

LETTER • OPEN ACCESS

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

To cite this article: Sayedeh Sara Sayedi *et al* 2020 *Environ. Res. Lett.* **15** 124075

View the [article online](#) for updates and enhancements.

Environmental Research Letters



LETTER

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

OPEN ACCESS

RECEIVED

14 September 2020

REVISED

27 October 2020

ACCEPTED FOR PUBLICATION

19 November 2020

PUBLISHED

22 December 2020

Original content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](https://creativecommons.org/licenses/by/4.0/).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.



Sayedeh Sara Sayedi¹ , Benjamin W Abbott¹ , Brett F Thornton² , Jennifer M Frederick³ , Jorien E Vonk⁴ , Paul Overduin⁵, Christina Schädel⁶ , Edward A G Schuur⁶, Annie Bourbonnais⁷, Nikita Demidov⁸, Anatoly Gavrilov⁹, Shengping He¹⁰ , Gustaf Hugelius¹¹, Martin Jakobsson², Miriam C Jones¹² , DongJoo Joung¹³ , Gleb Kraev^{4,14}, Robie W Macdonald¹⁵, A David McGuire¹⁶, Cuicui Mu¹⁷, Matt O'Regan² , Kathryn M Schreiner¹⁸, Christian Stranne² , Elena Pizhankova⁹, Alexander Vasiliev¹⁹ , Sebastian Westermann²⁰, Jay P Zarnetske²¹ , Tingjun Zhang²², Mehran Ghandehari²³ , Sarah Baeumler²⁴ , Brian C Brown¹ and Rebecca J Frei²⁵

- ¹ Department of Plant and Wildlife Sciences, Brigham Young University, Provo, UT, United States of America
- ² Department of Geological Sciences and Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden
- ³ Sandia National Laboratories, Albuquerque, NM, United States of America
- ⁴ Vrije Universiteit Amsterdam, Amsterdam, The Netherlands
- ⁵ Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Potsdam, Germany
- ⁶ Center for Ecosystem Science and Society and Department of Biological Sciences, Northern Arizona University, Flagstaff, AZ, United States of America
- ⁷ School of the Earth, Ocean and Environment, University of South Carolina, Columbia, SC, United States of America
- ⁸ Arctic and Antarctic Research Institute, St. Petersburg, Russia
- ⁹ Faculty of geology, Lomonosov Moscow State University, Moscow, Russia
- ¹⁰ Geophysical Institute, University of Bergen and Bjerknes Centre for Climate Research, Bergen, Norway
- ¹¹ Department of Physical Geography and Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden
- ¹² USGS, Florence Bascom Geoscience Center, Reston, VA, United States of America
- ¹³ Department of Earth and Environmental Sciences, University of Rochester, Rochester, NY, United States of America
- ¹⁴ Institute of Physicochemical and Biological Problems in Soil Science of the Russian Academy of Sciences, Pushchino, Russia
- ¹⁵ Department of Fisheries and Oceans, Institute of Ocean Sciences, Sidney, Canada
- ¹⁶ Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, AK, United States of America
- ¹⁷ College of Earth and Environmental Sciences, Lanzhou University, Lanzhou, Gansu, People's Republic of China
- ¹⁸ Large Lakes Observatory and Department of Chemistry & Biochemistry, University of Minnesota Duluth, Duluth, MN, United States of America
- ¹⁹ Tyumen scientific Center of SB RAS, Tyumen, Russia
- ²⁰ Department of Geoscience and Centre for Biogeochemistry in the Anthropocene, University of Oslo, Oslo, Norway
- ²¹ Department of Earth and Environmental Sciences, Michigan State University, East Lansing, MI, United States of America
- ²² National Snow and Ice Data Center—Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO, United States of America
- ²³ Medici Land Governance, UT, United States of America
- ²⁴ Ludwig Maximilians Universität, München, Germany
- ²⁵ Department of Renewable Resources, University of Alberta, Edmonton, Canada

E-mail: sarasayed191@gmail.com

Keywords: subsea permafrost, carbon stocks, climate change, expert assessment

Supplementary material for this article is available [online](#)

Abstract

The continental shelves of the Arctic Ocean and surrounding seas contain large stocks of organic matter (OM) and methane (CH₄), 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 CH₄. Current fluxes of CH₄ and carbon dioxide (CO₂) 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 CO₂-equivalent (CO₂e) by 2100 (14–110) and 190 Gt CO₂e by 2300 (45–590), with ~30% fewer

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>).

