Will Arctic Sea Ice Loss Trigger Abrupt Climate Change?

Stuart B. Heinrich
sbheinric@gmail.com

January 6, 2019

1 Introduction

The Arctic air is warming at more than double the rate of the global temperature increase (33), and is expected to experience the most intense warming over the remainder of this century (11). As a result of this warming, the extent and volume of sea ice in the Arctic Ocean during the summer has exhibited exponential decline, and if the current exponential trend continues, it appears likely that the Arctic will experience the first ice free period sometime within the next 5 years, with a best guess around the year 2022 (Section 2).

This is concerning, because Arctic sea ice, and the cold conditions it sustains in the water, serves to stabilize large deposits of methane hydrates (Section 3) in subsea permafrost, particularly in the shallow waters of the East Siberian Arctic Shelf (ESAS) (Section 4). Although the reserves of methane hydrate in the ESAS are highly uncertain, current resources estimates are close to 900 Gt of methane carbon (Section 5).

Unlike the carbon stored in terrestrial permafrost, which must first be converted into carbon dioxide or methane gas through microbial action before it can be released into the atmosphere, frozen methane hydrates in the ESAS merely require the surrounding ice to melt. If the sediment that contains hydrate is warmed, the hydrate will dissociate to produce methane gas bubbles that will mostly be released into the atmosphere. Thus, it is conceivable that the entire reserve of methane hydrates could be released into the atmosphere within a few years of the Arctic sea ice melting.

For reference, the atmosphere currently contains about 5 Gt of methane carbon, and the annual global carbon emmissions from all sources combined (human and natural) are currently less than 10 Gt carbon per year, mostly in the form of carbon dioxide. Thus, if all the methane from the ESAS were released in a single year, it would represent a nearly 100 fold increase in global carbon emmissions. Furthermore, this carbon would be in the form of methane, which has a warming effect approximately 84 times greater than carbon dioxide (over a 20 year period) (35).

The release of even a small fraction of the methane reserves in the ESAS could greatly accelerate the overall pace of global warming (Section 6). For example, Whiteman et al. (51) showed that a release of a mere 50 Gt methane (or 5% of the ESAS reserves) over a 10 year period would directly increase global average temperature to exceed 2 °C by 2035 and 3 °C by 2070, without considering additional feedbacks. However, this would surely trigger additional feedbacks, because for example terrestrial permafrost is thought to become susceptible to thawing after a 1.5 - 2 °C temperature rise (2, 44, 14, 50), and a temperature increase of 3 °C would likely result in destabilization of 85% of global hydrate deposits and release of 4000 Gt of methane carbon (3). In short, permafrost thawing of any kind leads to additional warming which further accelerates the thawing of more permafrost in a viscious feedback cycle that is likely to be unstoppable.

Although there exist some methane sinks that could prevent or delay some of this methane from reaching the atmosphere (Section 7), they are unlikely to make a significant difference in the face of widespread permafrost thawing. For these reasons, it is feared that impending summer ice loss in the Arctic as soon as 2020 could trigger abrupt climate change (35, 48) termed the 'Clathrate gun' (35), potentially leading to the initiation of a runaway greenhouse effect with drastic temperature increases in the span of only a few years or decades.

Not only do Intergovernmental Panel on Climate Change (IPCC) models grossly underestimate the rate of sea ice decline(16, 6) by decades, but positive feedbacks such additional emissions due to thawing of terrestrial and subsea permafrost are not even incorporated into IPCC or models, or models in the Coupled Carbon Cycle Climate Model Intercomparison Project (C^4MIP). As a result, these models may grossly over-estimate the amount of time that humanity has left, leading to a very false sense of future prosperity.

Schneider von Deimling et al. (36) proposed a model that does include feedbacks due to terrestrial permafrost melting, but their model still does not consider subsea permafrost, or the potential release of methane hydrates as discussed in this paper. As such, precise outcomes of dissociating methane hydrates on the global climate are still difficult to quantify (Section 8), but all evidence so far suggests the outcomes may be catastrophic, and may have the potential to disrupt world order within the next decade.

2 Ice-loss in the Arctic sea

Arctic sea ice volume naturally exhibits strong seasonal trends due to summer melting, with about 16,400 km^3 of sea ice being thawed each year (37) (Fig. 1). However, in recent years, the minimum sea ice volume during the summer has exhibited a clear downward exponential trend (Fig. 2). Looking over the past 1,500 years, it is clear that this rate of ice loss is truly unprecedented, and is very clearly correlated to increased greenhouse gasses causing global warming (Fig. 5).

Although we cannot know for sure if this exponential trend will continue, and seasonal variations create a large degree of yearly variation, there is no known effect that would cause the long-term trend to slow down. To the contrary, the general trend of increased greenhouse gasses and global warming is expected to continue the observed exponential trend. Therefore, based on current projections of the 95% confidence band of the observed exponential trend, it is likely that the first summer with complete ice melt will occur in the range of 2019 - 2030, with a best guess of 2022 (Fig. 2).

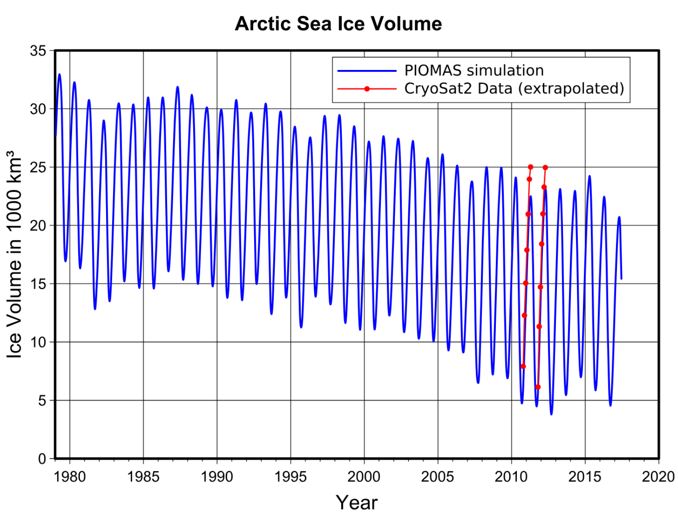

Figure 1. PIOMAS (37) estimates of Arctic sea ice volume. `https://commons.wikimedia.org/wiki/File:Plot_arctic_sea_ice_volume.svg`

It should be noted that the ability to continue making sea-ice measurements could end at any time, because the satellites used to track these conditions (F-16,F-17,F-18) have long ago reached end of life, and could fail at any time (52). A newer replacement, F-19, was launched in 2014 but already suffered a sensor failure and become inoperable. The final satellite in this series, F-20, had already been constructed and was scheduled to be launched in 2017, but the Trump administration ordered it's destruction citing "storage costs" of the satellite, and a new replacement cannot be launched until at least 2022 (52). This is akin to turning off the headlights in a car with the pedal to the metal while driving towards a brick wall at night.

