6. METHANE HYDRATE FEEDBACKS

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METHANE IS ABOUT 25 times as potent at trapping heat as carbon dioxide, and there is a huge amount of it stored as methane hydrates in the Arctic. The amount of methane stored in hydrate deposits is more than 13 times greater than the amount of carbon (as methane and carbon dioxide) in the atmosphere. There is more carbon in methane hydrates than in all the fossil fuel deposits in the world. As the climate warms, these deposits can be destabilised, with major climatic repercussions.

Key Findings:

- **Large amounts of methane are frozen in arctic methane hydrates.** Methane is a powerful greenhouse gas. A large amount of methane is frozen in methane hydrates, which are found in ocean sediments and permafrost. There is more carbon stored in methane hydrates than in all of Earth's proven reserves of coal, oil and natural gas combined.

- **Continental shelves hold most of this hydrate.** Most methane hydrates are stored in continental shelf deposits, particularly in the arctic shelves, where they are sequestered beneath and within the sub-sea permafrost. Since arctic hydrates are permafrost-controlled, they destabilise when sub-sea permafrost thaws.

- **Thawing sub-sea permafrost is already releasing methane.** Current temperatures in the Arctic are causing sub-sea permafrost to thaw. Thawed permafrost fails to reliably seal off the hydrate deposits, leading to extensive methane release into the ocean waters. Because of the shallow water depth of large portions of the arctic shelves, much methane reaches the atmosphere un-oxidized (not changed to carbon dioxide). It is not yet known how much this release contributes to current global atmospheric methane concentrations. Methane is about 25 times more potent a greenhouse gas than carbon dioxide.

- **Hydrates increase in volume when destabilised.** In addition, when methane hydrates destabilise, the methane within these hydrates increases tremendously in volume. The very high pressure that results may lead to abrupt methane bursts.

- **The most vulnerable hydrates are on the East Siberian Shelf.** The largest, shallowest, and thus most vulnerable fraction of methane deposits occurs on the East Siberian Shelf. Increased methane emissions above this shelf have been observed, but it is not yet known whether recent arctic warming is responsible for the increase in emissions.

Arctic marine ecosystems have not been widely considered to play a significant role in the global carbon cycle or in the methane cycle in particular, for three primary reasons:

1. The Arctic continental shelf represents only 2 per cent of the surface area of the world's oceans; thus, the amount of unfrozen sediments that accumulated during the current warm period (Holocene epoch), along with severe climate conditions, were not thought to be conducive for modern methane generation by microbes in sediments.
2. Organic carbon that accumulated during previous time periods of the Earth's history, before the sea invaded the arctic shelves as the glaciers began to retreat during the current warm period, was thought to be reliably preserved within the sub-sea permafrost and methane that was produced earlier would remain frozen within hydrate deposits.
3. Sub-sea permafrost was considered to be stable, and thus would prevent methane escape from the seabed.

At the same time, it is well-known that because it is enclosed on all sides by land, the arctic shelf has received a huge amount of organic carbon from land, through both coastal erosion and input from arctic rivers. In the Siberian Arctic Shelf alone, where the six great Siberian rivers deliver their waters, the amount of organic carbon that accumulates annually in the bottom sediments approximately equals that accumulated over the entire open-sea area of the World Ocean[1]. That is why sedimentary basins in the arctic continental shelf are the largest and thickest in the world (up to 20 kilometres), and the amount of carbon accumulated within them is called the "arctic super carbon pool"[2]. A large portion of this carbon is stored in methane hydrate deposits. The amount of methane currently stored in hydrate deposits (about 10,400 gigatonnes; 1 gigatonne of carbon equals 1 billion tonnes of carbon)[3] is more than 13 times greater than the amount of carbon (as methane and carbon dioxide) in the atmosphere (about 760 gigatonnes)[4].

"The amount of methane currently stored in hydrate deposits is more than 13 times greater than the amount of carbon in the atmosphere."

