Subsea Permafrost: Expert Assessment of Carbon Stocks and Fluxes

1. Introduction to Expert Assessment and Rational of this Project[1]

The goal of this survey is to document expert understanding of current, past, and future subsea permafrost carbon stocks and fluxes. Possible thresholds and tipping points in the relationship between climate change and subsea permafrost extent and carbon balance are of particular interest, because such non-linearity is difficult to predict on the basis of models. We recognize that climate-change-driven feedbacks in complex Earth systems are not, and cannot be, precisely and definitively characterized or predicted. As such, **we are only asking for your informed opinion**, realizing that many of the included parameters are not well understood. By administering this survey to scientists who have expertise relating to the subsea permafrost system, we strive to evaluate the possible response of Arctic continental shelves to past and future climate change. Even if you only have expertise pertaining to one or a few of the questions in this survey, your response is valuable because of the high level of scientific uncertainty and potentially large societal implications associated with the subsea permafrost system. Because participation in this survey entails a substantial time commitment and contribution of intellectual production (e.g. empirical results, model runs, and professional opinion), **all survey participants who give feedback on the manuscript will have the opportunity to be co-authors.** The dataset of estimates will be published without identifying information (i.e. individual estimates will be kept anonymous).

When management decisions are pressing but uncertainty is high, expert judgements have long informed possible system response and risk of dangerous or undesired outcomes (Aspinall 2010, Zickfeld et al. 2010, Morgan 2014). While expert assessment cannot definitively answer questions of future system response, it complements modeling and empirical approaches by allowing the synthesis of formal and informal knowledge about the system to inform decision makers and researchers (Fig. 1). The approach is similar to the concept of ensemble models, where multiple estimates built on different assumptions and data provide a more robust estimate of central tendency and measure of variance. Because the experimental unit is an individual researcher, each data point integrates multiple types of knowledge available to that person; including information not yet formalized enough to integrate into numerical models. Working with the Permafrost Carbon Network, we have previously used this methodology to estimate the timing and magnitude of greenhouse gas and fluvial carbon release from terrestrial permafrost, assess Arctic and Boreal wildfire, and quantify the potential for terrestrial vegetation to offset permafrost carbon losses through increased primary production (Schuur and Abbott 2011, Schuur et al. 2013, Abbott et al. 2016). These estimates should be considered as hypotheses of possible system response to be tested with future data collection and modeling.

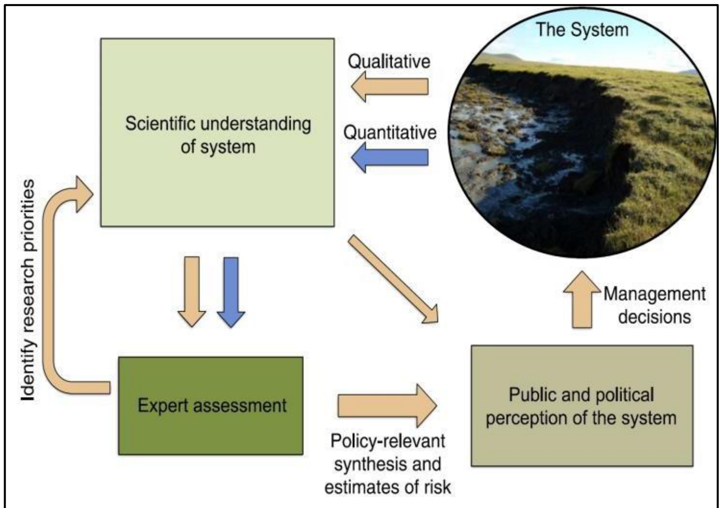

Figure 1. Diagram of the role of expert assessment in synthesizing and communicating scientific understanding (Abbott *et al.* 2016).

In the context of this project, expert assessment of subsea permafrost and carbon balance could: 1. assess risks of abrupt CO_2 and CH_4 release, two of the major anthropogenic greenhouse gases, 2. provide a critical long-term perspective on vulnerability of carbon currently being thawed from terrestrial permafrost, and 3. generate first-order estimates of energy resources on the continental shelves. These questions have been identified as critical research priorities (Lenton et al. 2008, Shakhova et al. 2010, Thornton and Crill 2015,

[1] Project supported by the Permafrost Carbon Network (permafrostcarbon.org) and the Brigham Young University Graduate School

Lindgren et al. 2018, Martens et al. 2018), but given the scarcity of data and complexity of subsea permafrost, precise empirical or model-based estimates of the critical factors driving subsea permafrost dynamics are unlikely in the near future.