3 Methane Hydrates

Approximately 30% of global permafrost carbon is concentrated in 7% of the permafrost region (1.32 million km^2) in North Siberia, Alaska, and northwest Canada (2). Here, ice organic rich silt-dominated sediments, termed yedoma, were deposited to an average depth of 25 m in unglaciated regions during the late Pleistocene glacial period (2). The average organic carbon contents of frozen yedoma, typically 2-5%, are higher and more decomposable than in most thawed mineral soils because fresh organic inputs from the tundra-steppe ecosystem were buried and frozen into rapidly accumulating sediment (2).

When permafrost thaws, it decomposes and is consumed by microbes that release the carbon either as carbon dioxide or methane gas, depending on the amount of oxygen present. Thus, methane that is released in this manner is limited by the growth rate of microbe populations, which may depend on other environmental conditions such as temperature.

Methane that is produced in sediments and subjected to the right pressure and temperature conditions may form methane hydrates. Methane hydrates (a.k.a. methane clathrates) are ice-like solids consisting of a lattice of hydrogen-bonded water molecules forming cage-like structures, each of which contain a single molecule of methane. Methane hydrate is stable within geologic settings where relatively high pressures and cold temperatures exist (23), typically forming at ocean depths greater than 500 m in temperature latitudes or greater than 300 m at high latitudes (35).

The unique molecular structure of methane hydrate is very concentrated such that one unit volume of methane hydrate expands approximately 160-180 times when dissociated to methane gas in response to warming temperature or decreasing pressure (35, 23). As a result, when hydrate in permafrost dissociates it creates immense pressure that causes cracks in the permafrost which rapidly accelerate the rate of additional thawing by around four orders of magnitude (48, 32).

Global estimates of the abundance of methane hydrate vary widely, but they all indicate that the amount of

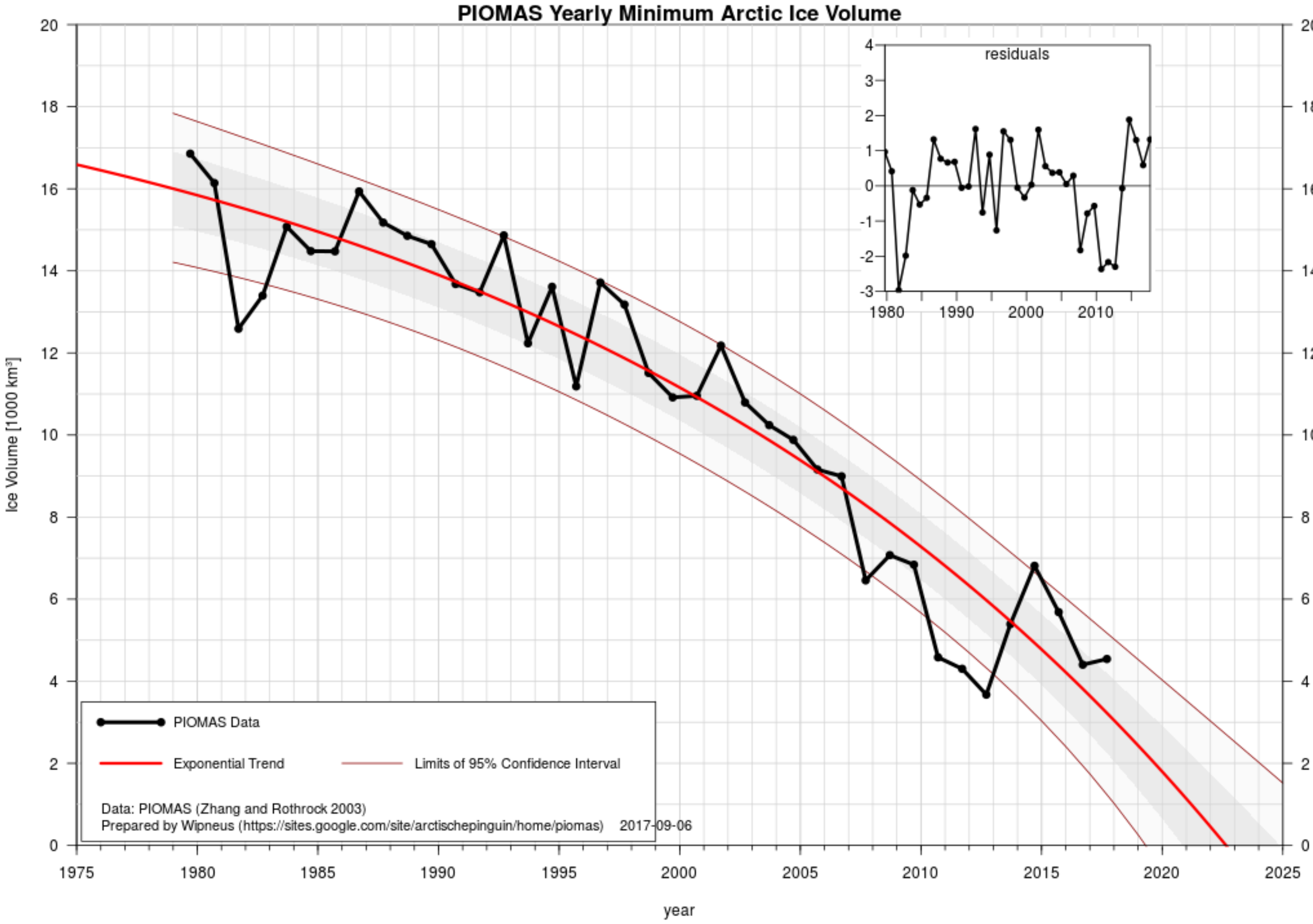

Figure 2. PIOMAS (37) estimates of minimum yearly Arctic sea ice volume. Figure reproduced from `https://sites.google.com/site/arctischepinguin/home/piomas`.

carbon stored within marine and terrestrial methane hydrate deposits is enormous (19, 26) and may rival all conventional and unconventional hydrocarbon sources combined.

A number of researchers have speculated that past periods of rapid atmospheric warming may have been initiated or significantly accelerated by the release of methane from dissociating methane hydrate deposits (17, 8, 23).

4 The East Siberian Arctic Shelf (ESAS)

The East Siberian Arctic Shelf (ESAS) is a large Arctic sea shelf, approximately 2.1 million km^2, which was formerly above ground yedoma permafrost and subsequently submerged in approximately 45 meters of Arctic water by post-glacial rise in sea level (32, 48). Normally, methane hydrate would not be able to form at such shallow depths, but the extremely cold conditions of Arctic water make it possible. Numerical modeling suggests that almost the entire ESAS region is likely to be saturated with gas hydrates (34) (Fig. 4).

Unlike the terrestrial permafrost in the Arctic which experienced a change in its thermal regime caused by the 6 - 7 °C mean annual air temperature increase since the last Glacial Maximum, sub-sea permafrost has been subjected to additional drastic transformations, e.g., inundation by the ocean, resulting in warming of the permafrost environment by as much as 17 - 20 °C (29). Thus, permafrost in the ESAS is expected to thaw first (48, 4).