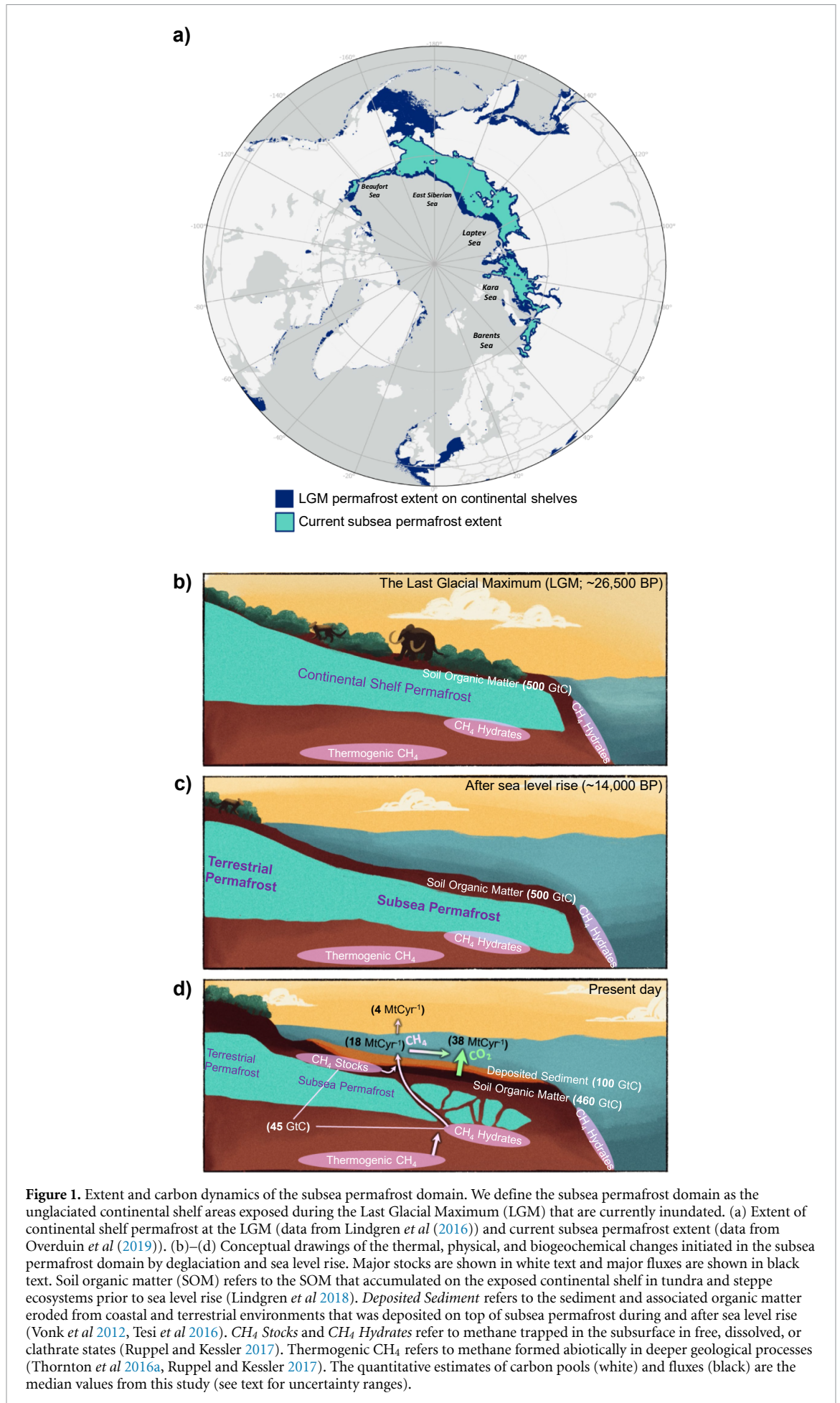
During the last glacial period (~115 000–11 700 years BP), permafrost formed on exposed portions of the continental shelves surrounding the Arctic Ocean (Osterkamp *et al* 1989, Lindgren *et al* 2016). Unglaciated portions of the exposed continental shelves accumulated billions of tons of undecomposed plant material in frozen sediment (figures 1(a) and (c); Clark *et al* 2009, Tesi *et al* 2016, Lindgren *et al* 2018). Methane (CH₄) 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 km² 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 CH₄ stocks on the continental shelves, (b). assess risk of carbon dioxide (CO₂) and CH₄ 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



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 environment 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 km² (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 km² in the Northern Hemisphere (Hugelius *et al* 2014, Schuur *et al* 2015). Experts estimated that the current extent of subsea permafrost was ~2 million km² (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)).

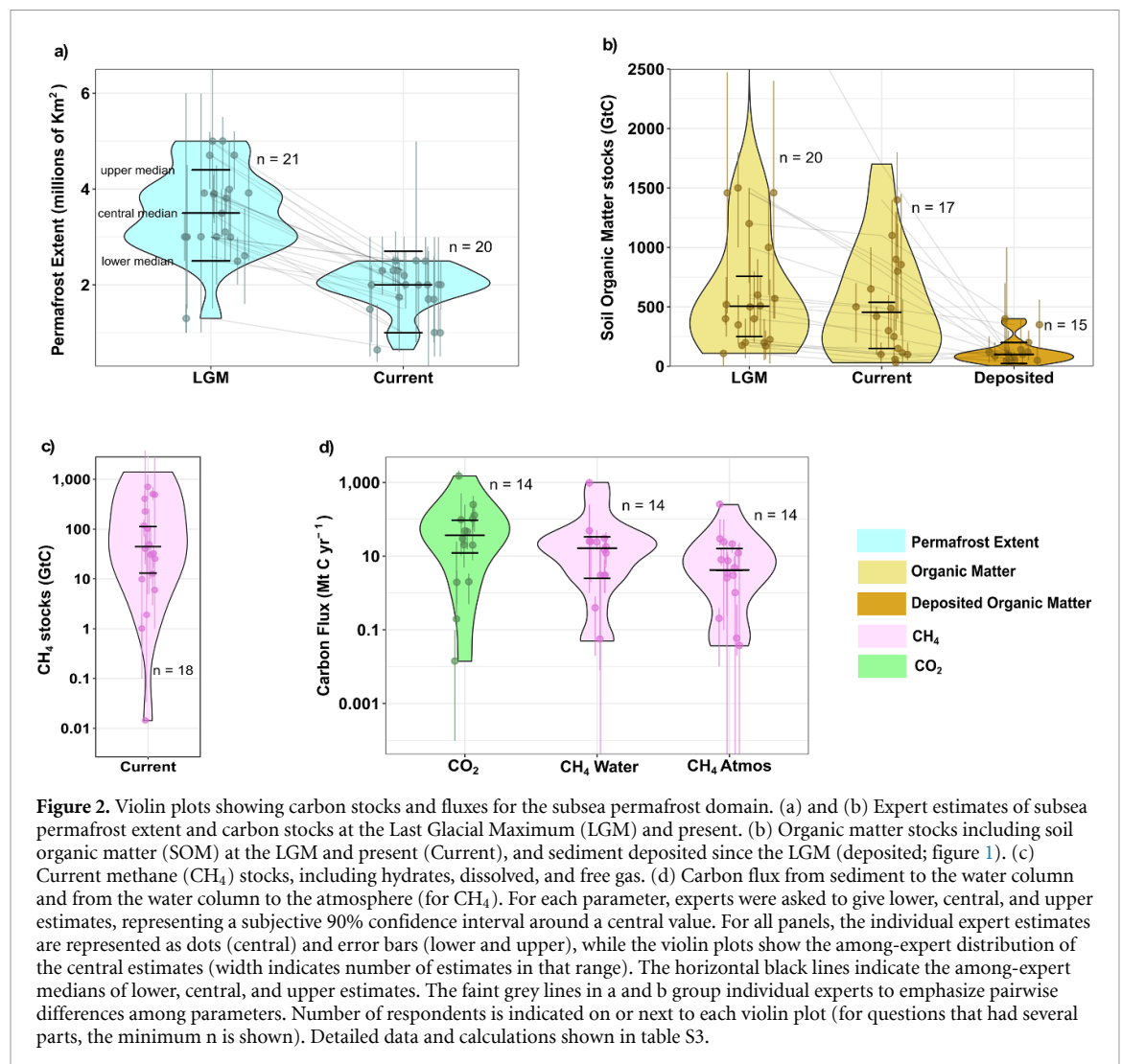
Experts estimated that 500 gigatons carbon (GtC) (250–750) in soil organic matter (SOM) was stored in and on the continental shelves at the LGM (figure 2(b)). Expressed on an areal basis (i.e. 140 kg C m⁻²), these estimates of SOM from the continental shelves are similar to carbon densities in the continuous 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 CH₄ and CO₂ 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 CH₄ 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 CH₄ 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