The stability of sub-sea permafrost is key to whether methane can escape from seabed hydrates and other deposits[5]. Relict sub-sea permafrost, which underlies the arctic continental shelf, is an overlooked sibling to on-land permafrost. They formed together, but sub-sea permafrost was flooded by the sea in the so-called "Holocene transgression," 7,000 to 15,000 years ago when glaciers melted in a warming climate[6]. This area is now several times larger than that covered by Siberian wetlands. Sub-sea permafrost is potentially much more vulnerable to thawing than land-based permafrost. Prior to the recent rapid climate warming, the temperature of the sub-sea permafrost's environment had already increased by 12 to 17°C when it was flooded[7], because the average temperature of seawater is much higher than the average temperature of the arctic atmosphere. In contrast, when the current, warm Holocene epoch replaced the previous colder glacial epoch, the atmosphere and, thus, terrestrial permafrost, warmed by only about 7°C[8]. This means that sub-sea permafrost is much closer to the temperature at which it thaws than is terrestrial permafrost.

The Arctic is warming more quickly than the rest of the world, and this warming is most pronounced in the arctic shelf[4,9]. The main reason for this is that arctic rivers bring to the arctic shelf continental-scale signals of the terrestrial ecosystems' response to global warming[11]. That is, the degradation of terrestrial permafrost leads to increasing river runoff, which warms the shelf water, which, in turn, transports heat down to shelf sediments and sub-sea permafrost. Shelf water and bottom sediments constitute the sub-sea permafrost environment. Like all physical systems, sub-sea permafrost must reach a thermal equilibrium with its environment, which is significantly warmer than the environment of terrestrial permafrost. The thermal environment of sub-sea permafrost fluctuates from slightly below to slightly above 0°C[11,12]. Since sub-sea permafrost is salty, it thaws even at temperatures slightly below zero[13]. Such temperatures of sub-sea permafrost have been observed recently on the Siberian arctic shelf[14]. When it thaws, sub-sea permafrost loses its ability to seal off the seabed deposits of methane, including hydrates[5,7].

"Recent observational data obtained from the largest and shallowest arctic shelf — the East Siberian Arctic Shelf — indicate that methane is already being released from seabed deposits."

Recent observational data obtained from the largest and shallowest arctic shelf — the East Siberian Arctic Shelf — indicate that methane is already being released from seabed deposits[15,16,17]. This is a worrisome indication that methane emissions from arctic seabed deposits of methane, including methane hydrates, will increase with the warming that has been predicted for the Arctic during this century, with unpredictable consequences for the future climate.

Large amounts of methane are frozen in arctic methane hydrates

Origin and amount of hydrates

Gas hydrates are compounds in which the gas molecules (20 per cent of the volume) are trapped in crystalline cells consisting of water molecules (80 per cent) held together by hydrogen bonds. Gas hydrates can be stable over a wide range of pressures and temperatures. For example, a unit volume of methane hydrate at a pressure of 26 atmospheres and 0°C contains 164 times that volume of gas; thus, 164 cubic metres of gas are contained in a hydrate volume of 0.2 cubic metres. The dissociation of hydrates in response to increasing temperature is accompanied by a substantial increase in pressure[5]. For methane hydrates that formed at 26 atmospheres and 0°C, it is possible to obtain a pressure increase of as much as 1,600 atmospheres upon dissociation. Hydrates are found in the Arctic and in deep water[18]. They can occur in the form of small nodules (5 to 12 centimetres), as small lenses, or even as pure layers that can be tens of metres thick[19]. Hydrates generally form in a sub-sea sediment zone where the combination of pressure and temperature guarantees their stable existence within the so-called hydrate stability zone[5,18]. In the regions where permafrost exists, hydrate-bearing sediment deposits can reach a thickness of 400 to 800 metres[19].

There are three types of hydrate deposits:

1. **Primary deposits** are formed from gases dissolved in reservoir water under conditions of low bottom temperature and high pressure exerted by the overlying water. They form where the water column is more than 700 to 1,000 metres deep (primarily non-arctic deposits) or more than 200 metres deep (primarily arctic deposits). These deposits can be stratigraphic, meaning that they do not depend on geological structures, have no seals, and occur in a widely dispersed (not localised) state or in the form of nodules. They can also be structural. In contrast to stratigraphic type hydrates, structural hydrates are usually massive, consisting of lumps of nearly pure hydrate. Alteration of the climate cycle affects the stability of these hydrates by changing the position and thickness of the hydrate stability zone[5], leading to release of some free gas to the water column, where it is usually altered by the presence of oxygen and does not reach the atmosphere[19].
2. **Secondary deposits** usually originate under extremely low temperatures and high pressure exerted by the overlying rock on arctic lands. They consist of gas frozen within the hydrate stability zone and free gas located above and beneath it[5,11], at depths as shallow as 70 metres beneath the seafloor and in layers up to 110 metres thick[19]. Permafrost seals off and controls the release of gas from these deposits.
3. **Relic deposits** are found within permafrost as shallow as 20 metres, and are thought to be formed when shallow fields of natural gas froze during the ice ages, when the arctic shelves were above sea level[20, 21].