Despite Arctic warming so far, sea surface temperatures in the ESAS have risen only about 0.5 °C per decade. Temperatures are now about 2 °C higher than 1980, but the trend is not well-defined (Fig. 3). So far, bottom sea temperatures in the ESAS have remained below freezing, ranging from -0.5 ˚C to -1.8 ˚C, such that permafrost degradation does not occur in it's present state (29). However, preliminary numerical experiments show that if the mean bottom surface temperature of the water within the thermokarst area is increased to 1 ˚C, then the upper permafrost ice complex would be completely destroyed (29), causing widespread thawing.

It is generally thought that the melting of sea ice has served to keep Arctic waters cold despite general Arctic warming. Therefore, once the sea ice completely melts, there will be nothing to prevent the additional summer heat from rapidly warming Arctic water temperatures, leading to the widespread thawing of subsea permafrost in the ESAS (48).

When this permafrost thaws, all of the carbon it contains will be potentially subject to release into the atmosphere, although raw carbon cannot be *immediately* released into the atmosphere because it must first be digested by growing microbe populations before it is converted into methane gas or carbon dioxide as waste, and this process could potentially take years or decades. However, some of this carbon will be in the form of methane hydrates or free methane gas, which could be released into the atmosphere almost immediately, and could potentially trigger a much more aggressive feedback loop. Therefore, it is critical to understand how much methane hydrate may be stored in the ESAS in order to accurately predict the resulting rate of global warming when it is released.

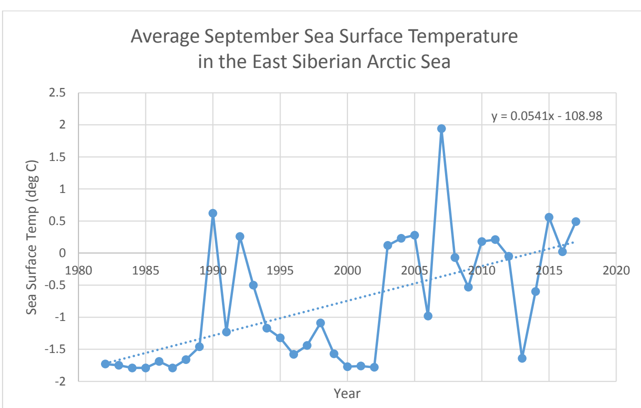

Figure 3. NOAA Optimum Interpolation (OI) Sea Surface Temperature (SST) (`https://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.html`) averaged over the month of September in the East Siberian Arctic Sea at (76.5, 168.5).

Already, partial thawing of permafrost in the ESAS is considered to be responsible for very high dissolved methane concentrations in the water column (42, 40, 43). In other areas such as the Laptev Sea, methane released from thawing permafrost is efficiently oxidized in the overlying frozen sediments such that methane concentrations in the water column have not yet significantly increased (49, 31). It is troubling that hydrate has even begun to dissociate at all, given that we do not anticipate the real increases in Arctic sea temperatures until the Arctic experiences an ice free summer.

5 How much is really there?

The global estimates of hydrate-bound gas in marine sediments vary by several orders of magnitude, and are thought to be highly uncertain (18). In a meta analysis, Milkov (26) found that global estimates can be distinguished by three periods: (1) pre-mapping and predrilling estimates from the 1970's to early 1980's, (2) predrilling estimates from the late 1980's to early 1990's; (3) estimates based on actual drilling results, from the late 1990's to present. In general, global estimates have decreased by at least one order of magnitude at transitions from one period to another, with global estimates initially coming in around 10,000 Gt methane hydrate, now reduced to about 500-2500 Gt (26, 35).

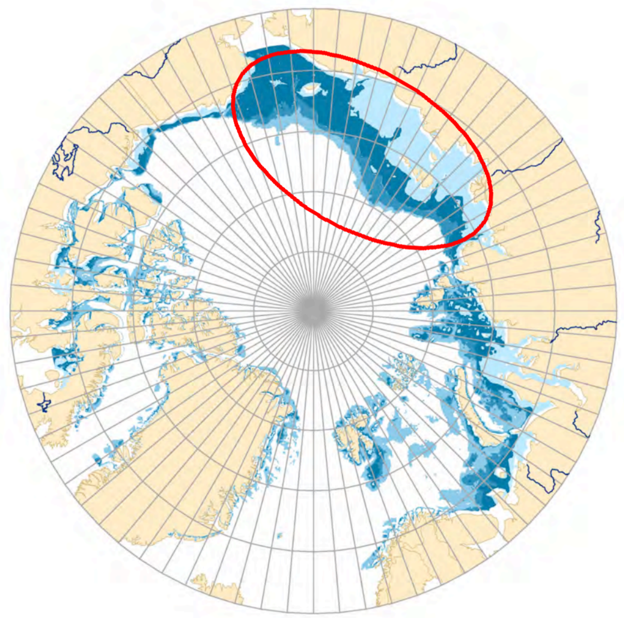

Figure 4. Map of methane hydrate potential associated with submarine permafrost, from Long et al. (21). Dark blue areas correspond to Bathymetric ranges of 30 - 100m, likely to be saturated with gas hydrates according to Romanovskii et al. (34). The East Siberian Arctic Shelf (ESAS) region is circled in red.

With that said, the drilling results leading to these reduced global hydrate estimes have thus far been restricted to non-Arctic regions. For example, the reduced global estimates of Milkov (26) were based on drilling estimates performed in the Gulf of Mexico (27), where they found only 10-30% of sediments in the presssure-temperature

(PT) stability zone to be hydrate bearing, with an average methane gas hydrate yield of 1.4-2.4 m^3 hydrate bound gas per cubic meter of hydrate bearing marine sediments.

If hydrate bearing sediments in the ESAS occurred with the same frequency and hydrate density as those sampled in the Gulf of Mexico (27), we can get an estimate of the total hydrate volume: using a land area 2.1 million km^2, assuming that 10-30% is hydrate bearing to a depth of 25 m, and using a hydrate yield of 1.2-2.3 m^3/m^3, this gives an estimate of 4-21 Gt of methane hydrate with likely an additional 2.7-14 Gt of free methane (9, 35), for a total of 6.7-35 Gt.

However, this estimate is likely grossly underestimated, because the climate and geological conditions in the Gulf of Mexico are completely different from the Arctic. In particular, there is no *in situ* source for methane in the Gulf of Mexico; rather, it has been hypothesized that hydrocarbons including methane may migrate from depth in the sediment section along fractures, faults, and other migration pathways (27). In contrast, approximately 80% of the ESAS is underlain with extremely carbon rich yedoma permafrost (47) which can be readily converted into methane by microbial action, and the region has already been observed to be venting unexpectedly large volumes of methane gas (42, 40, 43). Therefore, it seems much more likely that methane hydrates in the ESAS would have formed *in situ*, and at much higher methane concentrations than the Gulf of Mexico.

