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Potential for Climate Induced Methane Hydrate Dissociation

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Readers:
Branwen Williams
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Abstract

Methane hydrates are frozen deposits of methane and water found in high pressure or low temperature sediments. When these deposits destabilize, large quantities of methane can be emitted into the atmosphere. This is significant to climate change because methane has 25 times more greenhouse gas potential than Carbon Dioxide. Worldwide, it is estimated there are between 2500 and 10000 gigatons of methane stored in hydrate deposits. This represents more carbon than all fossil fuels on Earth. It is estimated that between 200 and 2000 gigatons of methane are stored in hydrates in Arctic waters acutely vulnerable to greenhouse warming. Over the last decade, researchers have identified instances of hydrate destabilization that have already begun. To gain insight into the potential climatic effects widespread hydrate dissociation would have, researchers have examined hydrate dissociation during the Paleocene Eocene Thermal Maximum 55 million years ago as a geologic precedent. In this period, large-scale hydrate dissociation contributed to 5-8 degree Celsius warming worldwide. If such a climatic shift were to transpire today, impacts on society would be enormous. There is currently a debate in the scientific community as to whether the risk of methane hydrate dissociation is relevant to the present generation. One side argues that not enough methane could be emitted into the atmosphere from today's hydrate sources to have a meaningful impact on climate warming, where the other side contends that more than enough methane could be emitted from present day hydrate deposits to cause significant impacts to the global greenhouse effect. Given the information currently known about hydrates, it is reasonable to conclude there is a moderate risk of widespread destabilization that could impact global climate change in the coming decades. Significant acceleration of the conversion to alternative energies and implementation of geoengineering strategies should be considered.

Introduction

0.1 Introducing Methane Hydrates

Since the second half of the 19th century, anthropogenic carbon emissions have resulted in greenhouse warming of the globe (IPCC, 2014). This warming has caused considerable environmental impact worldwide. The ice caps have lost 50 percent of their ice area and 80 percent of their ice volume since the middle of the 20th century, causing sea level rises of 10-20 centimeters (Berliner, 2003). Global precipitation has become more uneven, leading to either drought or flooding conditions. This has resulted in both droughts and flooding. Warmer ocean temperatures and a greater concentration of water vapor in the atmosphere are fueling more powerful hurricanes. Up from 270 ppm before 1880, the atmospheric Carbon Dioxide concentration is now 404 parts per million (Moss, 2010). This is projected to increase at a rate of 2 ppm per year for the foreseeable future, strongly suggesting that the 1 degree Celsius of greenhouse warming that has occurred since the industrial revolution will only further increase in the coming decades. This accelerating warming could potentially lead to several significant impacts that could exacerbate warming yet further. Among the most substantial of these impacts is the destabilization of methane hydrates. Methane hydrates are deposits of frozen methane occurring on the ocean floor. These deposits contain vast amounts of carbon, suggesting that their destabilization could result in substantial additional greenhouse warming should this gas be emitted into the atmosphere. This is because methane is 25 times more potent a greenhouse gas than CO_2 . Enough carbon is stored in methane hydrates that if even a small fraction of it were to be released into the atmosphere, resulting warming would potentially rival all anthropogenic warming since the industrial revolution. Perhaps what renders methane hydrate destabilization one of the most significant environmental impacts of existing climate change is that initial releases of methane would cause warming that would lead to further hydrate destabilization and methane release. This would cascade in a positive feedback loop that would result in considerable climate warming (Smith, 2006). Such global temperature increases could potentially occur very rapidly depending on the rate of venting from these methane deposits, resulting in considerable cost to both the biosphere and human society.

While hydrates have been studied since their discovery in the early 19th century, naturally occurring deposits have only been seriously investigated by the scientific community since the 1990's. It is only since the onset of this thorough investigation that researchers have acknowledged the possibility that hydrate methane venting could result in considerable climate change. To assess the potential environmental effects a hydrate methane release would have, investigators have looked at instances in the geologic past in which hydrate destabilization has taken place before, namely 56million years ago at the end of the Paleocene Epoch. To determine the extent of hydrate destabilization today, investigators have launched repeated expeditions to the Arctic Ocean, in which they have found instances of destabilization at the West Spitzbergen Continental Margin and the East Siberian Arctic Shelf (Westbrook et al., 2009, Shakhova et al., 2010). The scientific community is currently attempting to assess the risk hydrate destabilization could take place in the present day. To do this, they are actively debating several key characteristics of hydrates, such as how much of the hydrate reservoir worldwide is vulnerable to destabilization, how much methane that is vented from destabilizing hydrates is actually emitted into the atmosphere, and the timescales that destabilizing hydrates emit methane

(Ruppel, 2011). The extent of hydrate carbon vulnerable to destabilization and the fraction of vented methane emitted into the atmosphere suggest at least a moderate risk that significant emissions could transpire in the 21st century. Based on parallels of hydrate dissociation at the Paleocene Eocene Thermal Maximum 56million years ago, a present day hydrate methane release would result in warming between 5-8 degrees Celsius. This would cause significant environmental impacts around the world.

0.2 What are methane hydrates?

Methane hydrates are frozen cubic lattice structures found at the bottom of the ocean. They form under conditions of either high pressure or low temperature. As a result, they are found in either the deep ocean or in shallow water at the poles. They are less stable than ice due to fewer supports in their molecular structure, making them more prone to rapid melting. These hydrates hold vast amounts of methane, containing 164 volumes of methane gas for every volume of hydrate. Hydrates are highly significant because there are between 2500 and 10000 gigatons of methane contained in hydrates globally (Dickens, 1994). This represents more carbon than all fossil fuel reserves combined. While the vast majority of hydrate deposits occur in deep ocean not susceptible to climate warming, between 250 and 2000 gigatons of methane are present in shallow Arctic waters vulnerable to climate change (Dickens, 2003). These hydrates are more susceptible to dissociation because they formed due to the freezing temperatures of the Arctic climate. When this climate warms, rising temperatures spread rapidly through the shallow ocean water column, destabilizing frozen methane hydrates on the sea floor. This hydrate destabilization increases the likelihood of a significant release of methane that would be emitted into the atmosphere.