2. Background Information on Subsea Permafrost[2]

Subsea permafrost (perennially frozen sediment, soil, and other material) exists under portions of the shallow continental shelves of the Arctic Ocean (Fig. 2). This permafrost formed during the last ice age when unglaciated portions of the exposed continental shelves accumulated hundreds of billions of tons of carbon in soil profiles from undecomposed plant material (Osterkamp and Harrison 1982, Rekant et al. 2005, Romanovskii et al. 2005, Tesi et al. 2016, Lindgren et al. 2018). As ice sheets and glaciers melted after the Last Glacial Maximum, sea level rose ~130 m, inundating several million km^2 of terrestrial permafrost (Yokoyama et al. 2000, Bauch et al. 2001, Rachold et al. 2005, Lindgren et al. 2016). Seawater inundation fundamentally changes the thermal regime of permafrost, and consequently most subsea permafrost has been degrading since it was inundated after the Last Glacial Maximum (Osterkamp et al. 1989, Romanovskii and Hubberten 2001, Shakhova et al. 2009, 2017, Ruppel et al. 2016).

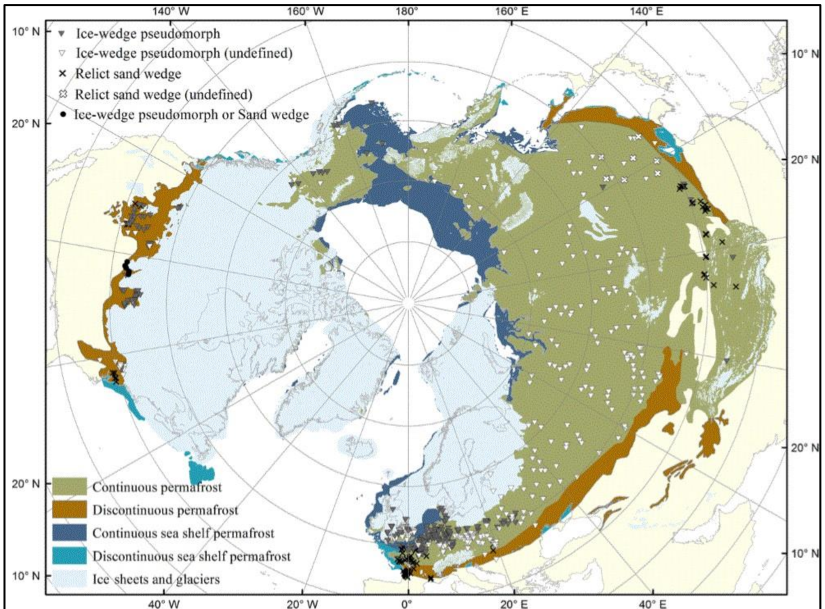

Figure 2. Reconstructed distribution of terrestrial and subsea permafrost and ice sheets and glaciers at the Last Glacial Maximum (Lindgren et al. 2016). We define the areas of discontinuous and continuous sea shelf permafrost as the *subsea permafrost domain.*

Diverse empirical and modeling methods have been used to estimate the extent and depth of subsea permafrost and associated organic carbon, including: Neumann solutions to estimate permafrost aggradation (Mackay et al. 1972); electromagnetic measurements (Sherman et al. 2017, Piskunova et al. 2018); cone penetrometry (Blouin et al. 1979); various drilling approaches to quantify temperature, ice content, and organic matter (Osterkamp and Harrison 1982, Osterkamp et al. 1985, Ruppel et al. 2016); velocity analysis (Brothers et al. 2016); seismoacoustic methods (Portnov et al. 2013); acoustic methods to detect gas release (Leifer et al. 2017); and numerical modeling of conductive heat transfer and hydrates (Romanovskii et al. 1998, Hutter and Straughan 1999, Delisle 2000, Romanovskii and Hubberten 2001). Technical and political challenges of obtaining measurements from the Arctic shelves means that subsea permafrost remains one of the least understood aspects of the permafrost zone and Earth system generally. Particularly uncertain parameters include, permafrost extent and degradation state (Nicolsky and Shakhova 2010, Nicolsky et al. 2012, Portnov et al. 2013), organic matter content (Tarnocai et al. 2009, Lindgren et al. 2018, Martens et al. 2018), and CH_4 stocks (Kvenvolden 1988, Frederick and Buffett 2014, Ruppel and Kessler 2017).

2.1 Net ecosystem carbon balance of the subsea permafrost domain

Organic carbon of the Arctic continental shelves can be divided into three general pools, each with different characteristics and potential vulnerability to climate change.

1. Prior to the marine transgression, tundra and steppe ecosystems on the continental shelf contained dense and deep soil organic matter (SOM) deposits because of limited decomposition at the surface and

[2] This document is not intended as a comprehensive or endorsed list of citations or information. It is a partial summary of the current understanding of subsea permafrost to be used as a reference while filling out the survey.

cryogenic processes that mixed or deposited SOM at depth (Zimov et al. 2006, Yu et al. 2010, Ciais et al. 2011, Schirrmeister et al. 2013, Anthony et al. 2014, Lindgren et al. 2018). Some of this SOM remains frozen in subsea permafrost deposits, while some has been thawed (Naidu et al. 2000, Karlsson et al. 2016, Lindgren et al. 2018). For the purposes of this survey, we refer to this SOM that accumulated in soil profiles of the continental shelves as ***subsea SOM***.