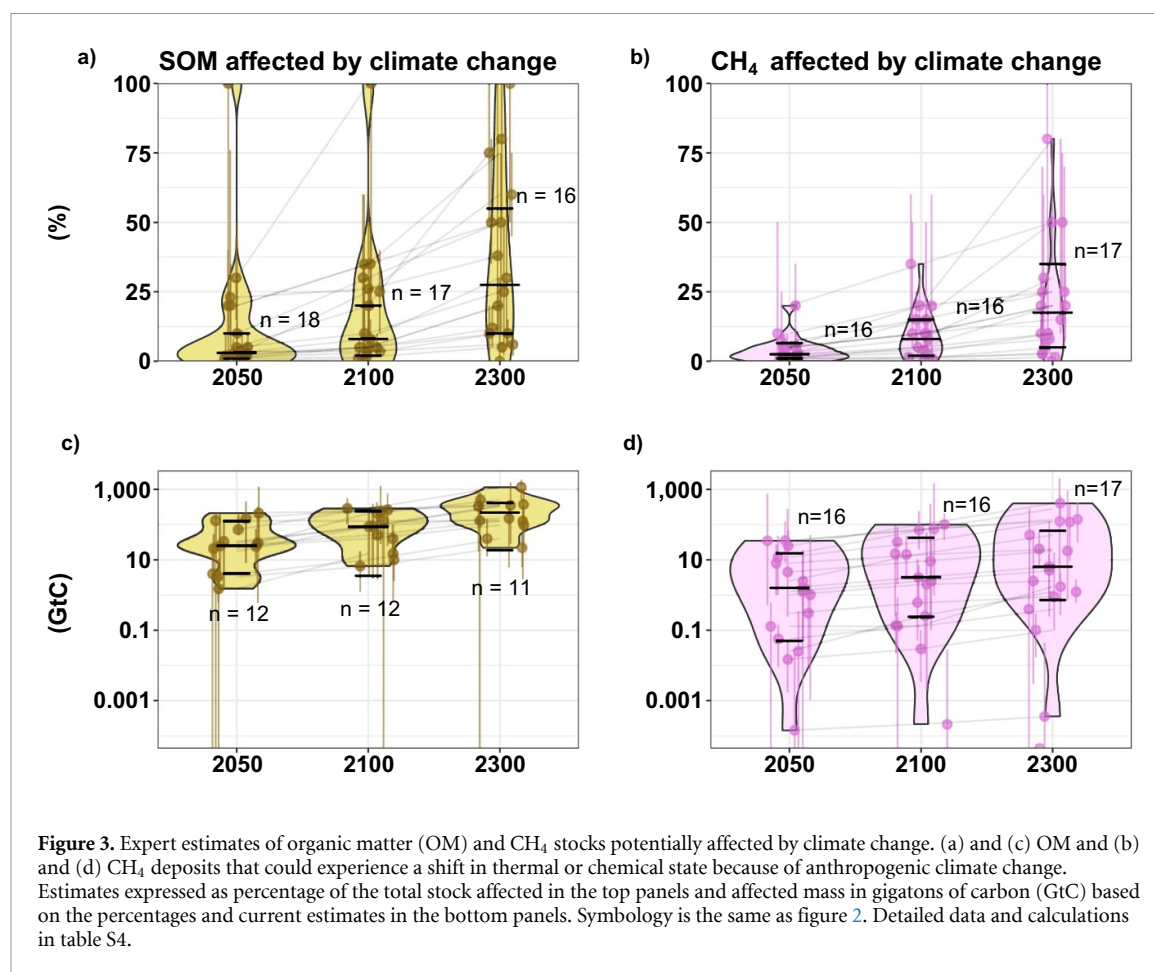
^a1 was defined as exclusively field research and 5 as exclusively modeling research.



lenging (Martens *et al* 2019), and quantifying CH₄ deposits requires more expensive and complicated drilling beneath the seafloor (Frederick and Buffett 2014, Ruppel and Kessler 2017). Experts mentioned that the scarcity of CH₄ 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 CO₂ and CH₄

We asked experts to estimate potential changes in CO₂ and CH₄ 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 CO₂-equivalent (CO₂e) reached before 2100, RCP4.5 with a peak of ~650 ppm CO₂e at 2100, and RCP8.5 with a peak of ~1400 ppm CO₂e at 2100 (Moss *et al* 2010, Koenigk *et al* 2013). There



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 CH₄ 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 CH₄ 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 CH₄ stocks (figure 2(c)), these percentages translate into highly uncertain but still substantial quantities of affected CH₄ by 2100 (0.2–42 GtC) and 2300 (0.6–64 GtC; figure 3(d)). Together,

these estimates suggest that CH₄ 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 CH₄ deposits support the growing evidence from paleoclimate studies that subsea hydrates contributed minimally to the abrupt climate change and correspondingly abrupt increase in CH₄ 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 CO₂ and CH₄ 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 CO₂ 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 CO₂ 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 CH₄ 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 CH₄ released from sediment is oxidized before reaching the atmosphere (figure 2(d); Thornton *et al* 2016a). The experts projected that the amount of CH₄ 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 CO₂ emissions for RCP2.6 versus RCP8.5 and a 73% (70–89) decrease in added CH₄ emissions (figure S4).