To our knowledge, there has never been any actual drilling estimates to confirm the methane hydrate yields in the Arctic, so the estimates remain highly uncertain. With that said, MacDonald (22) estimated the total permafrost reservoir of methane hydrate in the entire Arctic to be about 400 Gt, while Shakhova et al. (39) estimated 1400 Gt of total carbon stored in subsea permafrost of the ESAS. As was later explained in Shakhova et al. (41), this 1400 Gt estimate was based on an assumption of 540 Gt of frozen methane hydrate from Gramberg et al. (10) and Soloviev et al. (45), an additional 360 Gt of free methane gas based on the typical assumption that there will be 2/3 of the amount of free methane gas alongside hydrates (9, 35), and an additional 500 Gt of carbon based on Zimov et al. (54), under the stated assumption that the carbon content of subsea yedoma should be the same as terrestrial yedoma.

We were unable to acquire written proceedings for Gramberg et al. (10) and Soloviev et al. (45) due to their age, but these estimates are unlikely to be accurate because they are very outdated, and hence unlikely to be based on actual drilling results (26). Additionally, we note that Shakhova et al. (41) failed to account for the difference in land area when they estimated that the ESAS would contain 500 Gt of carbon based on Zimov et al. (54). Considering that the ESAS has an area of roughly 2.1 million km^2, and assuming yedoma deposits occupied 80% of the ESAS (47), using the carbon density of yedoma estimated by Zimov et al. (54) should lead to an estimate of 900 Gt carbon in the ESAS, rather than the 500 Gt assumed by Shakhova et al. (41). However, this is a moot point because Zimov et al. (54) were estimating the *total* carbon content of yedoma, so it would be redundant to add this to the carbon content due to methane hydrates if the hydrates were generated *in situ* from the existing carbon pool.

How much methane hydrate and free methane gas is actually there? It is likely much more than the upper bound of 35 Gt that would be estimated using conditions similar to the Gulf of Mexico where there is no *in situ* methane source (27), and likely less than the 900 Gt estimate of total permafrost carbon based on Zimov et al. (54). According to Gramberg et al. (10) and Soloviev et al. (45), the amount of methane hydrate and free methane could be close to 900 Gt, but without actual drilling estimates, there is so far no way to know.

6 Estimated rate of methane release

Shakhova et al. (40) estimated that a release of 50 Gt of methane from the ESAS might be emitted over a period of 1-5 years, which they predicted could lead to an increase in global surface temperature of 3.3 °C by 2100, and Whiteman et al. (51) estimated that Arctic ice melt could trigger the same 50 Gt of methane to be released over a 10 year period, which they assumed may start in 2015, and predicted a 4 °C rise by 2100. This simulation was criticized Nisbet et al. (30) in their unpublished letter to the editor, where they pointed out the geological record does not indicate any historical methane release of this magnitude, and that there is currently no release of methane in the Arctic of this scale.

Although it is true that methane has not been released from the ESAS at anywhere near this rate since 2015 as was predicted by Whiteman et al. (51), it was implied that this release would be subsequent to Arctic summer ice-melt, which has not fully occurred yet, but is nonetheless likely to occur soon. Furthermore, although the geological record may not contain any examples of methane release at this volume, there is ample evidence for rapid dissociation of methane triggering abrupt climate change in the past(17, 8, 23, 35), and conditions in the past are not always representative of the future – in particular, sediments in the past may have contained different amounts of hydrates, and the temperature rises in the past in the absence of human activity are not necessarily comparable.

Nonetheless, we are skeptical of the accuracy of Whiteman et al. (51)'s estimate for two major reasons: (a) the estimate of 50 Gt of methane being released was based on an earlier estimate by Shakhova et al. (39) that about 3.5% of the carbon in the ESAS could be released "at any time" due to openly venting talics and/or seismic faults, but we note that a release of methane due to seismic activity is not comparable to the release of methane due to widespread permafrost thawing. Arguably, a much larger percentage of the available hydrate pool would be subject to release due to permafrost thawing, perhaps 100%; (b) the assumption that it would take 10 years to release this methane was not informed by any educated guess or numerical modeling.

We are not aware of any numerical modeling to predict the actual rate that subsea permafrost would melt as a result of Arctic sea-ice loss. Therefore, we propose here a simple approximate guess based on the following observation: during each summer, the Arctic thaws approximately 16000 km^3 of sea-ice volume as a result of seasonal melt (37). Because the amount of seasonal ice melt is based mainly on the total solar radiation during summer, which remains roughly constant due to the Earth's rotation, we roughly assume that when the Arctic runs out of surface ice to melt, it will continue by melting subsea permafrost at roughly the same rate that surface sea ice was previously being melted. This is not a perfect assumption, as the actual rate would depend largely on the rate of mixing between sea surface water that is being directly heated and sea bottom among other potential factors, but in lieu of a more realistic numerical model it is the only estimate that we have.

Thus, we predict that seasonal melting will begin to directly melt subsea permafrost in the year after the Arctic sea ice minimum first reaches zero (i.e., the first "blue ocean" event), which we expect to occur sometime in the range of 2020 - 2025, and denote as year 0. Based on the current trendline, the minimum sea ice in summer is reduced by about 1000 km^3/yr each year, so we predict about 1000 km^3 of subsea permafrost to melt in year 1 (i.e., the first year subsequent to a blue ocean), 2000 km^2 in year 2, 3000 km^3 in year, 3, etc.

The gas hydrate yield could be as low as 2.4 m^3 hydrate bound gas per cubic meter of hydrate bearing marine sediments (for example, as in the Gulf of Mexico), or potentially as high as 42 m^3, according to earlier estimates (26). Therefore, each 1000 km^3 of permafrost could release 4,000 - 76,000 km^3 methane gas, or 1.92 - 36.5 Gt methane. After 10 years, this would amount to a release of 105 - 900 Gt methane (assuming a maximum of 900 Gt methane exists in the ESAS).

According to numerical models by Thatcher et al. (48), the delay between the onset of warming and emission of methane gas, resulting from the time taken for thermal diffusion, hydrate dissociation, and gas migration can be less than 30 years for hydrates submerged in water depths of approximately 400 meters, when waters are warmed linearly by 1 °C over a period of 30 years. However, temperature increases in the Arctic waters could rise drastically faster than 1 °over 30 years once the summer ice melts. In addition, the much shallower waters of the ESAS (approximately 45 m) and increasingly turbulent water conditions (32) would further reduce the delay in comparison to that modeled by Thatcher et al. (48).

7 Methane sinks

Not all of the methane that is dissociated from subsea permafrost will make it into the atmosphere. Ruppel and Kessler (35) identified several methane sinks that might prevent this methane from reaching the atmosphere or having its full potential warming effect:

- Anaerobic oxidation of methane (AOM) which is carried out by a consortium of microbes primarily in the centimeters to meters just below the ocean floor acts as a 'biofilter' that can prevent some of the upwardly migrating methane gas from deeper in the sediment from reaching the ocean floor (35). It has been estimated that up to 80-90% of the 400 Tg/yr methane that is currently released globally from marine sediments deeper down are absorbed in this layer (13). However, for efficient methane consumption the population of AOM communities must grow to accommodate additional methane. The doubling time is roughly 7 months, so the genesis of an effective AOM microbial filter would be on the order of decades (28, 32). Thus, it is unlikely that AOM filters would be able to compensate for a rapid increase in methane flux in the ESAS on a short enough timescale to matter (32). In general, the efficiency of AOM is reduced under higher flux scenarios which leads to the possibility of rapidly ascending gas bubbles that bypass this filter (35).