0.3 When have hydrates destabilized before?

In order to determine the climatic and environmental effects of a large scale methane release from Arctic hydrates, it is important to examine when such a release has occurred in the geologic past. One of the most significant of these instances is large scale hydrate destabilization at the end of the Paleocene Epoch 56 million years ago, known as the Paleocene Eocene Thermal Maximum. The climate warming was so significant that the event serves as the demarcation between the Paleocene and Eocene Epochs. Initially, greenhouse warming was caused by a combination of volcanism due to tectonic activity, wildfires caused by drought, and thawing permafrost resulting from warming temperatures. Climate warming ensuing from this resulted in the large scale destabilization of hydrate deposits. When these deposits melted, vast amounts of methane were released into the atmosphere. These emissions resulted in more warming, which caused more deposits to destabilize in a positive feedback loop. Over a period of 8000 years, all hydrates vulnerable to climate warming melted. The resulting increases in atmospheric methane caused the planet to warm between 5 and 8 degrees Celsius (Katz, 1999). This explanation for this warming is known by researchers as the Clathrate Gun Hypothesis (Kennet et al., 2002). Other explanations posit that the volcanism, wildfires, and thawing permafrost had a larger effect on the holistic warming present during this time than did dissociating hydrates. However, the hypothesis that hydrate dissociation was first triggered by volcanism, wildfires, and thawing permafrost and then became a primary cause of the resulting 5 to 8 degree warming is a leading explanation (Mcnerney et al., 2011).

The global environmental impacts of this temperature increase as a result of these emissions were enormous. Benthic Foramnifera, a species of deep water plankton, went extinct. Ranges of species worldwide were shifted by thousands of miles. Mammals diversified into the orders present in the world today (Mcnerney et al., 2011). As such, while the period of warming lasted only 200,000 years, the impacts on the planet's biological systems were permanent.

The geological instance of hydrate destabilization at the Paleocene Eocene Thermal Maximum reveals that warming temperatures can result in large scale methane emissions from hydrate deposits. If similar methane emissions from hydrate dissociation were to occur in the 21st century, they would have transformative impacts on both the biosphere and human society.

0.4 Instances of hydrate destabilization and risk assessment

While it is known from the Paleocene Eocene Thermal Maximum that hydrate dissociation can result in significant warming and environmental shifts worldwide, researchers are currently attempting to discern if the hydrate dissociation of the Clathrate Gun could transpire in the same way today. To do this, several expeditions have been undertaken to the Arctic Ocean to ascertain whether hydrate destabilization is currently occurring. These efforts have identified two major areas indicating that hydrate dissociation due to anthropogenic climate change has already begun. One area is the West Spitsbergen Continental Margin, where researchers have determined that up to 20 megatons of methane are being emitted annually (Westbrook et al., 2009). The other site identified is the East Siberian Arctic Shelf, at which 7.98 megatons of methane are being emitted each year (Shakhova et al., 2010). Here, researchers have determined that hydrate deposits on the East Siberian Arctic Shelf are at risk of rapid large scale melting. If such rapid destabilization were to occur, as much as 50 gigatons of methane would be released. This would cause significant increases in the concentration of atmospheric methane, resulting in accelerated greenhouse warming. Between 100 and 1000 gigatons of methane are present on the East Siberian Arctic Shelf, suggesting that later releases could have an even greater impact (Shakhova et al., 2010).

While hydrate melting in the Arctic Ocean has already begun, such destabilization alone does not signify the Clathrate Gun will fire in the 21st century. To determine the realistic risk that such significant methane emissions from melting hydrates will occur in our lifetimes, the scientific community is currently debating several critical aspects of hydrates. These aspects include the size of the global hydrate reservoir vulnerable to melting, the fraction of methane vented from hydrates that enters the atmosphere, and the timescale on which hydrate destabilization takes place. On one hand, several researchers arguing that hydrate destabilization is not relevant maintain that too little of the global hydrate reservoir is susceptible to climate change, methane emitted into the ocean water is dissolved or oxidized before it can be emitted into the atmosphere, and that significant hydrate melting does not take place on human timescales (Ruppel, 2011). In response, researchers arguing hydrate destabilization is a significant threat contend that 250-2000 gigatons of hydrate methane are vulnerable to climate change, hydrates vulnerable to destabilization due to climate change are present in shallow water which permits methane emission to the atmosphere, and up to 50 gigatons of methane could be released from the hydrates on the East Siberian Arctic Shelf at any time (Whiteman et al., 2013, Westbrook et al., 2009, Shakhova et al., 2010). While the risk of significant hydrate destabilization in the near future is not known, the information currently available suggests at least a moderate risk that large scale hydrate melting could occur in the coming decades. Both improvements in the techniques of hydrate research and an increase in the number of research investigations are necessary to exactly clarify this risk (O'Connor et al., 2010).

0.5 Implications for large scale hydrate destabilization

Despite arguments that hydrate dissociation does not pose a threat to global climatic stability, it appears that the risk this rapid melting could occur in the coming decades is credible. One implication of this substantial methane release is the potential for a positive feedback loop of hydrate melting. As was the case in the Paleocene Eocene Thermal Maximum, initial methane releases from hydrate destabilization could result in abrupt climate warming. This warming would increase water temperatures at the bottom of the Arctic Ocean, resulting in additional hydrate destabilization. The ensuing methane emissions would cause greater warming in a positive feedback loop that would occur independently of human carbon emissions. As such, the initial level of warming at which large scale hydrate melting begins represents a tipping point beyond which humans would not have control over the ensuing warming. Crossing this tipping point would result in an abrupt increase in the rate of global climate warming (Kvenvolden et al., 2003). This would leave human society with very little time to prepare for significant global environmental impacts. Were a 5-8 degree Celsius warming to take place today, a significant fraction of the polar ice caps would melt. This would result in a 100-250 foot sea level increase, displacing up to 40% of the world's population (Nicholls and

Cazenave, 2010). This would accompany significant pressures on the biosphere, increasing global extinction rates. Climate models have not meaningfully incorporated these contingencies into their projections, potentially painting an artificially optimistic picture of the effects of global climate change in the coming decades (IPCC, 2014). The fact that hydrates have not been widely studied and are still not well understood is not cause for dismissal of this scenario. Rather, it denotes that the risk of this realization is not exactly known, underscoring the need for further research. Despite this, enough evidence is present to generally characterize the risk of hydrate dissociation that would have significant impacts on the global environment. Methane hydrates pose a moderate risk of destabilizing in the coming decades that could potentially cause significant impacts to global climate change.

Chapter 1: What are Methane Hydrates?

Representing one of the most significant tipping points for global climate change, naturally occurring methane hydrates have only been discovered in the last few decades. Also known as clathrates, these hydrates are frozen deposits of composed of methane and water molecules. These deposits are less stable than ice and are prone to rapid melting. Hydrates are highly dense and contain significant quantities of methane per unit volume. Additionally, the global reservoir of methane hydrates is significant, containing between 2500 and 10,000 gigatons of methane. This is between 100 and 400 times greater than the total contribution of all human emissions since the dawn of the industrial revolution. Even a small release of hydrate methane could have significant impacts on the rate of climate warming. Understanding methane hydrates is critical to discerning their significance to climate change and their potential impact on the global environment and human society.