2. During deglaciation and subsequent permafrost degradation (including ongoing degradation), Arctic rivers and rapidly eroding coasts delivered huge quantities of terrestrial sediment and SOM to coastal seas, covering much of the continental shelf with additional carbon and nitrogen- rich material above the permafrost (Taylor et al. 1996, Mueller-Lupp et al. 2000, Gustafsson et al. 2011, Charkin et al. 2011, Vonk et al. 2012, Doxaran et al. 2015, Tesi et al. 2016, Irrgang et al. 2018, Martens et al. 2018). We refer to this pool as ***surface-sediment OM***.
3. Before and after the marine transgression, methane (CH_4) formed within and below permafrost deposits, constituting a potentially high-sensitivity carbon pool (Dmitrenko et al. 2011, Frederick and Buffett 2014, 2016, Thornton and Crill 2015, Ruppel and Kessler 2017). We refer to this pool, which includes all trapped CH_4 (whether gas or hydrate) stored below or on the seafloor as ***subsea*** $\boldsymbol{CH_4}$.

It remains highly uncertain how much shelf carbon existed at the Last Glacial Maximum, and how much persists today (Vonk et al. 2012, Schuur et al. 2015, Lindgren et al. 2018). When subsea permafrost degrades, the CH_4 and SOM it contains may be mobilized via several distinct pathways. Flowing water can transport dissolved organic matter (DOM) from subsea SOM and surface sediment OM to the water column, where it may be decomposed, immobilized biotically or abiotically, or transported via ocean currents (Guo et al. 2004, Frederick and Buffett 2014, Salvadó et al. 2015, Karlsson et al. 2016). Microbial decomposition of shelf carbon can create CO_2 and CH_4, which may remain trapped, diffuse into the water column, or be released directly to the atmosphere via ebullition. Because CH_4 is readily consumed by methanotrophs, which are abundant in surface sediments and in the overlying water column, some of the CH_4 released from subsea permafrost and surface sediment never reaches the atmosphere because of microbial immobilization and oxidation to CO_2 (Damm and Budéus 2003, Westbrook et al. 2009, Overduin et al. 2015, Thornton and Crill 2015, Sparrow et al. 2018, Winkel et al. 2018). Ebullition effectively bypasses zones of CH_4 uptake, and large-scale CH_4 release has been observed from some Arctic shelves (Shakhova et al. 2010, Portnov et al. 2013, Thornton et al. 2016, Leifer et al. 2017), though these fluxes appear to be highly variable geographically and temporally (Macdonald 1976, Savvichev et al. 2007, Nickel et al. 2012, Coffin et al. 2013, Lapham et al. 2017). Additionally, it remains unclear if these emissions are due to recent Arctic system warming, or how much of this CH_4 is from subsea permafrost (i.e. subsea SOM), recently deposited SOM (surface-sediment OM), CH_4 hydrates, or deeper hydrocarbon stocks (Kvenvolden et al. 1993, Cramer and Franke 2005, Lapham et al. 2010, Vonk et al. 2012, Sparrow et al. 2018).

2.2 Climate change in the subsea permafrost domain

Anthropogenic climate change is affecting subsea permafrost and the carbon it contains in three general and interconnected ways. **First**, high latitude air temperature is increasing approximately 6-times faster than the global mean (Huang et al. 2017). This increase in air temperature is a consequence and cause of a massive decline in Arctic sea ice over the past decades (Holland and Bitz 2003, Screen and Simmonds 2010, Parmentier et al. 2013, AMAP 2017), which in turn, decreases albedo and increases Arctic Ocean temperature (Johannessen et al. 2004, Screen and Simmonds 2010, Koenigk et al. 2016). **Second**, climate change is increasing freshwater runoff to the Arctic Ocean because of increased precipitation, glacial and ice-sheet melt, groundwater discharge, and river discharge (McClelland et al. 2006, Peterson 2006, Overeem and Syvitski 2010, Rawlins et al. 2010, AMAP 2017, Box et al. 2018, Trusel et al. 2018). This influx of freshwater is disrupting Arctic Ocean circulation, which directly and indirectly affects water temperature and associated changes on the continental shelves (Proshutinsky and Johnson 1997, Wassmann et al. 2011, Koenigk et al.