- Physical characteristics of marine sediments may prevent free gas that has dissociated deeper down from reaching the seafloor surface. For example, low-permeability sediments, structural traps, etc (35). However, these are unlikely to be effective during a period of rapid thawing, due to the immense pressure of dissociating hydrate that can form cracks in the permafrost and rapidly accelerate the rate of additional thawing by around four orders of magnitude (48, 32).

- Once methane is emitted from the seafloor, if the surrounding water has low methane concentration, it may diffuse out of the rising bubbles into the water column, replacing the methane in rising bubbles with oxygen and nitrogen. The amount of methane that reaches the water surface is largely a function of seafloor depth and bubble size (35). However, this sink is not very effective in the shallow waters of the ESAS – about 67-72% of the methane in the relatively small bubbles currently being released in the ESAS already reaches the surface (43), and if the rate of methane release increases, the bubbles will be larger and could retain closer to 100% of their methane. Furthermore, any methane that is absorbed into the water in this way is only delayed from reaching the atmosphere. It will eventually be released into the atmosphere by the action of wind and turbulence (43), which is already very high in the Arctic, and expected to increase as a result of further Arctic warming (32).

- Once dissolved in seawater, aerobic microbial oxidation (MOx) can limit the flux of dissolved methane into the atmosphere (35). MOx was traditionally thought to be a very slow process, although more recent research indicates it may become more effective when seawater with high methane concentrations is perturbed (25). Regardless, this would not have much effect once the size of bubbles increase, allowing methane to bypass absorption in the water column (43).

- An estimated 90% of all methane released into the atmosphere is eventually removed by oxidation with the hydroxyl radical in the troposphere within about a decade (7). The ultimate result of this oxidation is conversion into carbon dioxide (35), which is still a powerful greenhouse gas, but not as bad as methane. However, the fact hat methane's lifetime in the atmosphere is only temporary is already known, and assumed throughout all the simulations of warming due to methane release.

Ultimately, the rate of release matters because a higher proportion of methane can be absorbed by sinks when the rate of release is slow. However, all of the known sinks become less effective under scenarios of rapid release, as would be expected from a widescale thawing of subsea permafrost in the ESAS.

8 Why a few degrees matter

The atmosphere currently contains 5 Gt of methane, and about 730 Gt of carbon, approximately double that the 360 Gt of atmospheric carbon in pre-industrial times (54). In addition to the potentially 900 Gt of carbon in subsea permafrost, terrestrial permafrost contains approximately 900 Gt of carbon as well (54), and is widely thought to become susceptible to thawing after a 1.5 - 2 ˚C global average temperature rise (2, 44, 14, 50). The release of such a carbon pool would quickly take the planet to 3 ˚C warming, and at 3 ˚C temperature increase is predicted to result in destabilization of 85% of global marine hydrate deposits, releasing approximately 4000 Gt of methane carbon (3).

In total, there is approximately 40,000 Gt of carbon stored in ocean reserves, with another 1,500 Gt of carbon in soils and 650 Gt in vegetation (54), and all of these sources are subject to carbon release in positive feedback loops, so once the process is started, there would be no way to stop it. Although timescales are uncertain, such warming could eventually lead to the evaporation of all water on Earth in a runaway greenhouse effect, similar to the manner in which Mars is believed to have lost its oceans (38).

A full analysis of the economic, agricultural, humanitarian and ecological impacts on a degree by degree basis is far outside of the scope of this paper, and would be nearly impossible to validate. Some predictions can be found in Henson (12), although according to some more extreme predictions, it would seem unlikely for humanity to survive at 5-6 ˚C of warming (5).

In the short term, a few degrees of warming may not sound like much, but impacts would likely be widespread and severe. For example, Whiteman et al. (51) estimated that a mere 50 Gt release of methane would cause economic damages on the order of the entire global economy. We think that such economic outcomes are trivial in comparison to more tangible human costs resulting in reduced global food production. For example, it is expected that for every 1 ˚C temperature rise, global corn harvest yields could decline 7.4 % (53), while in the United States corn yields are expected to suffer 10.3% (53). Many other crops would be affected similarly.

Global food stocks are already tenuous (20), and it is predicted that the world will need to increase food production by 70% to meet global demand by 2050 (1), while at the same time the impact of a mere 2 ˚C could reduce food production by 15-20%. Thus, even with only a 2 ˚C increase this implies that there may only be enough food to feed $0.8/1.7 = 50\%$ of the world population.

The most immediate impact of global food shortages would likely be mass famine and starvation in third world countries. If shortages extend into the developed world, such that there is not enough food to feed the middle class, it could trigger hyperinflation of all major currencies, as one cannot put a price on the food needed to survive. Such hyperinflation could result in the collapse of financial institutions, making money held in stocks or banks inaccessible, grinding trade and business to a halt, and potentially collapsing governments. Ultimately, the result of a permanent reduction in food supply would inevitably be a mass dying of humans, and potentially a collapse of modern civilization as we know it. The scariest part is that all of this could potentially occur within our lifetimes.

References

[1] N. Alexandratos and J. Bruinsma. World agriculture towards 2030/2050: the 2012 revision. Technical report, ESA, Rome, 2012. Working paper No. 12-03.

[2] Kyle Anthony, Sergey A. Zimov, Gisela Grosse, M. C. Jones, Paige Anthony, F. Stuart Chapin, Jarod C. Finlay, M. Catherine Mack, S. N. Davydov, Peter Frenzel, and Steve Frolking. A shift of thermokarst lakes from carbon sources to sinks during the holocene epoch. *Nature*, 511:452–456, 2014.

[3] David Archer and Bruce Buffett. Time-dependent response of the global ocean clathrate reservoir to climatic and anthropogenic forcing. *Geochemistry, Geophysics, Geosystems*, 6(3), 2005. doi: 10.1029/2004GC000854. URL `https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2004GC000854`.

[4] David Archer, Bruce Buffett, and Victor Brovkin. Ocean methane hydrates as a slow tipping point in the global carbon cycle. *Proceedings of the National Academy of Sciences*, 106(49):20596–20601, 2009. ISSN 0027-8424. doi: 10.1073/pnas.0800885105. URL `http://www.pnas.org/content/106/49/20596`.

[5] Berrens. A degree by degree explanation of what will happen when the earth warms. URL `http://globalwarming.berrens.nl/globalwarming.htm`. Accessed: May 10, 2018.

[6] R. Bintanja and E. C. van der Linden. The changing seasonal climate in the arctic. *Sci Rep*, 3:1556, 2013. ISSN 2045-2322. URL `http://www.biomedsearch.com/nih/changing-seasonal-climate-in-Arctic/23532038.html`.