To compare the overall climate forcing from the subsea permafrost domain, we converted CH₄ emissions into CO₂e, 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), CH₄ contributed more than half of the overall climate forcing, accounting for a mean of 65%, 67%, and 72% of the cumulative CO₂e 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)).

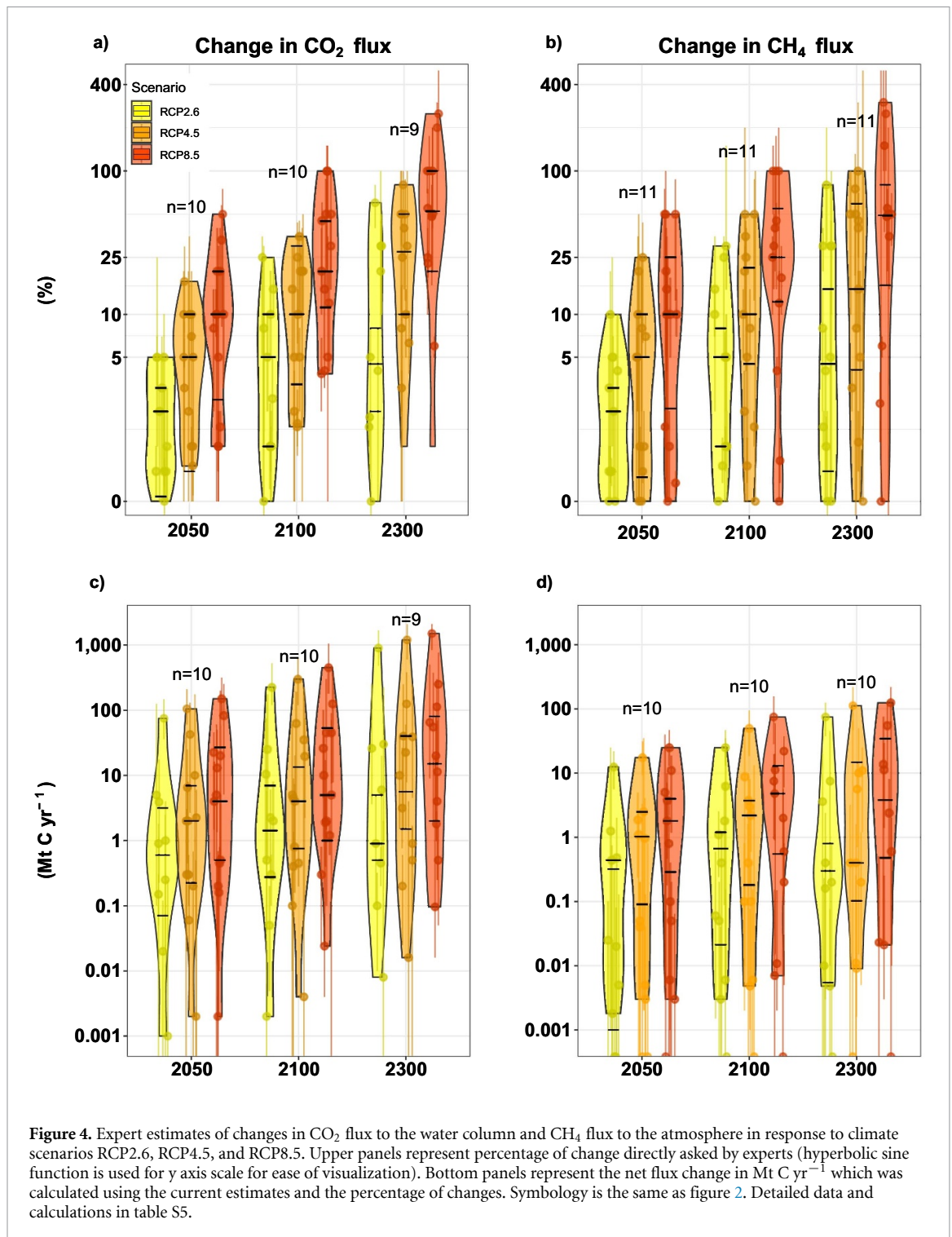
When summed to estimate total climate forcing in CO₂e, the cumulative greenhouse gas release from the subsea permafrost domain under RCP2.6 was 11 Gt CO₂e (4–30) by 2050, 35 (10–83) by 2100, and 130 (34–270) by 2300. Under RCP4.5, cumulative greenhouse gas emissions were similar to RCP2.6 for 2050 and 2100—12 (5–32) and 38 Gt CO₂e (14–96), respectively—but higher for 2300: 150 Gt CO₂e (49–380). For RCP8.5, emissions were substantially higher across 2050, 2100, and 2300, with 13 (5–36), 43 (14–110), and 190 Gt CO₂e (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