2013). **Third**, coastal and terrestrial permafrost degradation is altering the chemistry of estuarine and continental-shelf waters. Solute concentrations and fluxes have increased for virtually all rivers where long-term data exist (Frey et al. 2007, McClelland et al. 2007, Tank et al. 2012, 2016, Toohey et al. 2016, Kendrick et al. 2018), and erosion of Arctic coastlines is accelerating due to warming and increased exposure to wave action and storms due to reductions in sea ice cover (Stroeve et al. 2007, Screen and Simmonds 2010). Increased terrestrial and coastal erosion delivers solutes and particulates coastal waters, where they affect redox conditions, light penetration, and sedimentation (Rachold et al. 2007, Lantuit et al. 2009, Jones et al. 2009, Doxaran et al. 2015, McClelland et al. 2016, Ramage et al. 2018).

2.3 Executive summary:

1. Subsea permafrost has been degrading since the Last Glacial Maximum and it continues to degrade today
2. A portion of subsea SOM and surface-sediment OM has been decomposed since it was deposited by terrestrial processes prior to inundation (subsea SOM) or aquatic/marine processes after inundation (surface-sediment OM)
3. There appears to be spatially-variable CH_4 release from the subsea permafrost domain, but the source, magnitude, and trend (i.e. increasing or stable since pre-industrial) of CH_4 flux is unclear
4. Climate change is warming air and ocean temperature, decreasing sea ice, altering freshwater inputs and Arctic Ocean circulation, and changing the biogeochemistry of estuarine and marine waters
5. The potential effects of anthropogenic climate change on carbon pools and fluxes in the subsea permafrost domain remain unknown

3. Questionnaire instructions

You will be asked to provide estimates of the magnitude and timing of subsea permafrost carbon stocks and fluxes in the past (section 5.1), present (5.2), and future (5.3). Given the large spatial and temporal scales of interest, we ask you to consider the overall response of the circumarctic subsea permafrost domain, defined as the unglaciated continental shelf areas exposed during the Last Glacial Maximum that are currently inundated (Fig. 2). For the future (section 5.3), we ask for estimates of carbon fluxes for two warming scenarios from the most recent IPCC radiative forcing scenarios (RCP4.5 and RCP8.5; Figs. 3-6). We will ask for estimates over short (Present-2050), medium (Present-2100), and long (Present-2300) time frames for. Climate projections and estimates of system response become increasingly uncertain for distant time frames. However, because subsea permafrost can take many decades or centuries to fully respond to disturbance, we have included the 2300-time step to account for lags in this response.

Because of the compound assumptions inherent to this kind of assessment, you will be asked to provide a subjective confidence interval around your estimate defined as follows:

Lower = I consider there to be a 95% chance that the actual value is greater than this value
Central = This is my best estimate of system response
Upper = I consider there to be a 95% chance that the actual value is lower than this value

For each question, you will have a chance to indicate your level of confidence and expertise concerning your answer, make comments on how you selected your estimates, and identify key sources of uncertainty concerning the future response of the system (e.g. what data or processes missing from current understanding would most improve our ability to predict system behavior). If there is not yet clear supporting evidence in the literature, but you have some basis for an estimate based on professional judgment, please make a note of that. These supporting questions allow us to compare responses from multiple experts and are just as valuable as the quantitative estimates. If you feel you can truly provide no useful input on a question, you can leave it blank.

The five-point "**Confidence level**" scale is defined as follows:

1= My answer is my best guess, but I am not confident in it; it could easily be far off the mark.
2= My answer is an educated guess; it could be far off the mark, but I have some confidence in it.

3= I am moderately confident in my answer; the true value is likely different from my answer, but in the generally range.

4= I am confident in my answer; the true value is likely to be somewhat different from my answer, but it is unlikely to be dramatically different.

5= Given current understanding, I would be surprised if my answer were far off from the true value.

The five-point "**Expertise level**" scale is defined as follows:

1= I have little familiarity with the literature and I do not actively work on these particular questions.

2= I have some familiarity with the literature and I've worked on related questions but haven't contributed to the literature on this issue; it is not an area of central expertise for me.

3= I have worked on related issues and have contributed to the relevant literature but do not consider myself one of the foremost experts on this particular issue.

4= I am very familiar with relevant literature and have worked on related questions. This is an area of central expertise for me.

5= I contribute actively to the literature directly concerned with this issue, and I consider myself one of the foremost experts on it.