The Arctic Ocean contains all three types of hydrate deposits: primary arctic deposits, and secondary and relic hydrate deposits that formed when the arctic shelves were above sea level. Specific features of arctic hydrates include:

1. very high spatial concentration[11, 19] (**Figure 2a**);
2. extremely high pore saturation, from 20 to 100 per cent of pore space. In contrast, primary oceanic (non-arctic) hydrates occupy only 1 to 2 per cent of pore space[19];
3. extreme sensitivity to warming. Destabilising hydrates that formed at temperatures below 0˚C (primary arctic hydrates, secondary and relic) requires only one-third the energy required to destabilise hydrates that formed at temperatures above 0˚C[5] (primary non-arctic hydrates);
4. very thick layers (up to 110 metres)[19]; and
5. offshore occurrence, more than three times more frequent than onshore occurrence[20].

Continental shelves hold most of the methane hydrate

> "Release to the atmosphere of only 0.5 per cent of the methane stored within arctic shelf hydrates could cause abrupt climate change."

Terrestrial permafrost is estimated to contain 400 gigatonnes of methane hydrates, while sub-sea continental shelf reservoirs are estimated to contain 10,000 gigatonnes of methane hydrates[3]. For comparison, all recovered and non-recovered fossil fuels (coals, oil and natural gas) are estimated to contain about 5,000 gigatonnes of carbon[3]. Since the arctic continental shelf makes up 25 per cent of the entire area of the world's oceanic continental shelves (7 million square kilometres of the ocean's area, 28.8 million square kilometres), it is estimated to contain 2,500 gigatonnes of carbon in the form of methane hydrates, which is more than 3 times greater than the amount of carbon currently stored in the atmosphere and more than 600 times greater than the current atmospheric content of methane[4]. Release to the atmosphere of only 0.5 per cent of the methane stored within arctic shelf hydrates could cause abrupt climate change[22].

Vulnerability of hydrates and the role of permafrost

Since most hydrate deposits in the Arctic are permafrost-controlled, permafrost stability is key to hydrate stability. Permafrost is defined as soils (on-land permafrost) or sediments (sub-sea permafrost) that are frozen year-round. Anything that is frozen can thaw, and permafrost is no exception. Permafrost can degrade in two ways. It can thaw from the top downward, in which the active layer expands downward, creating taliks (bodies of thawed permafrost)[23]. The active layer is the upper layer of permafrost soils or sediments that thaws in summer, and is usually not more than 1 metre thick. However, beneath water more than 2 metres deep it can be thicker, because the water insulates the permafrost and prevents it from completely re-freezing during winter. Permafrost also can degrade from the bottom up as a result of geothermal heat flux, when heat from the interior of the Earth radiates upward, causing the frozen sediment to thaw from below[24]. Permafrost can be degraded from the top down and from the bottom up at the same time.

The temperature regime of sub-sea permafrost is determined by the annual temperature of the surrounding seawater (**Figure 1**), just like the thermal regime of terrestrial permafrost is determined by the arctic surface temperature. Annual average arctic shelf water temperature is more than 10°C higher than terrestrial arctic surface temperature. An increase in surrounding temperature changes the thermal regime of permafrost, and the permafrost temperature will slowly adjust to achieve a new equilibrium with its thermal environment. This process may take thousands of years.