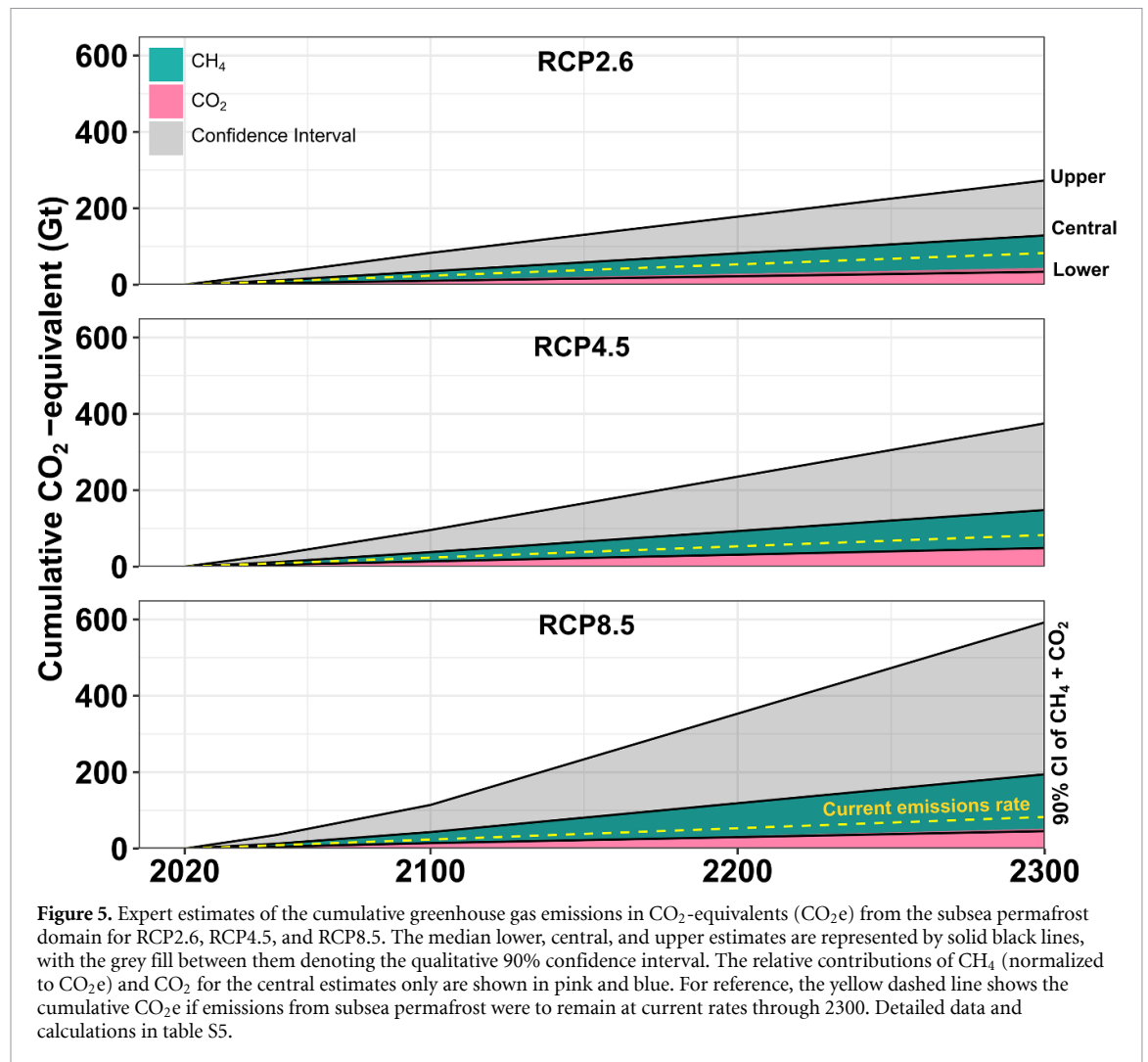
Evaluating how much subsea permafrost has degraded and how much SOM has been decomposed since sea levels rose ~14 000 years ago (Church *et al* 2010) can provide perspective on the current permafrost climate feedback. If the expert range of estimates of 30%–50% decline in area and 33%–40% decline in 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 CH₄ from the subsea permafrost domain equals 10%–40% of CH₄ 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 CO₂ 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 CO₂ 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 out-sized role in determining the overall carbon balance



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: $\sim 0.4\%$ of the Earth's surface area but up to 2% of global CH₄ release and 31% of oceanic surface sediment carbon (Sauniois *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 CO₂ and CH₄ 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



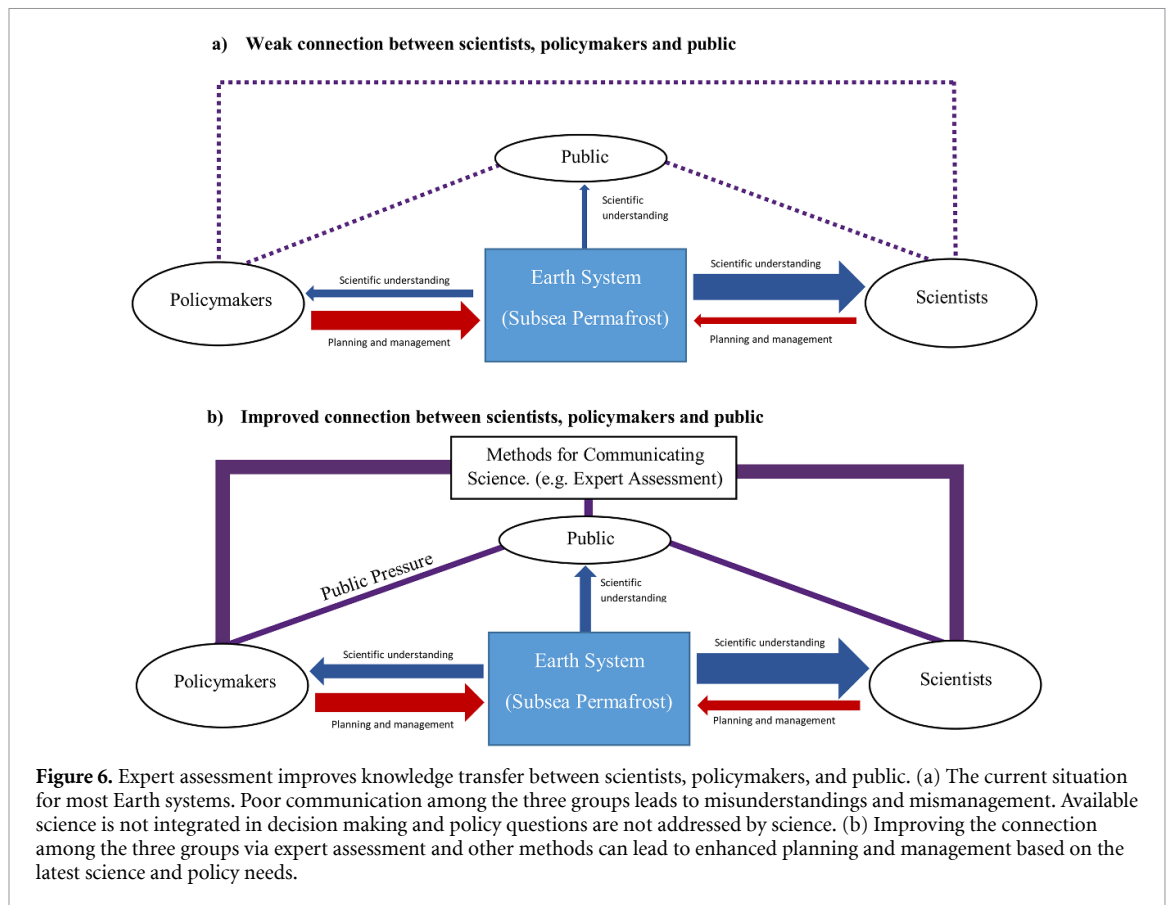
because the subsea and terrestrial permafrost zones are fundamentally linked (Vonk *et al* 2012, Tesi *et al* 2016), understanding the fate of old and new OM on the continental shelves of the Arctic Ocean basin should be a research priority.