4. Climate Scenarios

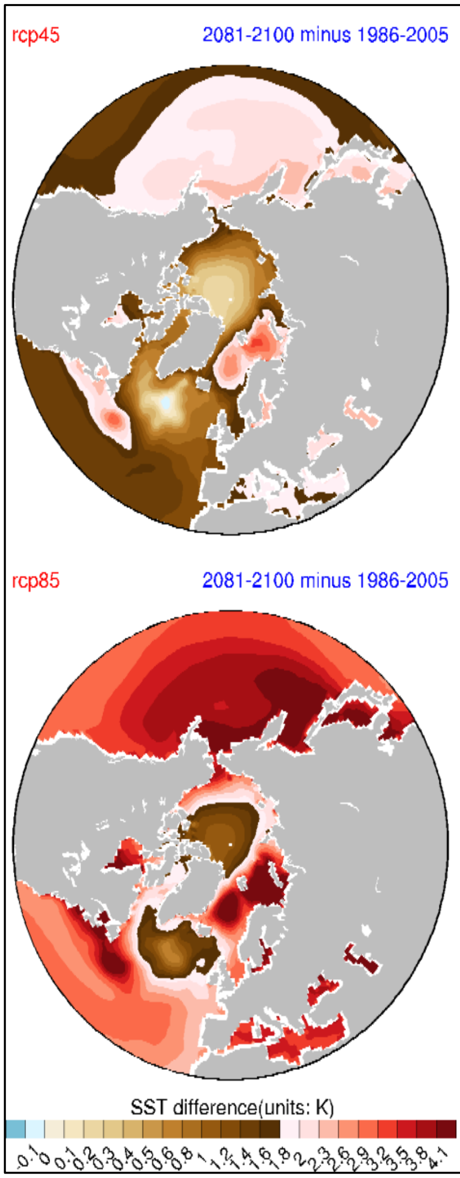

Figure 3. Projected changes in mean annual sea surface temperature (SST) from the recent past (1986-2005) to the end of century (2081-2100) for representative concentration pathway scenarios RCP4.5 and RCP8.5. The CMIP5 models included are bcc-csm1-1, bcc-csm1-1-m, CanESM2, CCSM4, CNRM-CM5,CESM1-CAM5, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, GISS-E2-H, HadGEM2-AO, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC5, ,MIROC-ESM, MIROC-ESM CHEM, MPI-ESM-LR, MPI-ESM- MR, MRI-CGCM3, NorESM1-M,NorESM1- ME. Data extracted and plotted by Shengpin He.

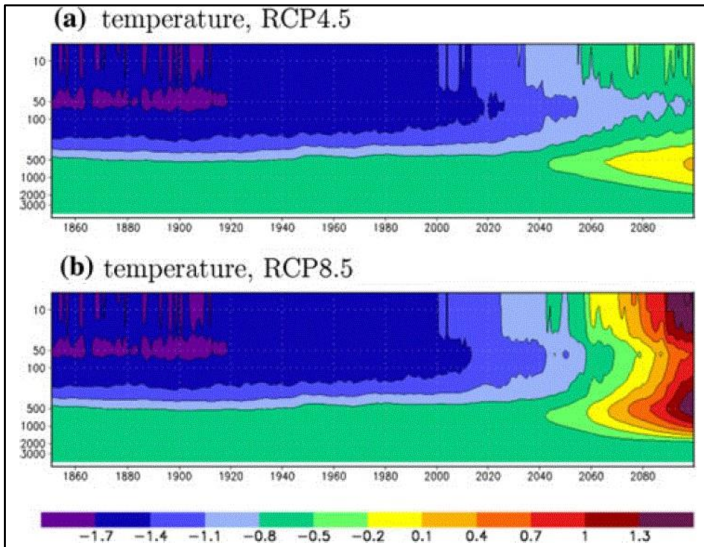

Figure 4. Vertical ocean temperature distribution (in ºC) from EC-Earth, averaged over the Arctic Ocean (Koenigk et al. 2013).

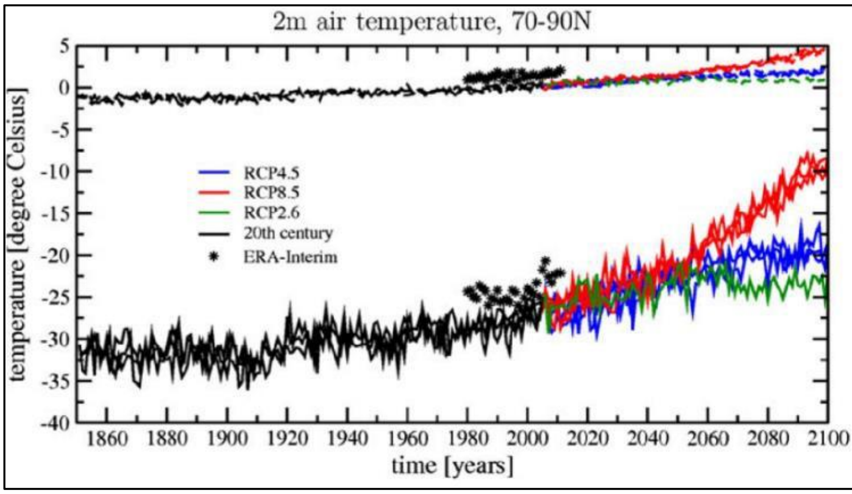

Figure 5. Summer (JJA, *dashed*) and winter (DJF, *solid*) mean 2m air temperature in °C averaged over 70-90 N in the twentieth century simulations (*black*) and three RCP scenarios from EC-Earth (a global coupled climate model) and the ERA-Interim reanalysis (*stars*). (Koenigk *et al*. 2013).