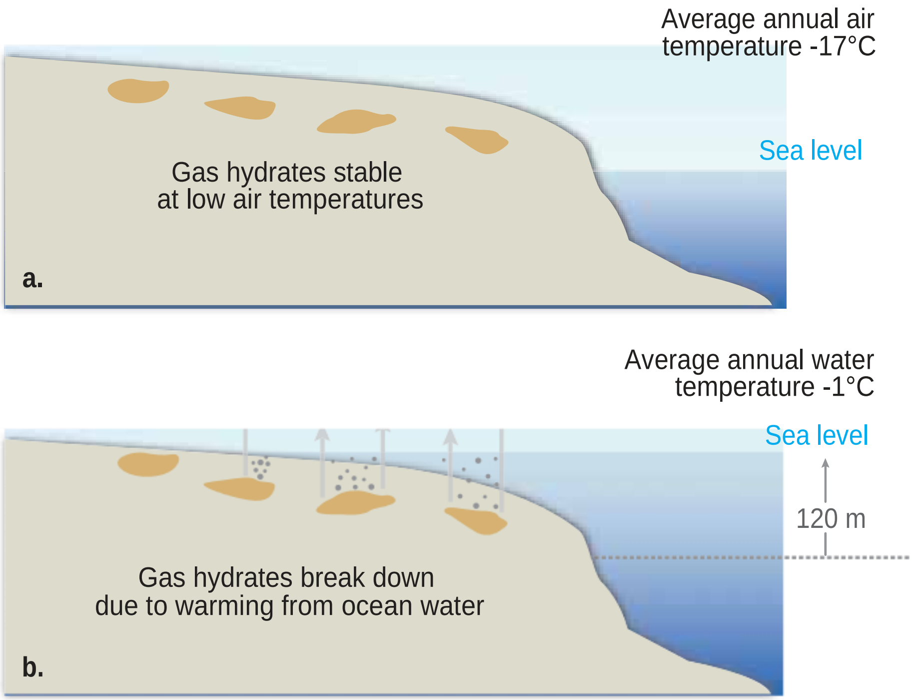

Figure 1. Illustration of how changes in sea level affect the stability of arctic hydrates: **a**) cold epochs: sea level is low, the arctic shelf is exposed above the water surface, average annual temperature is -17˚C; **b**) warm epochs: sea level is high, the arctic shelf is submerged, average annual temperature of sea water is -1˚C.

In the case of arctic sub-sea permafrost, this process began long ago, when the sea flooded the arctic shelves 7,000 to 15,000 years ago, increasing the temperature of the environment of the newly submerged permafrost by 12°C or more[24]. As the sub-sea permafrost moved toward thermal equilibrium, its temperature increased to near its thawing point[11], which for salt-containing permafrost occurs at temperatures slightly below 0°C[13]. Any further increase in temperature, resulting from, for example, continued global warming, will lead to thawing.

Thawing sub-sea permafrost is already releasing methane

Insufficient attention has been paid to using numerical models to project changes that might occur in sub-sea permafrost as a result of global warming. Modelling results have suggested that sub-sea permafrost should be stable across most of the arctic shelf. For example, permafrost on the East Siberian Arctic Shelf was predicted to be stable from the coast to a water depth of 70 metres[24], which encompasses more than 90 per cent of the shelf area. However, recent observational data obtained in the East Siberian Arctic Shelf showed that extensive methane release from the seafloor is occurring at depths ranging from 6 to 70 metres[16, 17], emerging as huge clouds of bubbles rising through the water column. This bubbling release of gas is called ebullition. Oxidation in the water column usually prevents methane released from oceanic hydrates in deep ocean waters from reaching the atmosphere. However, because the East Siberian Arctic Shelf is extremely shallow (more than 75 per cent of its entire area of 2.1 million square kilometres is shallower than 40 meters; **Figure 2b**), the majority of the methane gas released from the East Siberian Arctic Shelf seafloor avoids oxidation in the water column and is released to the atmosphere. Atmospheric concentrations of methane above the sea surface were found to be as much as 4 times greater than normal atmospheric levels[18] (**Figure 3**). Such outburst-like emissions have also been observed from shallow hydrate deposits at lower latitudes, where no permafrost seals exist to prevent methane release from hydrate deposits[25].