1.1 When were Methane Hydrates First Discovered?

The existence of methane hydrates was discovered relatively recently. The molecular structure of methane hydrates was first identified in the early 19th century by Sir Humphrey Davey. At this time their significance and natural occurrence was not known (Pelley, 2010). Hydrates were encountered in the field in the 1930's when they began clogging pipelines of energy companies extracting natural gas. This posed a severe engineering problem and the formations were viewed as a nuisance (Sloan, 2003). Hydrates found in nature formed from geologic processes were not discovered until the 1960's when they were found in Siberia. At the time they were viewed as an economically infeasible source of natural gas (Segers, 1998). From the 1960's to the 1990's, researchers began to understand that this immense concentration of methane could have significant impacts on the larger climate if these deposits were to be suddenly released (Whiteman et al., 2011). Because scientists have only conducted the bulk of their research on hydrates over the last twenty years, the attempt to characterize the climate risk of hydrates is a relatively new research initiative. Despite the field's novelty, researchers have identified many key aspects of hydrates relevant to their implications for climate change.

1.2 What is the Molecular Structure of Methane Hydrates?

While structurally hydrates resemble ice in their molecular orientation, key distinctions render them less stable than ice. Where ice freezes in a hexagonal structure, hydrates freeze in a cubic structure (Figure 3). Because hexagons have more sides than squares, hexagonal molecular configurations have more structural points of contact than cubic configurations. As such, a cubic structure entails less molecular support for hydrate formations than hexagonal ones for ice formations, rendering hydrates more vulnerable to structural instability in changing environmental conditions. This is exacerbated by the molecular incorporation of methane at the center of each cube within the hydrate structure. Because the methane molecules in the hydrate molecular structure are weaker than the water molecules in the ice molecular structure, hydrates are inherently less stable than ice and more prone to rapid melting. These key differentiating characteristics of methane hydrates and ice have considerable implications for their responses to warming temperatures resulting from climate change (Hornbach, 2004).

Another critical distinction between hydrates and ice is manifest by the volume of methane contained in hydrate structures. While ice does not contain significant quantities of any compound except for water, hydrates contain one molecule of methane for every 5.75 molecules of water. This signifies that a single cubic meter of solid hydrate contains up to 164 cubic meters of methane gas (Evans, 2007). This represents an enormous amount of methane for a single volume of solid hydrate, denoting that the melting of hydrates releases disproportionately large quantities of methane into the atmosphere. Whereas the melting of ice does not harbor substantial greenhouse warming potential, the destabilization and melting of hydrates represent considerable increase in the greenhouse gas emissions. This is particularly significant given the increasing temperatures in polar areas where hydrates are formed.

Figure 2: This cross section of a methane hydrate reveals the structural differences between hydrates and normal ice. This sample was taken from a subduction zone off the coast of Oregon. (The Guardian, 2015)

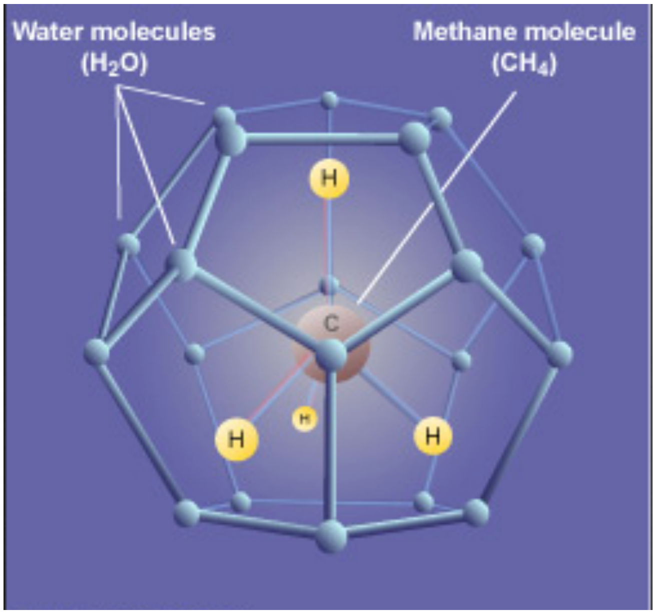

Figure 3: This illustrates the molecular structure of methane hydrates. Within each crystal lattice structure, a single methane molecule is surrounded by a cage of water molecules. In a given hydrate, one hundred fifty volumes of gas is present for every one volume of water. As such, this structure is incredibly dense and can store an immense amount of methane. It requires below freezing temperatures or high pressure conditions in order to form and maintain stability. (Kvenvolden, 2003)

1.3 How Are Methane Hydrates Formed?

Whereas ice requires only water and low temperatures to form, hydrate formation requires a ratio of 150 volumes of methane gas for each volume of water. Once this ratio of methane and water is achieved, low temperatures or high pressures are required in order for hydrates to form. While there are numerous regions of the globe with the sufficient temperature or pressure conditions, the areas in which the necessary quantities of methane are present are much more restricted (Abraham, 2015). When hydrates form due to natural processes, the methane required to achieve the necessary ratio is produced in three ways. The first is bacteriological activity on the seafloor. When primary producers such as plankton are trapped in low oxygen environments beneath sediments, bacteria decompose their organic matter over long periods. These decomposition reactions yield vast amounts of methane (Gornitz and Fung, 1994). The second means of methane supply is that of existing methane reservoirs. When methane deposits in polar regions are pushed upward over millions of years, a substantial amount of methane can be exposed to low temperature conditions at the surface of the deposits. When this occurs, it can meet the necessary ratio for hydrate formation (Howarth et al., 2011). A third avenue of methane supply occurs as a result of seepage from a deeply buried methane source. When a deeply buried methane reservoir is put under pressure, methane gas surges upward. If the surge is exposed to low temperature environments, conditions are met for hydrate formation (Klauda et al., 2005). As a result of the considerable amount of methane required to form hydrates, the areas in which sufficient bacteriological activity, shifting gas reservoirs, or seeping methane gas are found are relatively rare. As such, researchers can infer the areas of hydrate formation based on the presence of these methane sources and the necessary temperature conditions.