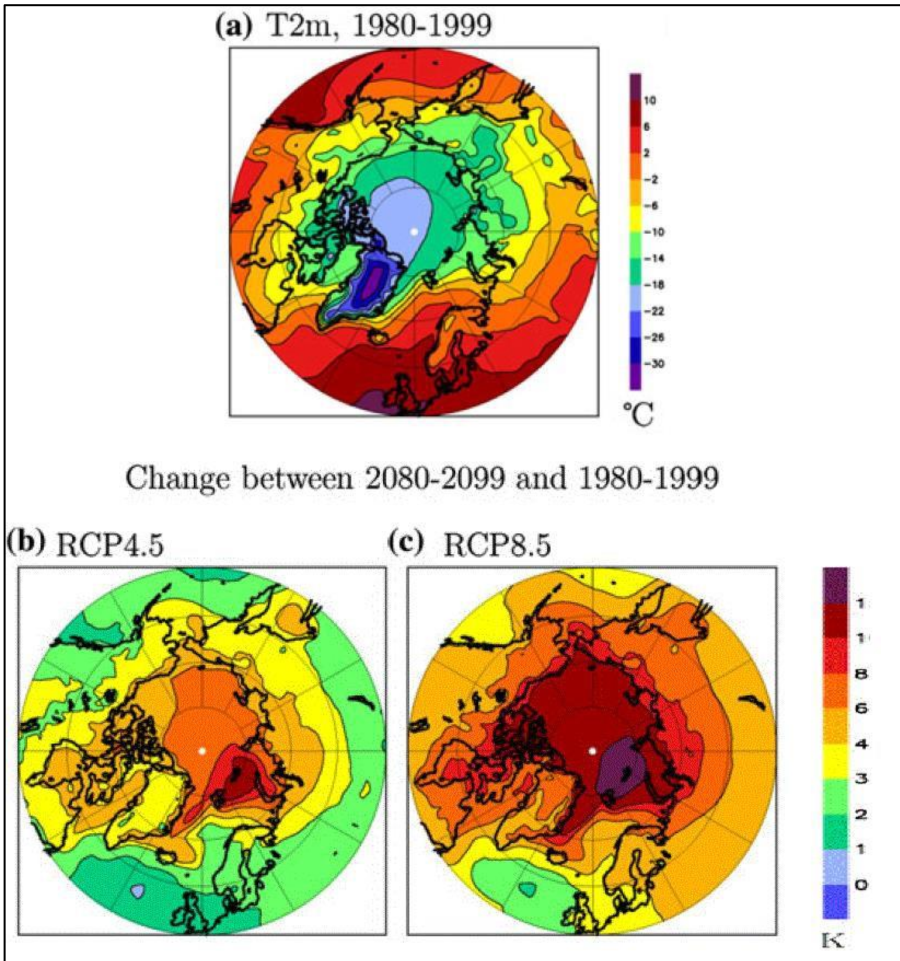

Figure 6. a) Mean annual air temperature at 2m in ºC from EC-Earth, averaged over 1980-1999. b-c) projected changes in mean annual air temperature at 2m by 2080-2099 for RCP4.5 (b) and RCP8.5 (c). (Koenigk et al.2013).

5. Questions

Respondent Information	
Gender	
Age	
General field (biogeochemistry, geophysics, marine biology, ecosystem ecology, industry etc.)	
Research discipline (subsea permafrost, general permafrost, methane hydrates, SOM etc.)	
Rate yourself on a scale of 1 to 5 where 1 is exclusively field research and 5 is exclusively modeling research.	
Country of origin	
Country of residence	
Have you previously participated in an expert assessment on any topic?	
How many years of experience do you have in subsea permafrost research?	
Primary geographic region/s of expertise	

Example question

Example response table. Please fill out each question completely as in the example below (example responses in red).

Your estimate in X			Confidence level (1-5)	Expertise level (1-5)
5% (Lower)	**Central**	**95% (Upper)**		
30	50	90	2	4
How did you generate these estimates (mark all that apply)? a) published empirical data: Yes b) published model estimates: Yes c) unpublished data: d) professional opinion: Yes e) other (please specify):			**What are the largest sources of uncertainty in this estimate?** The distribution of X is unknown. More measurements of Y in the Z geographic region would reduce this uncertainty.	
Additional comments: My guess is based on my study area, and I am only somewhat familiar with the rest of the areas.				