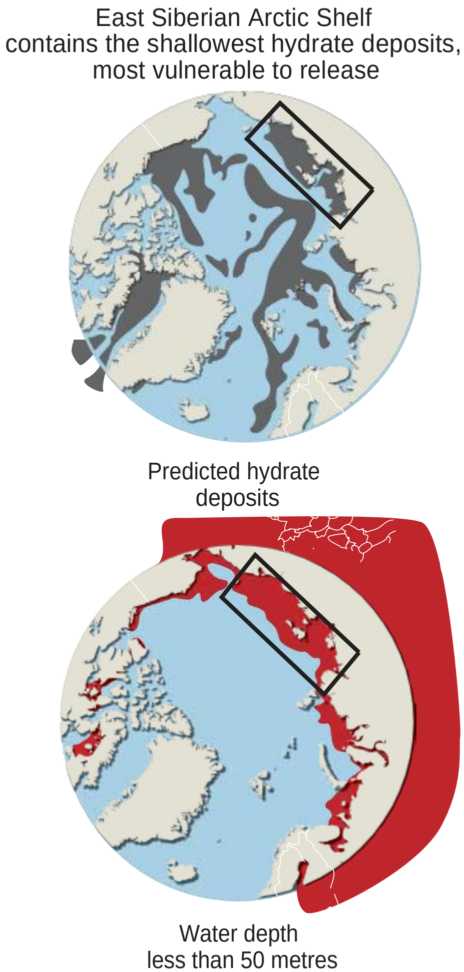

Figure 2. a) Map of predicted hydrate deposits (blue)[30], and **b**), map showing the sea floor topography of the Arctic Ocean [31]; red color refers to depths less than 50 metres. The largest, shallowest, and thus the most vulnerable fraction of the arctic shelf is the East Siberian Arctic Shelf, is enclosed by the square.

It has been widely assumed that no methane could be emitted from the arctic shelf during the winter ice-covered period. However, new observational data suggest that methane ebullition and other emissions occur throughout the year. Flaw leads (openings between sea ice) and polynyas (winter ice-free areas) compose 1 to 2 per cent of the winter shelf area. Methane fluxes from European arctic polynyas were found to be 20 to 200 times higher than the ocean average and, where concentrations of dissolved methane in the bottom water do not exceed 50 nanomoles (1 nanomole of methane = 16 billionths of a gram of methane per litre of water), can reach 20,000 tonnes of methane a year[26]. Where ice seals the water surface, methane accumulates beneath the ice. In some areas of the East Siberian Arctic Shelf, for example, concentrations of dissolved methane measured in winter beneath the ice were as high as 20,000 nanomoles[27]; when this ice melts in spring, methane is released to the atmosphere. A similar phenomenon has been observed in lakes on land. The isotopic signature of methane bubbles in seawater over the East Siberian Arctic Shelf indicates a mixture of a few possible sources, including hydrates[16]. This is true for summer as well as winter methane emissions. (Isotopic signatures are determined by small differences in the weight of molecules that make up gases such as methane.)

It is suggested that the natural degradation of sub-sea permafrost that occurs as a result of the combined effect of bottom-up geothermal and top-down seawater heat fluxes, possibly accelerated by amplified arctic warming, is leading to the partial destabilisation of sub-sea permafrost. As a result, methane is already being released from widespread seabed deposits, and vents extensively to the arctic atmosphere. In the East Siberian Arctic Shelf, which constitutes about 30 per cent of the entire arctic shelf area, more than 50 per cent of the area studied is currently releasing methane to the atmosphere.

Climate change and future methane release from arctic hydrates

The potential of climate change to destabilise arctic hydrates has significant implications both for the global climate and for arctic ecosystems. Previous results, based on studying less than 1 per cent of the total area of the arctic shelf and extrapolated to the entire area of the arctic shelf, implied that annual methane emissions to the atmosphere from decaying hydrate deposits could be equal to about 100,000 tonnes of methane[28]. However, more recent estimates suggest the amount of methane that could be released from the arctic continental shelf, which covers an area of 7 million square kilometres, could be two orders of magnitude greater. Indeed, methane release measured from the East Siberian Arctic Shelf alone (30 per cent of the arctic shelf seas) suggested total emissions as high as 5 million tonnes of methane[15]. If ebullition from arctic continental shelves is similar in proportion to that from northern lakes, then current annual emissions of methane from the arctic shelves could vary from 10 million to 50 million tonnes of methane. This estimate is based on findings from the East Siberian Arctic Shelf alone and does not include non-gradual releases of methane associated with hydrate deposit decay, because the time scale and spatial distribution of such episodes are still unknown. Therefore, the contribution of the arctic shelves to methane release is currently underestimated.