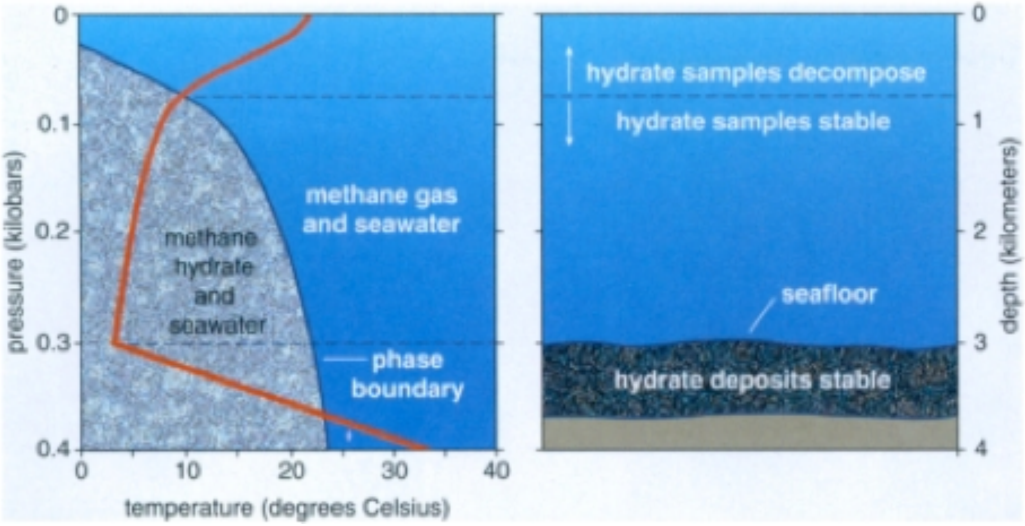

Figure 5: This illustrates the conditions under which hydrates can form and maintain stability. Hydrates require low temperature, high pressure, or a combination of the two in order to form. In addition to these conditions, a very large amount of methane is necessary for hydrate deposits to occur. As such, most hydrate deposits are found beneath subsea sediment where organic matter is decaying and the optimal conditions are present. (Beauchamp, 2004)

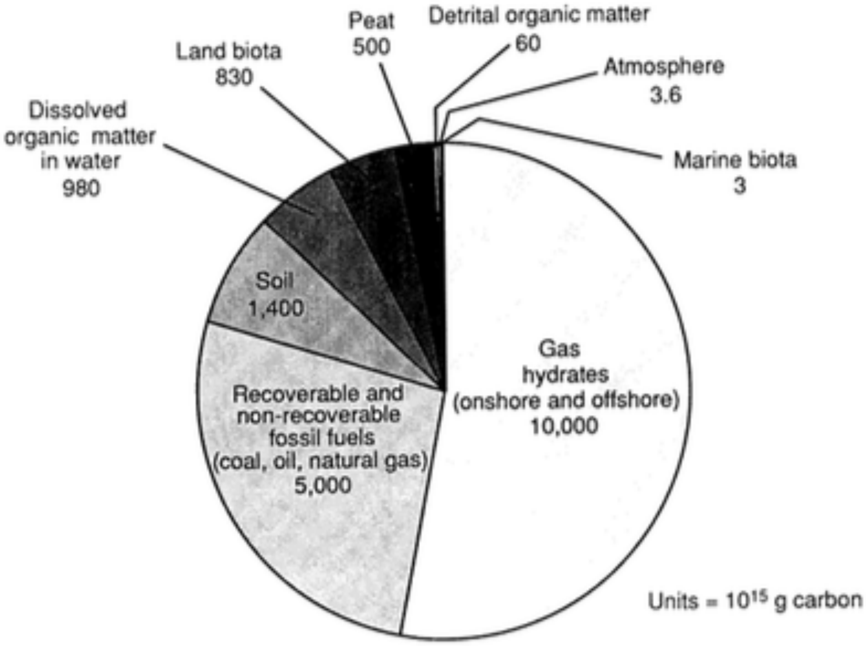

Figure 6: This shows the percent of organic carbon on Earth contained in methane hydrates. This figure does not incorporate kerogen and bitumen, which are much larger constituents of global carbon than methane hydrates. However, it conveys that gas hydrate deposits contain more carbon than all known fossil fuels on Earth. (Beauchamp, 2004).

Chapter 1.4 Where are Methane Hydrates found Globally?

The environments in which hydrates are found have been identified based on the necessary elements of hydrate formation. At the poles, hydrates exist in shallow water as a result of the prevalence of low temperatures. Here, they form where water depth is below 150 m and surface temperatures are below freezing. Hydrate deposits are often associated with polar permafrost as a result of the shared requirement for low temperatures (Milkov, 2004). However, at subpolar lower latitudes, only the sub zero temperatures of deep water enable hydrates to form and maintain stability. In these subpolar oceanic environments, hydrates occur at depths below 300 meters, with a lower depth limit of 2000 m. In these regions, hydrates are found in outer continental margins where cold bottom water is present (Davie and Buffett, 2001).

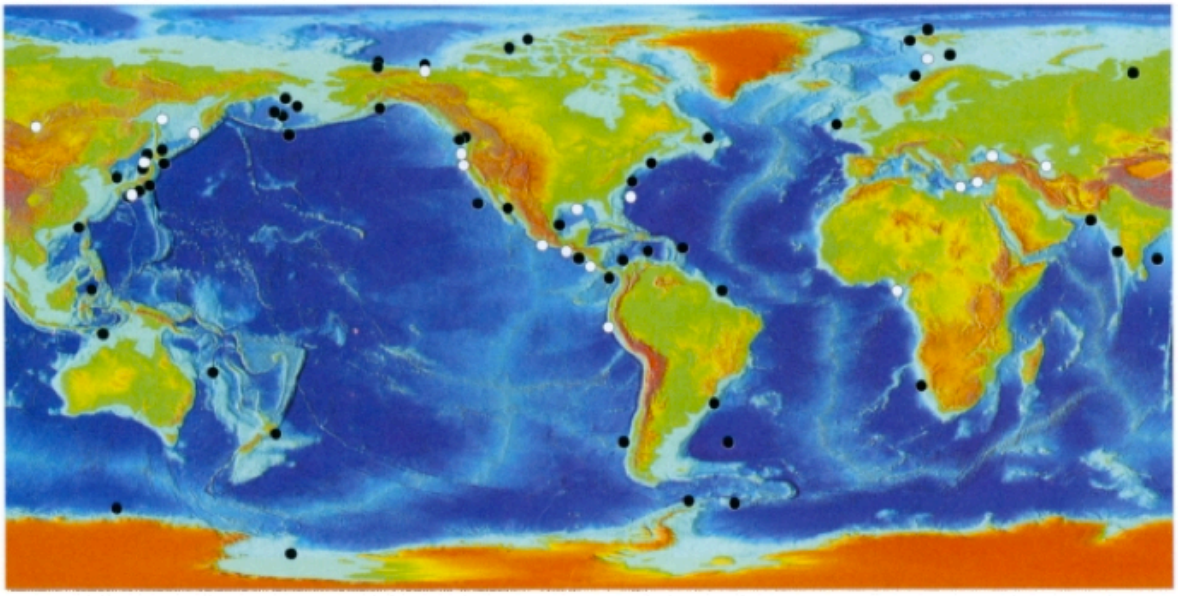

Figure 7: These represent the locations of methane hydrate deposits worldwide. Locations are determined by first identifying the geothermal gradient of sufficiently low temperature or high pressure where hydrates can form. Then, the Bottom Simulating Reflector is used to determine the precise location of the hydrates themselves. White locations represent confirmed sites. However, as many hydrate locations are inaccessible, black locations denote inferred sites. (Kleinberg and Brewer, 2001)