5.1 Permafrost extent and carbon stocks at the Last Glacial Maximum

Question 1. What is the area of formerly subaerial permafrost that was inundated after the Last Glacial Maximum (26,500 years before present)?

Note: This does not include areas that were glaciated or covered by perennial ice.

Your estimate in km²			**Confidence level (1-5)**	**Expertise level (1-5)**
5% (Lower)	**Central**	**95% (Upper)**		
How did you generate these estimates (mark all that apply)? a) published empirical data: b) published model estimates: c) unpublished data: d) professional opinion: e) other (please specify):			**What are the largest sources of uncertainty in this estimate?**	
Additional comments:				

Question 2. At the Last Glacial Maximum how much organic carbon was stored in and on the continental shelves that are now submerged?

Note: This question only considers soil organic matter (SOM) present at that time, not including CH_4 stocks.

Your estimate in Gt C (1Gt = 10^{12} Kg = 10^{15}g)			**Confidence level (1-5)**	**Expertise level (1-5)**
5% (Lower)	**Central**	**95% (Upper)**		
How did you generate these estimates (mark all that apply)? a) published empirical data: b) published model estimates: c) unpublished data: d) professional opinion: e) other (please specify):		**What are the largest sources of uncertainty in this estimate?**		
Additional comments:				

5.2 Current permafrost extent, carbon stocks, and carbon fluxes

Question 3. What is the current area of subsea permafrost?

Note: This question concerns the area of the subsea permafrost domain (Fig. 2) still underlain by perennially-frozen material.

Your estimate in millions of km^2			Confidence level (1-5)	Expertise level (1-5)
5% (Lower)	Central	95% (Upper)		

How did you generate these estimates (mark all that apply)?	What are the largest sources of uncertainty in this estimate?
a) published empirical data: b) published model estimates: c) unpublished data: d) professional opinion: e) other (please specify):	
Additional comments:	

Question 4. What are current organic carbon stocks in and on the continental shelves of the Arctic Ocean (subsea SOM + surface-sediment OM)?

Note: This question only considers organic carbon in sediment and soil on the continental shelves and excludes CH_4 stocks, which will be addressed in the next question.

Your estimate in Gt C			Confidence level (1-5)	Expertise level (1-5)
5% (Lower)	Central	95% (Upper)		

How did you generate these estimates (mark all that apply)?	What are the largest sources of uncertainty in this estimate?
a) published empirical data: b) published model estimates: c) unpublished data: d) professional opinion: e) other (please specify):	
Additional comments:	

Question 5. How much CH_4 is stored in and on the continental shelves of the permafrost zone?

Note: This question includes all CH_4 stocks, hydrate or otherwise.

Your estimate in Gt C (100 Gt of C = 133 Gt of CH_4)			**Confidence level (1-5)**	**Expertise level (1-5)**
5% (Lower)	**Central**	**95% (Upper)**		

How did you generate these estimates (mark all that apply)?	**What are the largest sources of uncertainty in this estimate?**
a) published empirical data: b) published model estimates: c) unpublished data: d) professional opinion: e) other (please specify):	
Additional comments:	

Question 6. What is the current net flux of CO_2 from the subsea permafrost domain (Figure 2) to the water column?

Note: A positive value indicates net release of CO_2 to the water column.

Your estimate in Tg yr^{-1} ($1Tg = 10^9$ Kg $= 10^{12}$g)			**Confidence level (1-5)**	**Expertise level (1-5)**
5% (Lower)	**Central**	**95% (Upper)**		

How did you generate these estimates (mark all that apply)?	**What are the largest sources of uncertainty in this estimate?**
a) published empirical data: b) published model estimates: c) unpublished data: d) professional opinion: e) other (please specify):	
Additional comments:	

Question 7. What is the current net CH_4 release from the subsea permafrost domain to the water column?

Note: A positive value indicates net release of CH_4 to the water column.

Your estimate in Tg C yr^{-1} (100 Tg of C = 133 Tg of CH_4)			**Confidence level (1-5)**	**Expertise level (1-5)**
5% (Lower)	**Central**	**95% (Upper)**		

How did you generate these estimates (mark all that apply)?	**What are the largest sources of uncertainty in this estimate?**
a) published empirical data: b) published model estimates: c) unpublished data: d) professional opinion: e) other (please specify):	
Additional comments:	

Question 8. What is the current net CH_4 release from the subsea permafrost domain to the atmosphere?

Note: A positive value indicates net release of CH_4 to the atmosphere. This question tries to assess CH_4 uptake during transport through the water column (i.e. if your answers below equal your answers from the previous question, it would signify that no CH_4 was oxidized during transport).