[7] R.J. Cicerone and R.S. Oremland. Biogeochemical aspects of atmospheric methane. *Global Biogeochemical Cycles*, 2(4):299–327, 1988. doi: 10.1029/GB002i004p00299. URL `https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/GB002i004p00299`.

[8] Gerald R. Dickens. A methane trigger for rapid warming? *Science*, 299(5609):1017–1017, 2003. ISSN 0036-8075. doi: 10.1126/science.1080789. URL `http://science.sciencemag.org/content/299/5609/1017.1`.

[9] Peter B. Flemings, Xiaoli Liu, and William J. Winters. Critical pressure and multiphase flow in blake ridge gas hydrates. *Geology*, 31(12):1057, 2003. doi: 10.1130/G19863.1. URL `+http://dx.doi.org/10.1130/G19863.1`.

[10] I.S. Gramberg, Kulakov Yu. N, Yu. E. Pogrebitsky, and D.S. Sorokov. Arctic oil and gas super basin. In *Proc. 10th World Petroleum Congress*, pages 93–99, London, 1983.

[11] S.J. Hassol. *Impacts of a warming Arctic : Arctic Climate Impact Assessment*. Cambridge University Press, Cambridge, U.K., 2004.

[12] Robert Henson. Warming world: Impacts by the degree, 2011. URL `http://dels.nas.edu/resources/static-assets/materials-based-on-reports/booklets/warming_world_final.pdf`.

[13] K.-U. Hinrichs and A. Boetius. *The Anaerobic Oxidation of Methane: New Insights in Microbial Ecology and Biogeochemistry*, pages 457–477. Springer Berlin Heidelberg, Berlin, Heidelberg, 2003. ISBN 978-3-662-05127-6. doi: 10.1007/978-3-662-05127-6_28. URL `https://doi.org/10.1007/978-3-662-05127-6_28`.

[14] IPCC. *Summary for Policymakers*, book section SPM, pages 1–30. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013. ISBN ISBN 978-1-107-66182-0. doi: 10.1017/CBO9781107415324.004. URL `www.climatechange2013.org`.

[15] Christophe Kinnard, M. Zdanowicz, Christian Fisher, David Isaksson, Elisabeth Anne de Vernal, and G. Thompson Lonnie. Reconstructed changes in arctic sea ice over the past 1,450 years. *Nature*, 479: 509–12, 11 2011.

[16] Torben Koenigk, Laurent Brodeau, Rune Grand Graversen, Johannes Karlsson, Gunilla Svensson, Michael Tjernström, Ulrika Willén, and Klaus Wyser. Arctic climate change in 21st century cmip5 simulations with ec-earth. *Climate Dynamics*, 40 (11):2719–2743, Jun 2013. ISSN 1432-0894. doi: 10.1007/s00382-012-1505-y. URL `https://doi.org/10.1007/s00382-012-1505-y`.

[17] Keith A. Kvenvolden. Methane hydrate - a major reservoir of carbon in the shallow geosphere? *Chemical Geology*, 71(1):41 – 51, 1988. ISSN 0009-2541. doi: https://doi.org/10.1016/0009-2541(88)90104-0. URL `http://www.sciencedirect.com/science/article/pii/0009254188901040`. Origins of Methane in the Earth.

[18] Keith A. Kvenvolden. Potential effects of gas hydrate on human welfare. *Proceedings of the National Academy of Sciences*, 96(7):3420–3426, 1999. ISSN 0027-8424. doi: 10.1073/pnas.96.7.3420. URL `http://www.pnas.org/content/96/7/3420`.

[19] Keith A. Kvenvolden and Thomas D. Lorenson. *The Global Occurrence of Natural Gas Hydrate*, pages 3–18. American Geophysical Union (AGU), 2013. ISBN 9781118668412. doi: 10.1029/GM124p0003. URL `https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/GM124p0003`.

[20] Francesco Laio, Luca Ridolfi, and Paolo D'Odorico. The past and future of food stocks. *Environmental Research Letters*, 11(3):035010, 2016. URL `http://stacks.iop.org/1748-9326/11/i=3/a=035010`.

[21] Philip Long, Signe White, Charlotte Sullivan, Herbert T. Schaef, and Donald J. Bradley. Preliminary geospatial analysis of arctic ocean hydrocarbon resources. 05 2018.

[22] Gordon J. MacDonald. Role of methane clathrates in past and future climates. *Climatic Change*, 16(3):247–281, Jun 1990. ISSN 1573-1480. doi: 10.1007/BF00144504. URL `https://doi.org/10.1007/BF00144504`.

[23] David McGuire, A. Anderson, Leif Christensen, Torben Rojle, Scott Dallimore, Laodong Guo, J. Hayes, Daniel Heimann, Thomas Lorenson, W. Macdonald, and Robie Roulet. Sensitivity of the carbon cycle in the arctic to climate change. 79, 12 2007.

[24] N. P. Mckay and Darrell S. Kaufman. An extended arctic proxy temperature database for the past 2,000 years. In *Scientific data*, 2014.

[25] C. D. Meile, K. S. Hunter, A-R. Diercks, V. L. Asper, V. J. Orphan, P. L. Tavormina, L. M. Nigro, J. J. Battles, J. P. Chanton, A. M. Shiller, D-J. Joung, R. M. W. Amon, A. Bracco, J. P. Montoya, T. A. Villareal, A. M. Wood, and S. B. Joye. The rise and fall of methanotrophy following a deepwater oil-well blowout. *Nature Geoscience*, 7:423–427, 2014. doi: 10.1038/ngeo2156. URL `http://dx.doi.org/10.1038/ngeo2156`.

[26] Alexei V. Milkov. Global estimates of hydrate-bound gas in marine sediments: how much is really out there? *Earth-Science Reviews*, 66(3):183 – 197, 2004. ISSN 0012-8252. doi: https://doi.org/10.1016/j.earscirev.2003.11.002. URL `http://www.sciencedirect.com/science/article/pii/S0012825203001296`.

[27] Alexei V. Milkov and Roger Sassen. Two-dimensional modeling of gas hydrate decomposition in the northwestern gulf of mexico: significance to global change assessment. *Global and Planetary Change*, 36(1):31 – 46, 2003. ISSN 0921-8181. doi: https://doi.org/10.1016/S0921-8181(02)00162-5. URL `http://www.sciencedirect.com/science/article/pii/S0921818102001625`.

[28] K Nauhaus, M. Albrecht, M. Elvert, A. Boetius, and F. Widdel. In vitro cell growth of marine archaeal-bacterial consortia during anaerobic oxidation of methane with sulfate. *Environ. Microbiol.*, 9:187–196, Jan 2007.

[29] D. Nicolsky and N. Shakhova. Modeling sub-sea permafrost in the east siberian arctic shelf: the dmitry laptev strait. *Environmental Research Letters*, 5(1):015006, 2010. URL `http://stacks.iop.org/1748-9326/5/i=1/a=015006`.

