determining greenhouse gas release will remain unknown until better empirical and modeling estimates are available (Mcguire *et al* 2018, Overduin *et al* 2019, Turetsky *et al* 2020). We emphasize that

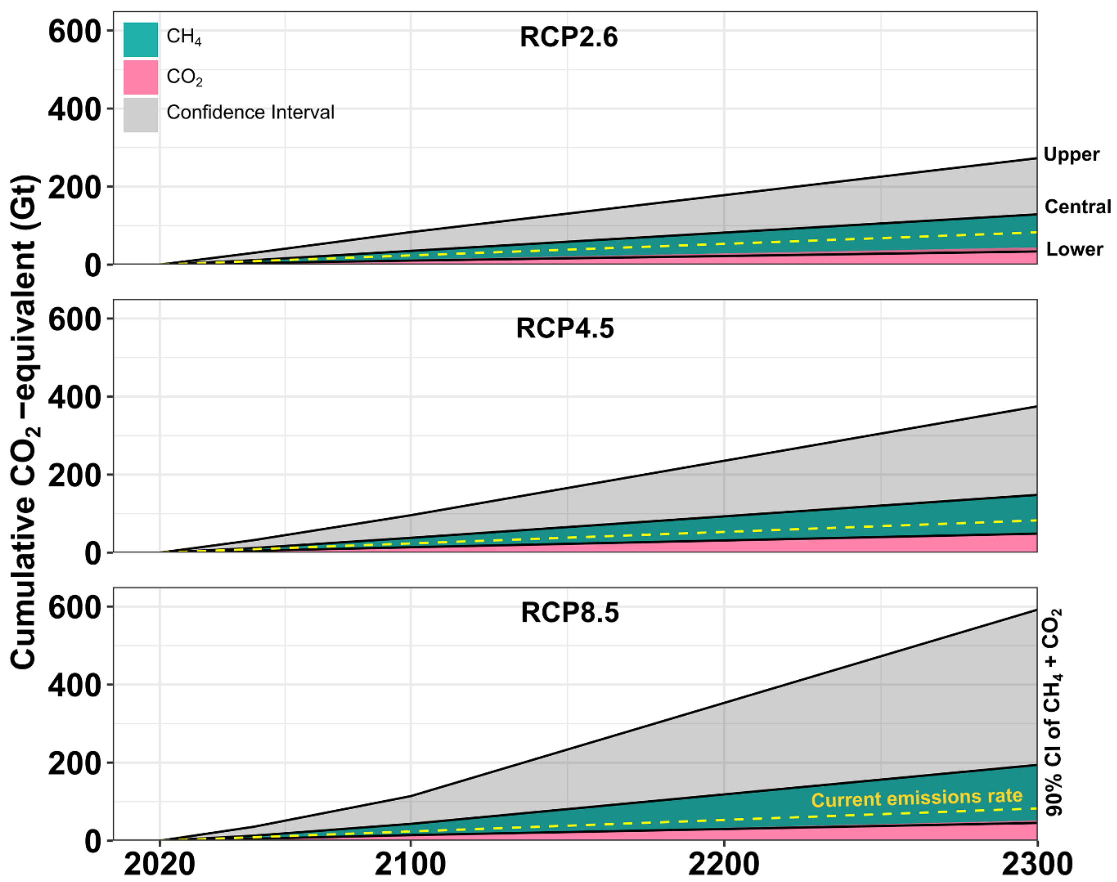

Figure 5. Expert estimates of the cumulative greenhouse gas emissions in CO_2-equivalents (CO_2e) from the subsea permafrost domain for RCP2.6, RCP4.5, and RCP8.5. The median lower, central, and upper estimates are represented by solid black lines, with the grey fill between them denoting the qualitative 90% confidence interval. The relative contributions of CH_4 (normalized to CO_2e) and CO_2 for the central estimates only are shown in pink and blue. For reference, the yellow dashed line shows the cumulative CO_2e if emissions from subsea permafrost were to remain at current rates through 2300. Detailed data and calculations in table S5.

because the subsea and terrestrial permafrost zones are fundamentally linked (Vonk *et al* 2012, Tesi *et al* 2016), understanding the fate of old and new OM on the continental shelves of the Arctic Ocean basin should be a research priority.