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 CH₄-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 CH₄) 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



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 CO₂ and CH₄ 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).

Acknowledgments

This work was supported by the Brigham Young University Graduate Studies and the Permafrost Carbon Network through the National Science Foundation (NSF) Study of Environmental Arctic Change (SEARCH) Grant No. 1331083. Benjamin Abbott was supported by NSF award number 1916565. Cuicui Mu was supported by The National Key R&D Program of China (2019YFA0607003). Gleb Kraev was supported by the Russian Science Foundation (project 19-77-10065). Nikita Demidov was supported by the Russian Science Foundation (project 19-77-10066). Alexander Vasiliev was supported by the Russian Foundation for Basic Research, project No. 18-05-60004. Christian Stranne was supported by the Swedish Science Foundation (VR, project 2018-04350). Jennifer M Frederick was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories, a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525. We thank Sebastien Wetterich and Vladimir Romanovsky for providing input on the manuscript and M Bayani Cardenas for input on the questionnaire and conceptual framing of the project. The background drawings in figure 1, were created by Anna Wright.

ORCID iDs

Sayedeh Sara Sayedi  <https://orcid.org/0000-0001-5272-4383>

Benjamin W Abbott  <https://orcid.org/0000-0001-5861-3481>

Brett F Thornton  <https://orcid.org/0000-0002-5640-6419>

Jennifer M Frederick  <https://orcid.org/0000-0003-2414-778X>

Jorien E Vonk  <https://orcid.org/0000-0002-1206-5878>

Christina Schädel  <https://orcid.org/0000-0003-2145-6210>

Shengping He  <https://orcid.org/0000-0003-4245-357X>

Miriam C Jones  <https://orcid.org/0000-0002-6650-7619>

DongJoo Joung  <https://orcid.org/0000-0002-2711-3780>

Matt O'Regan  <https://orcid.org/0000-0002-6046-1488>

Christian Stranne  <https://orcid.org/0000-0003-1004-5213>

Alexander Vasiliev  <https://orcid.org/0000-0001-5483-8456>

Jay P Zarnetske  <https://orcid.org/0000-0001-7194-5245>
 Mehran Ghandehari  <https://orcid.org/0000-0002-7372-7687>
 Sarah Baeumler  <https://orcid.org/0000-0003-1772-8180>