Because hydrates have only been studied in detail for the last two to three decades, and as a result of the extreme temperature and pressure conditions of these remote environments in which they are found, relatively few hydrates have actually been identified. To identify hydrates, depth of a given subsea sediment is determined where temperatures are sufficiently low or pressures are sufficiently high for hydrates to form. This depth where hydrates are stable is typically only a few hundred meters thick (Wuethrich, 1993). To detect the presence of a hydrate deposit within this zone, the transition between a hydrate and the compressed methane gas beneath the hydrate is identified. This transition point is known as the Bottom Simulating Reflector, and gives off a distinctive signature for vessels scanning with remote instrumentation (Street, 2008). Despite the ability of research vessels to identify the presence of hydrate deposits using remote instrumentation, relatively few expeditions have been undertaken to identify hydrate deposits worldwide. This is due to the inaccessibility of most of the locations of hydrate formation. As a result, in lieu of confirmation of the presence of hydrates through identification of the Bottom Simulating Reflector, the existence of most hydrate deposits worldwide are inferred using seismic data. Based on this data, teams have composed the global map of verified (white dots) and inferred (black dots) hydrate deposits shown in Figure 7 (Kleinberg and Brewer, 2001). Because the majority of the hydrate deposits worldwide are only inferred and have not been confirmed by independent expeditions, the estimated size of the global hydrate reservoir is uncertain. This variability has implications for the significance of hydrates to global climate change.

1.5 What is the Scale, and What are the Implications of Methane Hydrate Deposits?

Geologists have roughly estimated that that 1% of the global hydrate reservoir exists in terrestrial permafrost above sea level, 10-20% exists in shallow polar waters 50-100 meters in depth, and the remaining 80-90% is found in deep waters 300-2000 meters in depth (Shakhova et al., 2010). With our present understanding, the estimated quantity of methane stored in hydrates worldwide ranges from 2,500-10,000 gigatons (Street, 2008). Even towards the lower end of this estimate, this is more carbon than all fossil fuel deposits on Earth today (Kvenvolden, 2003). A hydrate release of even 1% of the (lower bound estimate) methane stored would be larger than the contribution of all human emissions to the atmosphere since the industrial revolution. Even a small release of hydrate methane would have significant effects on atmospheric greenhouse gas concentrations.

Chapter 2: Instances of Hydrate Dissociation

Methane hydrates are highly significant as a result of their storage of enormous amounts of carbon. The relevance of this carbon to the larger climate depends on the stability of hydrate deposits worldwide. Most hydrates worldwide are currently stable. This is a result of their location in deep water in which temperatures remain relatively constant. This temperature stability is the result of the relatively high water volume between the deep water hydrate deposit and the surface, meaning that temperature fluctuations present at the surface do not usually reach the deposit. The converse is true with hydrates in shallow water. Usually occurring at the poles due to low temperatures, shallow water hydrates do not have the same amount of water volume between them and the surface, resulting in warmer ambient water temperatures around hydrate deposits. This increases the likelihood of polar shallow water hydrate destabilization in the event of climate warming of surface waters. Researchers have already identified instances of climate induced hydrate destabilization in Arctic marine sediments (Westbrook et al., 2009). This destabilization poses considerable risk to accelerating climate change should this destabilization amplify in the coming years (Westbrook et al., 2009, Shakhova et al., 2010).

2.1 How Hydrates Destabilize Structurally

As discussed in section 1.2, hydrate deposits are not as stable as ice and are more prone to rapid melting. This sudden melting is known as dissociation, and can be triggered by both rising temperature and decreasing pressure (Li et al., 2014). When hydrate dissociation takes place, the deposit separates into its constituents of methane gas, sediment, and water (Blunier, 2000). When the methane gas is separated from the rest of the hydrate, it naturally travels upward through the water column towards the surface where it is emitted into the atmosphere. The process by which this gas is vented from the hydrate deposit upon dissociation is known as Ebulition (Brewer et al., 2002). The tendency of hydrates to melt very rapidly has considerable implications for the rate of methane emitted into the atmosphere when hydrates destabilize. As opposed to ice which melts gradually when it encounters above freezing conditions, hydrates initially retain their solid molecular structure when exposed to warmer temperatures until large sections of the deposit change state immediately. This signifies that huge quantities of methane are released into the atmosphere nearly instantly upon hydrate destabilization, having considerable impacts on the concentration of atmospheric greenhouse gasses.

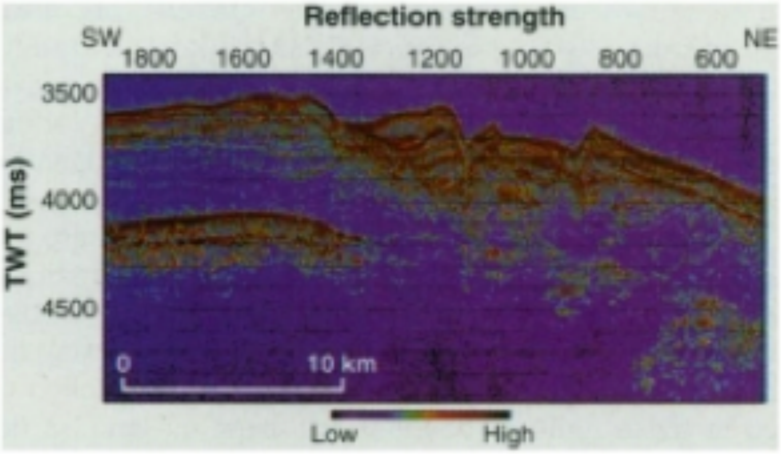

Figure 8: This depicts a methane hydrate after rapid dissociation. The image is generated from reflection readings from the boundary between the hydrate and a methane gas pocket beneath the hydrate. The jagged portion at the center of the image indicates where the deposit has melted due to rising temperatures, resulting in the release of large quantities of methane into the water column. This methane was then emitted into the atmosphere. (Haq, 1999).