3.2. Uncertainties of subsea permafrost estimates and greenhouse gas exchange

Based on expert comments, the primary contributor to uncertainty in the subsea permafrost domain is insufficient field observations. Almost every expert mentioned this conspicuous knowledge gap. The lack of data reduces the reliability of estimates of carbon pools and fluxes as well as the thermal and hydrological conditions of submerged permafrost. Experts pointed out that our ignorance of terrestrial and marine permafrost linkages does not simply create uncertainty in current estimates, it limits our ability to anticipate thresholds and unexpected linkages. For example, the subsea permafrost climate feedback could follow qualitatively different trajectories than identified here, if changes in Arctic runoff, sediment balance, and sea ice alter organic carbon inputs or the location of the CH_4-hydrate stability zone (Lenton *et al* 2008, Wrona *et al* 2016, Bamber *et al* 2018, Trusel *et al* 2018). Specific questions raised by experts that cannot currently be answered with satisfactory certainty include: what were rates of sedimentation and OM burial at the sea bottom during the last several thousand years (Martens *et al* 2019); what was and is the vertical and lateral distribution of carbon (OM and CH_4) in paleosols and marine sediments on the continental shelves (Lindgren *et al* 2018); how much local variability was there in climate and ecosystem type before the LGM (Huang *et al* 2017); what was the effect of marine transgression on the OM stocks of shelf sediments and their resulting re-distribution (Winterfeld *et al* 2011, Günther *et al* 2013); and where are different kinds of microbial metabolism active in the subsea permafrost domain (Overduin *et al* 2015, Winkel *et al* 2018)?

One unexpected finding of this research was that the dearth of data on the subsea permafrost domain is partially due to divisions in the subsea permafrost research community. While previous expert assessments on other topics have always involved strong opinions and evidence-based disagreements (Schuur *et al* 2013, Abbott *et al* 2016), we found that many

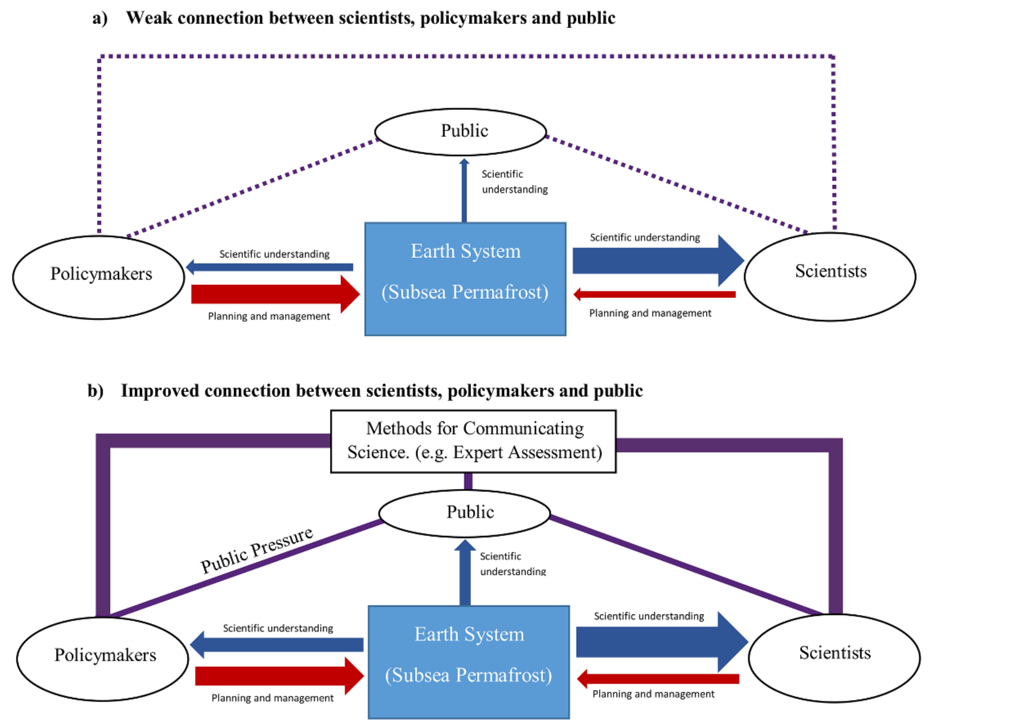

Figure 6. Expert assessment improves knowledge transfer between scientists, policymakers, and public. (a) The current situation for most Earth systems. Poor communication among the three groups leads to misunderstandings and mismanagement. Available science is not integrated in decision making and policy questions are not addressed by science. (b) Improving the connection among the three groups via expert assessment and other methods can lead to enhanced planning and management based on the latest science and policy needs.