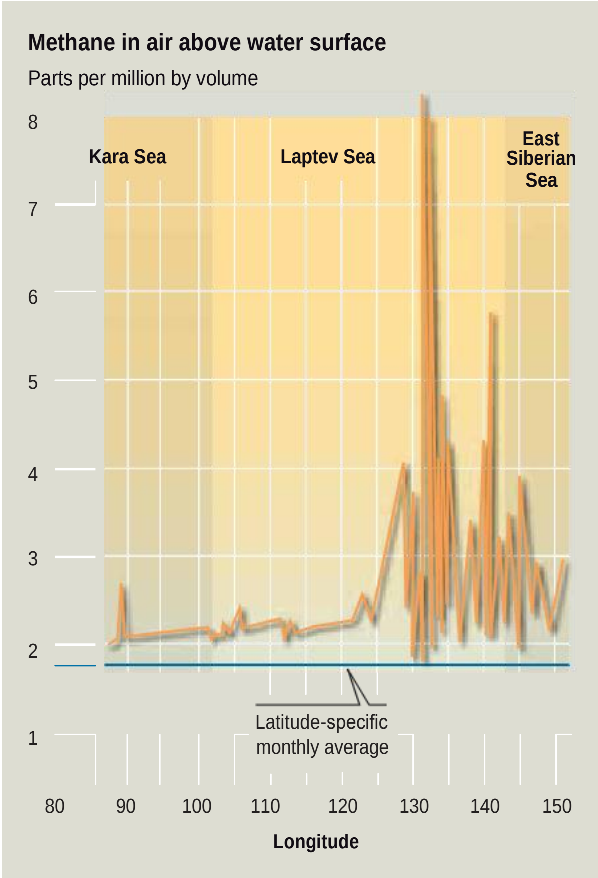

Figure 3. Mixing ratio of methane in the air above the water surface measured along a ship's route in September 2005. The dotted line shows the Latitude-specific monthly average of 1.85 parts per million by volume established for the Barrow, Alaska, USA, monitoring station at 71° 19' N, 156° 35' W (http://www.cmdl.noaa.gov/ccgg/insitu.html); this is the normal level of methane in the atmosphere at this latitude.

The most vulnerable hydrates are on the East Siberian Shelf

The amount of methane that could theoretically be released from decaying hydrate deposits in future episodic events could be enormous. As the East Siberian Arctic Shelf is the largest and the shallowest part of the arctic shelf, methane emissions from the East Siberian Arctic Shelf would contribute the most significantly. Given that this shelf comprises about 30 per cent of the arctic shelf, the amount of methane stored within its seabed could be as much as 750 gigatonnes. It is currently suggested that about two-thirds of the methane preserved in hydrates is stored as free gas[11], which would add about an additional 500 gigatonnes. Because sub-sea permafrost is similar to its terrestrial counterpart, the carbon pool held within it is comparable to that within terrestrial permafrost; about 500 gigatonnes of carbon is contained within a 25-metre thick permafrost body, which is available for methane or carbon dioxide production when the permafrost thaws[29]. Thus, the entire amount of carbon stored in the East Siberian Arctic Shelf (1,750 gigatonnes) is equal to that held in the entire remaining area of the Arctic continental shelf as hydrate deposits' carbon. Recent studies have examined two possible cases of how surface air temperature could respond to release of only 2 per cent (50 gigatonnes) of the total amount of methane preserved in arctic continental shelf hydrate deposits if this amount is released in either of two ways: slowly over 50 to 100 years, or quickly over approximately 5 to 10 years. When methane is released quickly over the brief 5 to 10 year time period, the maximum temperature increase is higher by about a factor of three compared to the "slow" case. This greater temperature response is more likely to produce irreversible consequences.

Conservative modelling shows that about 5 to 10 per cent of the East Siberian Arctic Shelf area may be underlain by open taliks[24], which provide a pathway for methane to escape from deeper parts of the sediments to the water column. The amount of methane that could potentially be released from disturbed hydrates might reach 37.5 to 75 gigatonnes, and the shallow waters of the East Siberian Arctic Shelf would allow a large fraction of this methane to reach the atmosphere. Multi-year observational data obtained in the East Siberian Arctic Shelf suggest that, contrary to modelling results, more than 80 per cent of bottom water and 50 per cent of surface water in the study area is supersaturated with methane by a factor of 10 to 1,000 relative to the background level of 3.5 nanomoles[18]. That means that very likely more than 5 to 10 per cent of the East Siberian Arctic Shelf area is already affected by sub-sea permafrost destabilisation. Nevertheless, it is still very uncertain whether this methane enters the water column after slowly diffusing through the sediments, allowing part of it to be oxidized within the upper sediment layers, or if it could burst out suddenly from time to time in a violent episodic event that would allow no time for oxidation before the methane is released to the atmosphere.

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