[30] E.G. Nisbet, G. Allen, M. Cain, E.J. Dlugokencky, R.E. Fisher, J.L. France, M.W. Gallagher, D. Lowry, C. Lund Myhre, T.A. Minshull, J.A. Pyle, C.D. Ruppel, N.J. Warwick, G.K. Westbrook, and D.E.J. Worthy. Response of methane sources to rapid arctic warming. Letter to the Editor, Nature. URL `http://equianos.com/wordpress/wp-content/uploads/Response-to-Whiteman_et-al-Comment.pdf`.

[31] Pier Paul Overduin, Susanne Liebner, Christian Knoblauch, Frank Gunther, Sebastian Wetterich, Lutz Schirrmeister, Hans-Wolfgang Hubberten, and Mikhail N. Grigoriev. Methane oxidation following submarine permafrost degradation: Measurements from a central laptev sea shelf borehole. *Journal of Geophysical Research: Biogeosciences*, 120(5):965–978, 2015. doi: 10.1002/2014JG002862. URL `https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2014JG002862`.

[32] James H. Rachael, Bousquet Philippe, Bussmann Ingeborg, Haeckel Matthias, Kipfer Rolf, Leifer Ira, Niemann Helge, Ostrovsky Ilia, Piskozub Jacek, Rehder Gregor, Treude Tina, Vielstadte Lisa, and Greinert Jens. Effects of climate change on methane emissions from seafloor sediments in the arctic

ocean: A review. *Limnology and Oceanography*, 61(S1):S283–S299, 2016. doi: 10.1002/lno.10307. URL https://aslopubs.onlinelibrary.wiley.com/doi/abs/10.1002/lno.10307.

[33] J. Richter-Menge, J.E. Overland, J.T. Mathis, and E. Osborne. Arctic report card 2017. http://www.arctic.noaa.gov/Report-Card, 2017.

[34] N. N. Romanovskii, Hans-Wolfgang Hubberten, A. V. Gavrilov, A. A. Eliseeva, and G. S. Tipenko. Offshore permafrost and gas hydrate stability zone on the shelf of east siberian seas. *Geomarine letters*, 25(2):167–182, 2005. doi: 10.1007/s00367-004-0198-6. URL http://dx.doi.org/10.1007/s00367-004-0198-6.

[35] Carolyn D. Ruppel and John D. Kessler. The interaction of climate change and methane hydrates. *Reviews of Geophysics*, 55(1):126–168, 2016. doi: 10.1002/2016RG000534. URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2016RG000534.

[36] T. Schneider von Deimling, M. Meinshausen, A. Levermann, V. Huber, K. Frieler, D. M. Lawrence, and V. Brovkin. Estimating the near-surface permafrost-carbon feedback on global warming. *Biogeosciences*, 9(2):649–665, 2012. doi: 10.5194/bg-9-649-2012. URL https://www.biogeosciences.net/9/649/2012/.

[37] Axel Schweiger, Ron Lindsay, Jinlun Zhang, Mike Steele, Harry Stern, and Ron Kwok. Uncertainty in modeled arctic sea ice volume. *Journal of Geophysical Research: Oceans*, 116(C8), September 2011. doi: 10.1029/2011JC007084. URL http://psc.apl.washington.edu/research/projects/arctic-sea-ice-volume-anomaly/.

[38] Teresa L. Segura, Christopher P. McKay, and Owen B. Toon. An impact-induced, stable, runaway climate on mars. *Icarus*, 220 (1):144 – 148, 2012. ISSN 0019-1035. doi: https://doi.org/10.1016/j.icarus.2012.04.013. URL http://www.sciencedirect.com/science/article/pii/S0019103512001510.

[39] N. Shakhova, I. Semiletov, A. Salyuk, and D. Kosmach. Anomalies of methane in the atmosphere over the east siberian shelf: Is there any sign of methane leakage from shallow shelf hydrates. *Geophysical Research Abstracts*, 10, 2008. doi: EGU2008-A-01526. URL http://www.cosis.net/abstracts/EGU2008/01526/EGU2008-A-01526.pdf.

[40] N. E. Shakhova, V. A. Alekseev, and I. P. Semiletov. Predicted methane emission on the east siberian shelf. *Doklady Earth Sciences*, 430(2):190–193, 2 2010. ISSN 1028-334X. doi: 10.1134/S1028334X10020091.

[41] Natalia Shakhova, Igor Semiletov, Ira Leifer, Anatoly Salyuk, Rekant P.V., and Denis Kosmach. Geochemical and geophysical evidence of methane release over the east siberian arctic shelf. *Journal of Geophysical Research*, 115, August 2010.

[42] Natalia Shakhova, Igor Semiletov, Anatoly Salyuk, Vladimir Yusupov, Denis Kosmach, and Örjan Gustafsson. Extensive methane venting to the atmosphere from sediments of the east siberian arctic shelf. *Science*, 327(5970):1246–1250, 2010. ISSN 0036-8075. doi: 10.1126/science.1182221. URL http://science.sciencemag.org/content/327/5970/1246.

[43] Natalia Evgenievna Shakhova, Igor Petrovich Semiletov, Valentin Sergienko, Leopold Lobkovsky, Vladimir Yusupov, Anatoly Salyuk, Alexander Salomatin, Denis Chernykh, Denis Kosmach, Gleb Panteleev, Dmitry Nicolsky, Vladimir Samarkin, Samantha Joye, Alexander Charkin, Oleg Victorovich Dudarev, Alexander Meluzov, and Orjan Gustafsson. The east siberian arctic shelf: Towards further assessment of permafrost-related methane fluxes and role of sea ice. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 373(2052), 10 2015. ISSN 0962-8428. doi: 10.1098/rsta.2014.0451.

[44] Andrew G. Slater and David M. Lawrence. Diagnosing present and future permafrost from climate models. *Journal of Climate*, 26(15):5608–5623, 2013. doi: 10.1175/JCLI-D-12-00341.1. URL https://doi.org/10.1175/JCLI-D-12-00341.1.

[45] V.A. Soloviev, G.D. Ginzburg, E.V. Telepnev, and Yu. N Mikhaluk. Cryothermia and gas hydrates in the arctic ocean. In *Proc. of Sevmorgeologia*, page 150, Leningrad, 1987.

[46] Robert F. Spielhagen, Kirstin Werner, Steffen Aagaard Sørensen, Katarzyna Zamelczyk, Evguenia Kandiano, Gereon Budeus, Katrine Husum, Thomas M. Marchitto, and Morten Hald. Enhanced modern heat transfer to the arctic by warm atlantic water. *Science*, 331(6016):450–453, 2011. ISSN 0036-8075. doi: 10.1126/science.1197397. URL http://science.sciencemag.org/content/331/6016/450.

[47] Jens Strauss, Lutz Schirrmeister, Guido Grosse, Daniel Fortier, Gustaf Hugelius, Christian Knoblauch, Vladimir E. Romanovsky, Christina Schädel, Thomas Schneider von Deimling, Edward A. G. Schuur, Denis Shmelev, Mathias Ulrich, and Alexandra Veremeeva. Deep yedoma permafrost: A synthesis of depositional characteristics and carbon vulnerability. *Earth-Science Reviews*, 172:75–86, August 2017. doi: 10.1016/j.earscirev.2017.07.007. URL `http://www.sciencedirect.com/science/article/pii/S0012825217300508?via%3Dihub`.