References

- Aarstad J 2010 Expert credibility and truth *Proc. Natl Acad. Sci.* **107** E176–76
- Abbott B W *et al* 2016 Biomass offsets little or none of permafrost carbon release from soils, streams, and wildfire: an expert assessment *Environ. Res. Lett.* **11** 034014
- Aspinall W 2010 A route to more tractable expert advice *Nature* **463** 294–5
- Bamber J L and Aspinall W P 2013 An expert judgement assessment of future sea level rise from the ice sheets *Nat. Clim. Change* **3** 424–7
- Bamber J L, Tedstone A J, King M D, Howat I M, Enderlin E M, van den Broeke M R and Noel B 2018 Land ice freshwater budget of the Arctic and North Atlantic Oceans: 1. Data, methods, and results *J. Geophys. Res. Oceans* **0** 1827–37
- Barrett S and Dannenberg A 2012 Climate negotiations under scientific uncertainty *Proc. Natl Acad. Sci.* **109** 17372
- Biskaborn B K *et al* 2019 Permafrost is warming at a global scale *Nat. Commun.* **10** 264
- Bradshaw G A and Borchers J G 2000 Uncertainty as information: narrowing the science-policy gap *Conserv. Ecol.* **4**
- Brownell K D and Roberto C A 2015 Strategic science with policy impact *Lancet* **385** 2445–6
- Cherubini F *et al* 2016 Bridging the gap between impact assessment methods and climate science *Environ. Sci. Policy* **64** 129–40
- Church J A *et al* 2010 Sea-level rise and variability: synthesis and outlook for the future *Understanding Sea-Level Rise and Variability* ed J A Church, P L Woodworth, T Aarup and W S Wilson (Oxford: Wiley) pp 402–19
- Clark P U, Dyke A S, Shakun J D, Carlson A E, Clark J, Wohlfarth B, Mitrovica J X, Hostetler S W and McCabe A M 2009 The last glacial maximum *Science* **325** 710–4
- Core Team R 2013 R: a language and environment for statistical computing (Vienna: R Foundation for Statistical Computing) (available at: www.R-project.org/)
- Cortner H J 2000 Making science relevant to environmental policy *Environ. Sci. Policy* **3** 21–30
- Dyonisius M N *et al* 2020 Old carbon reservoirs were not important in the deglacial methane budget *Science* **367** 907–10
- Fischer H *et al* 2008 Changing boreal methane sources and constant biomass burning during the last termination *Nature* **452** 864–7
- Frederick J M and Buffett B A 2014 Taliks in relict submarine permafrost and methane hydrate deposits: pathways for gas escape under present and future conditions *J. Geophys. Res. Earth Surf.* **119** 106–22
- Friedlingstein P *et al* 2019 Global carbon budget 2019 *Earth Syst. Sci. Data* **11** 1783–838
- Günther F, Overduin P P, Sandakov A V, Grosse G and Grigoriev M N 2013 Short- and long-term thermo-erosion of ice-rich permafrost coasts in the Laptev Sea region *Biogeosciences* **10** 4297–318
- Huang J *et al* 2017 Recently amplified arctic warming has contributed to a continual global warming trend *Nat. Clim. Change* **7** 875
- Hubberten H-W and Romanovskii N N 2001 Terrestrial and offshore permafrost evolution of the Laptev sea region during the last Pleistocene-Holocene glacial-eustatic cycle *Permafrost Response on Economic Development, Environmental Security and Natural Resources* (Berlin: Springer) pp 43–60
- Hugelius G *et al* 2014 Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps *Biogeosciences* **11** 6573–93
- Joly J L, Reynolds J and Robards M 2010 Recognizing when the best scientific data available isn't *Stanf. Environ. Law J.* **29** 247
- Jurikova H *et al* 2020 Permian–Triassic mass extinction pulses driven by major marine carbon cycle perturbations *Nat. Geosci.* **13** 1–6
- Koch K, Knoblauch C and Wagner D 2009 Methanogenic community composition and anaerobic carbon turnover in submarine permafrost sediments of the Siberian Laptev Sea *Environ. Microbiol.* **11** 657–68
- Koenigk T, Brodeau L, Graversen R G, Karlsson J, Svensson G, Tjernström M, Willén U and Wyser K 2013 Arctic climate change in 21st century CMIP5 simulations with EC-Earth *Clim. Dyn.* **40** 2719–43
- Koksalimis E and Kabak Ö 2019 Deriving decision makers' weights in group decision making: an overview of objective methods *Inf. Fusion* **49** 146–60
- Lambeck K, Rouby H, Purcell A, Sun Y and Sambridge M 2014 Sea level and global ice volumes from the last glacial maximum to the Holocene *Proc. Natl Acad. Sci.* **111** 15296–303
- Laufkötter C *et al* 2015 Drivers and uncertainties of future global marine primary production in marine ecosystem models *Biogeosciences* **12** 6955–84
- Lenton T M, Held H, Kriegler E, Hall J W, Lucht W, Rahmstorf S and Schellnhuber H J 2008 Tipping elements in the Earth's climate system *Proc. Natl Acad. Sci.* **105** 1786–93
- Lenton T M, Rockström J, Gaffney O, Rahmstorf S, Richardson K, Steffen W and Schellnhuber H J 2019 Climate tipping points—too risky to bet against *Nature* **575** 592–5
- Lindgren A, Hugelius G and Kuhry P 2018 Extensive loss of past permafrost carbon but a net accumulation into present-day soils *Nature* **560** 219
- Lindgren A, Hugelius G, Kuhry P, Christensen T R and Vandenbergh J 2016 GIS-based maps and area estimates of Northern Hemisphere permafrost extent during the last glacial maximum: LGM permafrost *Permafr. Periglac. Process.* **27** 6–16
- Liu Y, Gupta H, Springer E and Wagener T 2008 Linking science with environmental decision making: experiences from an integrated modeling approach to supporting sustainable water resources management *Environ. Model. Softw.* **23** 846–58
- Martens J *et al* 2019 Remobilization of old permafrost carbon to Chukchi Sea sediments during the end of the last deglaciation *Glob. Biogeochem. Cycles* **33** 2–14
- Maxim L and van der Sluijs J P 2011 Quality in environmental science for policy: assessing uncertainty as a component of policy analysis *Environ. Sci. Policy* **14** 482–92
- Mcguire A D *et al* 2018 Dependence of the evolution of carbon dynamics in the northern permafrost region on the trajectory of climate change *Proc. Natl Acad. Sci.* **115** 3882–7
- Mcguire A D, Anderson L G, Christensen T R, Dallimore S, Guo L, Hayes D J, Heimann M, Lorenson T D, Macdonald R W and Roulet N 2009 Sensitivity of the carbon cycle in the Arctic to climate change *Ecol. Monogr.* **79** 523–55
- Morgan M G 2014 Use (and abuse) of expert elicitation in support of decision making for public policy *Proc. Natl Acad. Sci.* **111** 7176–84
- Moss R H *et al* 2010 The next generation of scenarios for climate change research and assessment *Nature* **463** 747–56
- Natali S M *et al* 2019 Large loss of CO₂ in winter observed across the northern permafrost region *Nat. Clim. Change* **9** 852–7
- Oppenheimer M, Oreskes N, Jamieson D, O'Reilly J, Brysse K, Shindell M and Wazeck M 2019 *Discerning Experts: The Practices of Scientific Assessment for Environmental Policy* (Chicago, IL: University of Chicago Press)
- Osterkamp T E, Baker G C, Harrison W D and Matava T 1989 Characteristics of the active layer and shallow subsea permafrost *J. Geophys. Res. Oceans* **94** 16227–36