Your estimate in Tg C yr^{-1} (100 Tg of C = 133 Tg of CH_4)			**Confidence level (1-5)**	**Expertise level (1-5)**
5% (Lower)	**Central**	**95% (Upper)**		

How did you generate these estimates (mark all that apply)?	**What are the largest sources of uncertainty in this estimate?**
a) published empirical data: b) published model estimates: c) unpublished data: d) professional opinion: e) other (please specify):	
Additional comments:	

5.3 Projections of carbon fluxes in the future

Question 9. What percentage of the subsea SOM stocks estimated in Question 4 could be affected by anthropogenic climate change for the following time steps?

Note: This question seeks to understand what portion of subsea SOM is potentially responsive to climate change on decadal to centennial timescales (e.g. it could experience a change in thermal or chemical state) versus subsea SOM that is effectively isolated from anthropogenic climate change because of its location, physical protection, or other factors. The question is **not** asking how much of the SOM will be mineralized or otherwise destabilized, just how much could experience any change in state because of anthropogenic climate change. Given the general nature of this question, we do not ask you to provide independent estimates for different warming scenarios.

	Your estimate in %			**Confidence level (1-5)**	**Expertise level (1-5)**
Year	**5% (Lower)**	**Central**	**95% (Upper)**		
2050					
2100					
2300					

How did you generate these estimates (mark all that apply)?

a) published empirical data:
b) published model estimates:
c) unpublished data:
d) professional opinion:
e) other (please specify):

What are the largest sources of uncertainty in this estimate?

Additional comments:

Question 10. What percentage of the subsea CH_4 stocks estimated in Question 5 could be affected by anthropogenic climate change for the following time steps?

Note: This question seeks to understand what portion of subsea CH_4 is potentially responsive to changes climate change on decadal to centennial timescales (e.g. it could experience a change in thermal or chemical state) versus subsea CH_4 that is effectively isolated from anthropogenic climate change because of its location, physical protection, or other factors. The question is **not** asking how much of the CH_4 will released, just how much could experience any change in state because of anthropogenic climate change. Given the general nature of this question, we do not ask you to provide independent estimates for different warming scenarios.

	Your estimate in %			**Confidence level (1-5)**	**Expertise level (1-5)**
Year	**5% (Lower)**	**Central**	**95% (Upper)**		
2050					
2100					
2300					

How did you generate these estimates (mark all that apply)?

a) published empirical data:
b) published model estimates:
c) unpublished data:
d) professional opinion:
e) other (please specify):

What are the largest sources of uncertainty in this estimate?

Additional comments:

Question 11. How much could CO_2 flux from the subsea permafrost domain to the water column change for the following climate scenarios and time steps?

Note: This question asks for percentage change relative to estimates of current CO_2 flux from Question 6. Possible responses range from -100% to +∞, with negative values indicating a decrease and positive values indicating an increase.

	Your estimate in %						**Confidence level (1-5)**	**Expertise level (1-5)**
	RCP4.5			**RCP8.5**				
	5% (Lower)	**Central**	**95% (Upper)**	**5% (Lower)**	**Central**	**95% (Upper)**		
2050								
2100								
2300								

How did you generate these estimates (mark all that apply)?

a) published empirical data:
b) published model estimates:
c) unpublished data:
d) professional opinion:
e) other (please specify):

What are the largest sources of uncertainty in this estimate?

Additional comments:

Question 12. How much could CH_4 flux from the subsea permafrost domain to the atmosphere change for the following climate scenarios and time steps?

Note: This question asks for percentage change relative to estimates of current CH_4 flux from Question 8. Possible responses range from -100% to +∞, with negative values indicating a decrease and positive values indicating an increase. While responding, please consider possible changes in CH_4 release from the continental shelves and possible changes in uptake/oxidation dynamics in the water column.

	Your estimate in %						**Confidence level (1-5)**	**Expertise level (1-5)**
	RCP4.5			**RCP8.5**				
	5% (Lower)	**Central**	**95% (Upper)**	**5% (Lower)**	**Central**	**95% (Upper)**		
2050								
2100								
2300								

How did you generate these estimates (mark all that apply)?

f) published empirical data:
g) published model estimates:
h) unpublished data:
i) professional opinion:
j) other (please specify):

What are the largest sources of uncertainty in this estimate?

Additional comments:

5.4 Final questions

Question 13. As this assessment is not comprehensive (i.e. there are many pools and fluxes that are not explicitly estimated in this survey), what additional carbon pools or fluxes are or could be influential in determining the net ecosystem carbon balance of the subsea permafrost domain?

Pool or flux not considered in previous questions	**Potential impact on total net ecosystem carbon balance of the subsea permafrost domain** (% increase or decrease or mass of C in units you specify)	**Comments**

Question 14. Do you have any final comments or know of any other experts qualified to answer one or more of these questions?

Comments		
Expert name	**Email**	**Area of expertise**

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