[48] K. E. Thatcher, G. K. Westbrook, S. Sarkar, and T. A. Minshull. Methane release from warming-induced hydrate dissociation in the west svalbard continental margin: Timing, rates, and geological controls. *Journal of Geophysical Research: Solid Earth*, 118(1):22–38, 2013. doi: 10.1029/2012JB009605. URL `https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2012JB009605`.

[49] Brett F. Thornton, Marc C. Geibel, Patrick M. Crill, Christoph Humborg, and Carl-Magnus Morth. Methane fluxes from the sea to the atmosphere across the siberian shelf seas. *Geophysical Research Letters*, 43(11):5869–5877, 2016. doi: 10.1002/2016GL068977. URL `https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2016GL068977`.

[50] A. Vaks, O.S. Gutareva, S.F.M. Breitenbach, E. Avirmed, A.J. Mason, A.L. Thomas, A.V. Osinzev, A.M. Kononov, and G.M. Henderson. Speleothems reveal 500,000-year history of siberian permafrost. *Science*, 340(6129):183–186, 4 2013. ISSN 0036-8075. doi: 10.1126/science.1228729.

[51] Gail Whiteman, Chris Hope, and P Wadhams. Vast costs of arctic change. *Nature*, 499:401–3, 07 2013.

[52] Alexandra Witze. Ageing satellites put crucial sea-ice climate record at risk. *Nature*, 551:13–14, November 2017. doi: 10.1038/nature.2017.22907.

[53] Chuang Zhao, Bing Liu, Shilong Piao, Xuhui Wang, David B. Lobell, Yao Huang, Mengtian Huang, Yitong Yao, Simona Bassu, Philippe Ciais, Jean-Louis Durand, Joshua Elliott, Frank Ewert, Ivan A. Janssens, Tao Li, Erda Lin, Qiang Liu, Pierre Martre, Christoph Müller, Shushi Peng, Josep Peñuelas, Alex C. Ruane, Daniel Wallach, Tao Wang, Donghai Wu, Zhuo Liu, Yan Zhu, Zaichun Zhu, and Senthold Asseng. Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences*, 2017. ISSN 0027-8424. doi: 10.1073/pnas.1701762114. URL `http://www.pnas.org/content/early/2017/08/10/1701762114`.

[54] Sergey A. Zimov, Edward A. G. Schuur, and F. Stuart Chapin. Permafrost and the global carbon budget. *Science*, 312(5780):1612–1613, 2006. ISSN 0036-8075. doi: 10.1126/science.1128908. URL `http://science.sciencemag.org/content/312/5780/1612`.

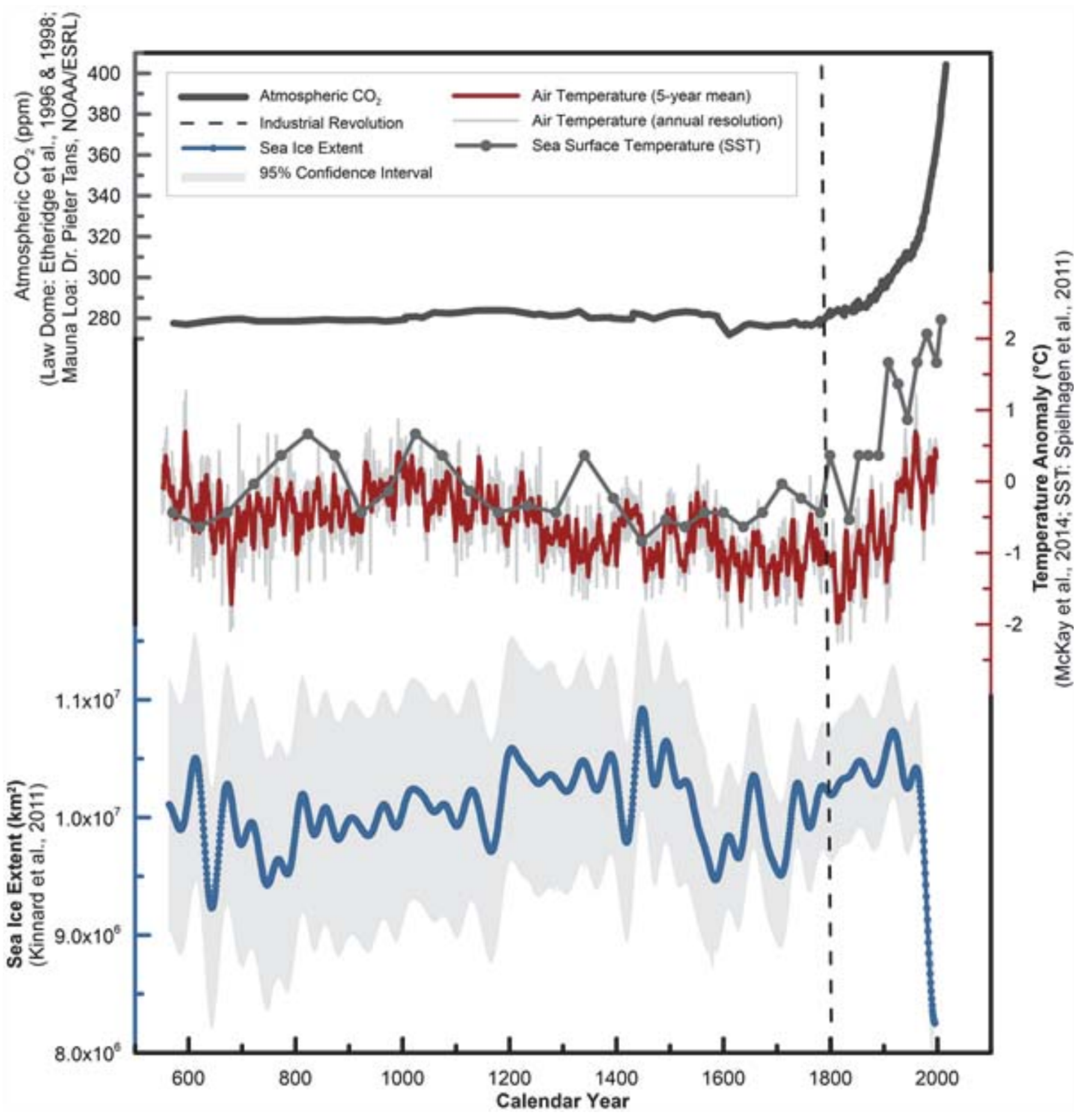

Figure 5. Paleoclimate reconstructions of approximately 5-year mean Arctic sea ice extent (15), atmospheric temperature (24) and sea surface temperature anomalies (46) spanning the last 1,500 years. Figure reproduced from the Arctic Report Card 2017 (33)