- Overduin P P, Deimling S von T, Miesner F, Grigoriev M N, Ruppel C, Vasiliev A, Lantuit H, Juhls B and Westermann S 2019 Submarine permafrost map in the Arctic modeled using 1-D transient heat flux (SuPerMAP) *J. Geophys. Res. Oceans* **124** 3490–507
- Overduin P P, Liebner S, Knoblauch C, Günther F, Wetterich S, Schirrmeister L, Hubberten H-W and Grigoriev M N 2015 Methane oxidation following submarine permafrost degradation: measurements from a central Laptev Sea shelf borehole *J. Geophys. Res. Biogeosci.* **120** 2014JG002862
- Petrenko V V et al 2017 Minimal geological methane emissions during the Younger Dryas–Preboreal abrupt warming event *Nature* **548** 443–6
- Ruppel C D, Herman B M, Brothers L L and Hart P E 2016 Subsea ice-bearing permafrost on the U.S. Beaufort Margin: 2. borehole constraints *Geochem. Geophys. Geosyst.* **17** 4333–53
- Ruppel C D and Kessler J D 2017 The interaction of climate change and methane hydrates *Rev. Geophys.* **55** 126–68
- Saunois M et al 2016 The global methane budget 2000–2012 *Earth Syst. Sci. Data* **8** 697–751
- Schuur E A G et al 2013 Expert assessment of vulnerability of permafrost carbon to climate change *Clim. Change* **119** 359–74
- Schuur E A G et al 2015 Climate change and the permafrost carbon feedback *Nature* **520** 171–9
- Shakhova N E, Nicolsky D Y and Semiletov I P 2009 Current state of subsea permafrost on the East Siberian Shelf: tests of modeling results based on field observations *Dokl. Earth Sci.* **429** 1518–21
- Shakhova N et al 2013 Ebullition and storm-induced methane release from the East Siberian Arctic Shelf *Nat. Geosci.* **7** 64–70
- Shakhova N et al 2017 Current rates and mechanisms of subsea permafrost degradation in the East Siberian Arctic Shelf *Nat. Commun.* **8** 15872
- Shakhova N, Semiletov I, Salyuk A, Yusupov V, Kosmach D and Gustafsson O 2010 Extensive methane venting to the atmosphere from sediments of the East Siberian Arctic Shelf *Science* **327** 1246–50
- Shmelev D, Veremeeva A, Kraev G, Kholodov A, Spencer R G M, Walker W S and Rivkina E 2017 Estimation and sensitivity of carbon storage in permafrost of North-Eastern Yakutia *Permafrost. Periglac. Process.* **28** 379–90
- Singh G G, Sinner J, Ellis J, Kandlikar M, Halpern B S, Satterfield T and Chan K 2017 Group elicitation yields more consistent, yet more uncertain experts in understanding risks to ecosystem services in New Zealand bays *Plos One* **12** e0182233
- Sowers T 2010 Atmospheric methane isotope records covering the Holocene period *Quat. Sci. Rev.* **29** 213–21
- Steffen W, Rockström J, Richardson K, Lenton T M, Folke C, Liverman D, Summerhayes C P, Barnosky A D, Cornell S E and Crutcher M 2018 Trajectories of the Earth System in the Anthropocene *Proc. Natl Acad. Sci.* **115** 8252–9
- Sutherland W J and Burgman M 2015 Policy advice: use experts wisely *Nat. News* **526** 317
- Tesi T et al 2016 Massive remobilization of permafrost carbon during post-glacial warming *Nat. Commun.* **7** 13653
- Thornton B F and Crill P 2015 Arctic permafrost: microbial lid on subsea methane *Nat. Clim. Change* **5** 723
- Thornton B F, Geibel M C, Crill P M, Humborg C and Mörth C-M 2016a Methane fluxes from the sea to the atmosphere across the Siberian shelf seas *Geophys. Res. Lett.* **43** 5869–77
- Thornton B F, Geibel M C, Crill P M, Humborg C and Mörth C-M 2019 Comment on ‘understanding the permafrost–hydrate system and associated methane releases in the East Siberian Arctic Shelf’ *Geosciences* **9** 384
- Thornton B F, Wik M and Crill P M 2016b Double-counting challenges the accuracy of high-latitude methane inventories *Geophys. Res. Lett.* **43** 12–569
- Trusel L D, Das S B, Osman M B, Evans M J, Smith B E, Fettweis X, McConnell J R, Noël B P Y and van den Broeke M R 2018 Nonlinear rise in Greenland runoff in response to post-industrial Arctic warming *Nature* **564** 104–8
- Turetsky M R et al 2020 Carbon release through abrupt permafrost thaw *Nat. Geosci.* **13** 138–43
- Vonk J E et al 2012 Activation of old carbon by erosion of coastal and subsea permafrost in Arctic Siberia *Nature* **489** 137–40
- Vonk J E, Semiletov I P, Dudarev O V, Eglinton T I, Andersson A, Shakhova N, Charkin A, Heim B and Gustafsson Ö 2014 Preferential burial of permafrost-derived organic carbon in Siberian–Arctic shelf waters *J. Geophys. Res. Oceans* **119** 8410–21
- Winkel M et al 2018 Anaerobic methanotrophic communities thrive in deep submarine permafrost *Sci. Rep.* **8** 1291
- Winterfeld M, Schirrmeister L, Grigoriev M N, Kunitsky V V, Andreev A, Murray A and Overduin P P 2011 Coastal permafrost landscape development since the Late Pleistocene in the western Laptev Sea, Siberia *Boreas* **40** 697–713
- Wrona F J, Johansson M, Culp J M, Jenkins A, Mård J, Myers-Smith I H, Prowse T D, Vincent W F and Wookey P A 2016 Transitions in Arctic ecosystems: ecological implications of a changing hydrological regime *J. Geophys. Res. Biogeosci.* **121** 2015JG003133
- Yang M, Wang X, Pang G, Wan G and Liu Z 2019 The Tibetan Plateau cryosphere: observations and model simulations for current status and recent changes *Earth Sci. Rev.* **190** 353–69