2.2 Which regions are more vulnerable to dissociation

Shallow water polar hydrates and terrestrial hydrates found in polar permafrost are most at risk of dissociation. This is a result of their exposure to warming environmental conditions at the polar sea level due to anthropogenic climate change (IPCC, 2014). Because the poles have undergone substantial warming as a result of anthropogenic climate change, temperatures at the polar sea level and shallow polar water are far warmer than those encountered by deep water hydrates in the rest of the world ocean. Hydrates that form in deep water do so because the freezing temperatures required for their formation occur independently of surface climate conditions at the site of their formation. Conversely, hydrates that form in shallow polar water and terrestrial permafrost do so because of the colder polar climate provides the below freezing temperatures required for hydrate formation (Winton, 2006). When the polar environment begins to warm as a result of anthropogenic climate change, these low temperatures upon which shallow water and terrestrial permafrost deposits depend are replaced with warmer environmental conditions (IPCC, 2014). When polar surface and shallow water temperatures rise to above freezing, polar terrestrial permafrost hydrates and shallow water hydrates begin to dissociate (Johannessen et al., 2003). Deep water hydrates are insulated from the warming surface temperatures due to below freezing temperatures naturally existing in the zone of deep water hydrate formation. As a result, only terrestrial permafrost hydrates and polar shallow water hydrates are vulnerable to dissociation.

While terrestrial permafrost hydrates are arguably more susceptible to dissociation than polar shallow water hydrates due to polar shallow water hydrates' insulation from warming temperatures by 50-100 meters of the ocean water column, researchers have spent considerably more resources investigating the destabilization of polar shallow water hydrates. This is due to the difference in the amount of carbon stored in polar shallow water deposits versus terrestrial permafrost deposits. Terrestrial hydrates only compose 1% of the global hydrate reservoir, where hydrate deposits in shallow polar water make up 10-20%. Due to this order of magnitude difference, dissociation from shallow polar water hydrates would have much more significant impacts on atmospheric greenhouse gas concentrations (Shakhova et al., 2010, Ruppel, 2011). Stemming from the considerable difference between the amount of carbon stored in deep water and shallow water hydrates and that stored in terrestrial permafrost hydrates, the scientific discourse has centered around marine hydrates as opposed to terrestrial permafrost hydrates.

Researchers have identified significant differentiating characteristics between deep water and polar shallow water marine hydrate deposits (Lenton, 2012). These distinctions center on how easily polar hydrates dissociate and the relative density of polar hydrate deposits. Because polar hydrate deposits form under the low pressure conditions of shallow water, they can dissociate with an energy input three times less than deep-water hydrate deposits (Winton, 2006). This signifies that any variation in temperature will have a substantially greater effect on polar hydrates than it would on a deep water marine hydrate. Polar shallow water hydrate deposits are also more dense than deep water hydrate deposits. While hydrate molecular structure is constant regardless of the depth at which hydrates form, hydrate deposit concentrations vary based on formation depth. This is a result of the amount of available methane at the zone of hydrate formation. Because substantially more methane is present in polar shallow water than is found at the zone of hydrate formation in deep water, polar shallow water hydrate deposits are between twenty and one hundred times more concentrated than deep water hydrate deposits (Shakhova et al., 2010). As a result, if a given unit volume of polar hydrates were to dissociate, it would represent a twenty to one hundred times greater methane release than it would when this volume of deep water hydrate dissociated. Due to these differentiating characteristics, the warming polar environment is far more significant with respect to how easily polar shallow water hydrates dissociate when exposed to warming conditions and to how much methane is released when such a dissociation does take place. The relevance of the amount of methane contained in polar shallow water hydrates and of the increased susceptibility of these hydrates to destabilization is predicated on the degree of polar warming due to accelerating anthropogenic climate change.

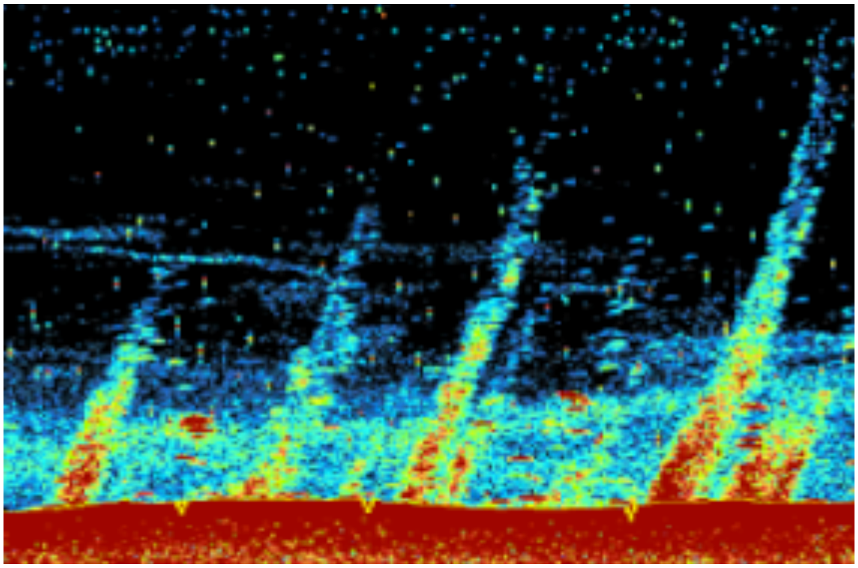

Figure 9: This shows sonar data from a zone of polar shallow water hydrate dissociation. Red denotes concentrated sonar readings whereas blue represents diffuse sonar readings. Each vertical column rising from the red hydrate at the bottom of the image is methane gas venting towards the surface of the water column. The dim horizontal lines are schools of fish. When methane is emitted from dissociating hydrate deposits, it rises through the ocean water column to enter the atmosphere, contributing to climate change (Yurganov et al., 2012).

2.3 Climate change in the arctic

Over the last half century, warming at the poles and at continental high latitudes due to human greenhouse gas emissions has been substantially larger than the global average. Of the two poles, warming in the Arctic has been more acute. This is because of the geographic position of the Arctic is surrounded by landmasses as well as the fact that the wind and ocean currents around the arctic region link it more with the climate of lower latitudes than do those around Antarctica (Screen and Simmonds, 2013).