invited experts declined to participate or at least expressed serious concerns because of political and territorial considerations, including perceived or real threat of retribution or negative professional consequences. These rifts between research groups and culture of antagonistic competition long precede this paper, as evidenced by unsuccessful synthesis efforts in the past and frequent rebuttals and conflict surrounding published and presented research products (e.g. Thornton *et al* (2019)). We hope that this exercise, which involved permafrost researchers from many research groups, institutions, career stages, and cultural backgrounds, can contribute to a détente and improvement of collaborative research. At the least, we trust that these initial and uncertain estimates will encourage the publication of expansions and rebuttals. Indeed, new (or newly published) observations of the physical state (e.g. subsurface geologic structure, temperature, pressure), chemical state (e.g. pore-water chemistry, pH, redox conditions, hydrate composition), and biological state (rates of aerobic and anaerobic metabolisms (Koch *et al* 2009, Overduin *et al* 2015, Winkel *et al* 2018)) of the subsea permafrost domain are desperately needed to reduce the uncertainty around the estimates presented here and in recent work (Vonk *et al* 2014, Shakhova *et al* 2017, Lindgren *et al* 2018). These data could better constrain models of present and future biogeochemistry as well as reveal past behavior of subsea permafrost and OM, generating fundamental insights into biological dynamics at millennial timescales. Because of the logistical challenges of collecting data from the continental shelves, which ultimately requires deep scientific drilling within the exclusive economic zones of various countries, international collaborations as well as private-public partnerships will be required to meet these goals.

3.3. Improving integration of science and policy

Although there is evidence that subsea permafrost could be a major greenhouse gas source, it has not been quantitatively considered in any major climate change reports (table S1). This is attributable to the lack of data and published estimates of policy-relevant information. For example, in the few reports that do mention subsea permafrost, there is no detail on the extent and magnitude of subsea carbon stocks or potential greenhouse gas release (table S1). The readers of these reports, which are mainly written for public and policymakers, cannot therefore have an accurate understanding of the potential influence of this ecosystem feedback on the climate system.

While policymaking is inherently based on values, it should be informed by the best available scientific evidence (Joly *et al* 2010, Sutherland and Burgman 2015). To integrate the latest science into policymaking and to direct scientific inquiry to address societally relevant problems, it is important to ensure the timely communication of relevant information between policymakers and scientists (figure 6).

Despite the necessity of the relationship between science and policy, this link is often indirect or weak (Brownell and Roberto 2015, Cherubini *et al* 2016). The uncertainty and complexity involved in both science and policymaking can make it difficult for representatives from one world to appreciate the implications of uncertainties presented by the other (Bradshaw and Borchers 2000, Maxim and van der Sluijs 2011). The communication of these compound uncertainties between science, policy, and public circles is inherently challenging, potentially causing frustration and even undermining science and policy objectives (Morgan 2014, Sutherland and Burgman 2015). Consequently, for many environmental issues, which always involve high levels of complexity and uncertainty, much of the latest science is not considered by policymakers and much of the best policy knowledge is unknown by researchers (Cortner 2000, Liu *et al* 2008). In the case of the permafrost climate feedback (both terrestrial and subsea), we suggest that expert assessment should be more regularly implemented to quantify uncertainties and identify research priorities. As more data and simulations become available, repeat assessments (e.g. every 5 or 10 years) could reveal whether estimates are converging and ensure that the most up-to-date information is available to policymakers.

4. Conclusion

In this study, we used expert assessment to combine available information on the past, present, and future carbon stocks and fluxes of the subsea permafrost domain. According to the experts, subsea permafrost contains large stocks of organic carbon and globally relevant fluxes of CO_2 and CH_4 from the subsea permafrost domain are already influencing climate change, and future projections are substantial relative to carbon release and uptake in the terrestrial permafrost zone. However, based on the slow response of this system to paleoclimate change (e.g. deglaciation), it appears that subsea permafrost is relatively stable on centennial to millennial timescales. Experts emphasized that the lack of field data creates high uncertainty regarding carbon stocks and emissions. Additionally, experts agreed that subsea permafrost will degrade faster and contribute more emissions under RCP8.5 compared to RCP2.6, suggesting that this system is still responsive to short-term anthropogenic forcing. Therefore, ignoring this system in climate change policies exacerbates the risk of underestimating ecosystem feedbacks and overshooting climate targets.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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