In the Arctic, climate warming is much greater than in other regions on Earth as a result of several dynamics. The largest of these dynamics is the changing reflectivity of melting of polar sea ice. Because polar sea ice is white, it reflects much more of the sun's heat back into space than does the darker sea water beneath it. When polar sea ice melts, more dark water is exposed. Water absorbs more of the sun's heat than the ice, resulting in greater Arctic temperature increase and the melting of additional sea ice (Smith, 2008). As such, this represents a feedback loop by which warming that melts an initially small portion of ice has disproportionate effects on the larger temperature change of the region. Another feedback loop contributing to Arctic Amplification is disruptions in atmospheric currents. When the Arctic atmosphere warms, subpolar current systems shift northward, bringing warm air from the Atlantic to the Arctic. This shift causes sea ice to melt. This absorption warms the air yet further, resulting in more displacement of subpolar current systems and increased warm air brought to the Arctic (Vonk et al., 2012). This atmospheric feedback loop is echoed by Arctic Ocean currents. When Arctic ice melts, circulation and convection patterns are disrupted in the Arctic Ocean. This is because convection patterns rely on the temperature difference between the frozen Arctic sea ice and the warmer water of lower latitudes to drive their motion. When Arctic sea ice melts, this necessary temperature difference is diminished, weakening the strength of the currents. As a result of this diminished current strength, the patterns of the currents are disrupted, bringing warmer water from the Atlantic Ocean and Barents Sea. This warmer water results in the melting of Arctic ice, disrupting convection yet further. When this ocean circulation is altered, more warm water is brought to the Arctic (Shakhova et al., 2005). These dynamics amplifying Arctic warming are tightly connected and strongly effect one another because they are all driven by the melting of Arctic ice. These factors work in concert to significantly expand any initial temperature increase resulting in the melting of this ice. Because of these dynamics unique to the Arctic, hydrate deposits located in the Arctic ocean are at acute risk for dissociation due to rising temperatures caused by anthropogenic climate warming.

Over the last half century, the Arctic effects of anthropogenic climate change have been substantial (IPCC, 2014). Where most of the world has warmed an average of 1 degree Celsius, the Arctic has warmed an average of 2-3 degrees Celsius (Stroeve et al., 2008). This has greatly diminished the extent of Arctic sea ice. Arctic ice area has reached four record lows in the last fifteen years, with the most recent record low in 2012 (Serreze and Stroeve, 2015). At the time of its record low, ice area was 50% below the 1979-2000 average. Ice volume has shrunk even more precipitously, at 80% below 1979 levels (Vihma, 2014). Rising Arctic temperatures raises questions regarding the stability of Arctic polar hydrates. Researchers predict these warming trends to accelerate in the coming years, with some investigators projecting that ice free summers could occur as soon as 2030 (Overland and Wang, 2013). As melting ice drives an increase in Arctic water temperatures that could destabilize shallow water hydrate deposits, these trends suggest a substantial risk of large scale Arctic polar hydrate dissociation in the coming years.

To determine the likelihood and possible extent to which Arctic marine hydrate deposits could dissociate, researchers have undertaken several expeditions to the Arctic to study hydrate stability (Westbrook et al., 2009, Shakhova et al., 2010). There, they have identified hotspots where hydrate dissociation has already begun.

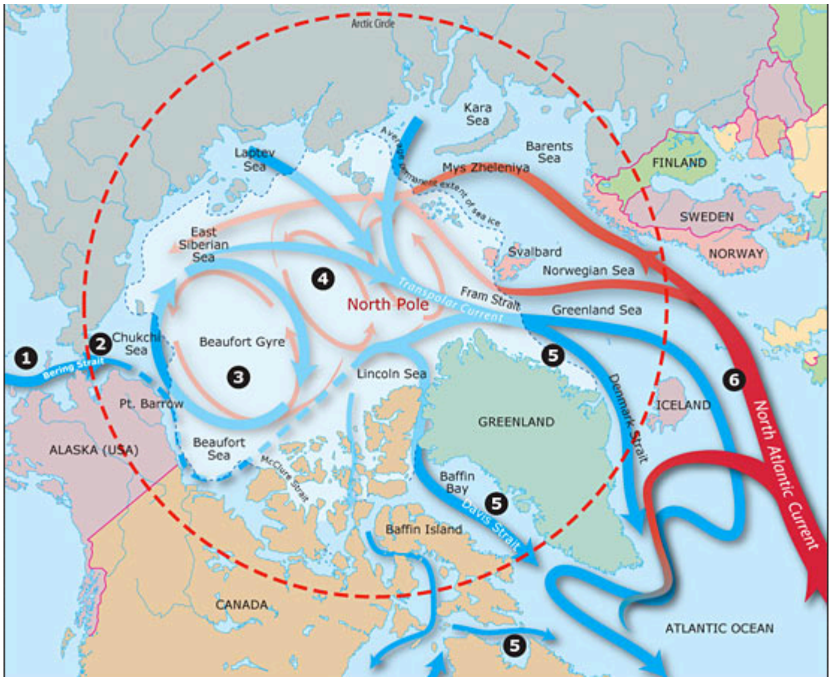

Figure 10: This image underscores the degree to which the Arctic is linked to the warmer climate of lower latitudes through ocean convection currents. The dotted line shows the Arctic Circle. Red currents represent flows of warm water and blue currents represent flows of cold water. These convection systems are driven by the temperature difference of cold Arctic sea ice and warm water of lower latitudes. These currents linking the climate of the Arctic with that of lower latitudes make the Arctic more susceptible to anthropogenic climate warming (IPCC, 2014).

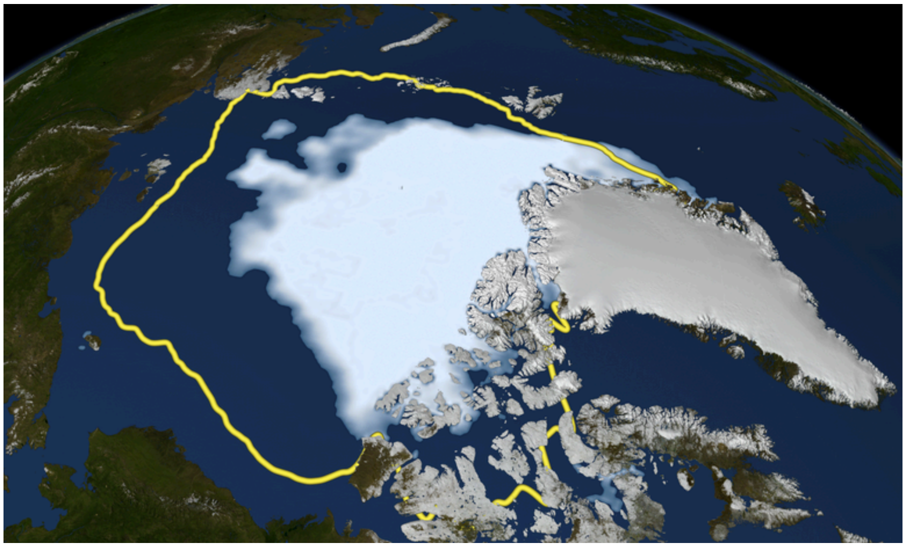

Figure 11: This shows the most recent record arctic ice low in summer 2012. The yellow outline represents the ice extent in summer of 1979. Since 1979, 50% of Arctic ice area and 80% of Arctic ice volume have diminished. It is projected that ice-free summers in the Arctic Ocean could occur as soon as 2030. These warming climate conditions in the Arctic render Arctic Polar hydrates more vulnerable to dissociation (The Guardian, 2012).

2.4 Examples of Arctic shallow water hydrate dissociation

Over the last decade, researchers have documented significant instances in which Arctic shallow water hydrates are dissociating as a result of warming climate conditions (Westbrook et al., 2009, Shakhova et al., 2010). In each of the hotspots, investigators suggest that methane gas emissions from the sites were present over a much larger area than was directly observed (Westbrook et al., 2009, Shakhova et al., 2010). This would suggest significantly larger methane emissions to the atmosphere than were empirically confirmed. The discovery of Arctic hydrates that are currently venting methane to the atmosphere demonstrates that dissociation of Arctic shallow water hydrates has already begun. The studies extrapolate emissions for the area around each hotspot discovered and do not extend to the Arctic as a whole. It is likely that the locations identified represent a small fraction of the total hydrate dissociation that is currently taking place in the Arctic. As such, these locations serve as valuable indicators as to what is occurring on a much larger scale throughout the Arctic Ocean. As the releases at each location are the result of current anthropogenic climate change, the acceleration of Arctic warming in the coming years will likely cause augmented ebullition from the locations identified and those yet undiscovered.

Hydrate Dissociation Instance 1

One such hotspot is the West Spitsbergen Continental Margin. Located north of Norway and East of Greenland, the continental margin was identified as harboring a site of hydrate dissociation in 2008. This dissociation was manifest through the presence of 250 plumes of methane venting into the seawater from the site of the hydrate. The team found that over the area documented, there were 900 kg of methane vented into the ocean water column annually per meter of the hydrate. Over 30 kilometers of the hydrate deposit, the researchers determined that the methane venting observed represented an emission of 27,000 tons per year (Westbrook et al., 2009). However, the team also detected other plumes using sonar at significant distances from the observed site on the continental margin, suggesting that the region of dissociation was much larger than could be directly confirmed (Westbrook et al., 2009). Based on the larger dissociation area implied by the additional sightings, the team posited that the methane emissions from hydrates on the West Spitsbergen Continental Margin could be as large as 20 megatons per year. This alone represents between 3 and 4 percent of the total methane emissions from natural sources worldwide (Reagan and Moridis, 2009). At the time of the observation, warmer water was encroaching on the Continental Margin, increasing the risk the quantities of methane venting from the Margin could rise even further in the near future. The fact that dissociating hydrates already contribute such a significant a fraction of global methane emissions suggests that future hydrate dissociation due to accelerating warming could play a much larger role in worldwide atmospheric methane concentrations. The hydrate dissociation documented on the West Spitsbergen Continental Margin reveals that changing climate conditions in the Arctic are causing methane hydrates to melt, resulting in large scale releases of carbon into the atmosphere. This phenomenon not only extends to hydrates not directly observed throughout the present day Arctic Ocean, but suggests that greater scales of hydrate dissociation will occur with accelerating climate change in the coming years.

Hydrate Dissociation Instance 2

Another instance of documented hydrate dissociation is methane emissions from the East Siberian Arctic Shelf. The existence of dissociating hydrates was discovered at this location in 2005. Upon arriving at the shelf, Russian research expeditions found that the entire water column above the shelf hydrate deposits was supersaturated with methane. This indicates extensive methane emissions from the shelf hydrates. The team determined that the total annual methane emissions from hydrates across the entire East Siberian Arctic Shelf was 7.98 megatons (Shakhova et al., 2010). However, this only represents methane emissions resulting from gradual hydrate melting. If these deposits were to dissociate immediately, the research team investigating the site determined that up to 50 gigatons of methane would be released almost instantly (Shakhova et al., 2010). This is conservative, as it represents only 10% of the methane stored in hydrates on the shelf. The team determined that such a release is possible in the present day. Such an emission would increase atmospheric methane by a factor of twelve (Shakhova et al., 2008). This could have considerable impacts on worldwide greenhouse warming. The possibility of these emissions from the East Siberian Arctic Shelf today demonstrates the potential atmospheric effects of Arctic methane hydrates. This scenario only accounts for emissions from the East Siberian Arctic Shelf, and does not consider methane venting from hydrates throughout the Arctic. The 7.98 megatons of methane currently venting annually from the site represents clear evidence that the process of hydrate dissociation on both the East Siberian Arctic Shelf and the Arctic as a whole has already begun.

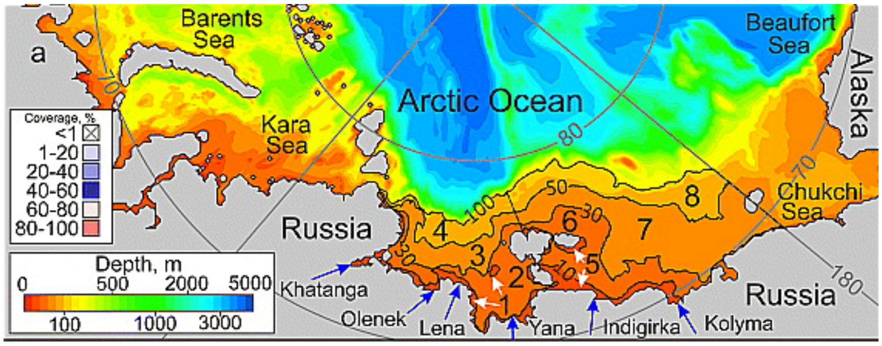

Figure 12: This depicts ocean depth (bathymetry) measurements of the East Siberian Arctic Shelf. The shelf is the largest continental shelf in the world ocean, extending an average distance of 600 kilometers from the shoreline with a total area of 2.1 million square kilometers. The shelf is very shallow with an average depth of only 20-30m. As a result of this shallow depth, hydrates on the East Siberian Arctic Shelf are more susceptible to water temperature changes due to climate shift than other hydrates in deeper water (Dmitrenko et al., 2011).

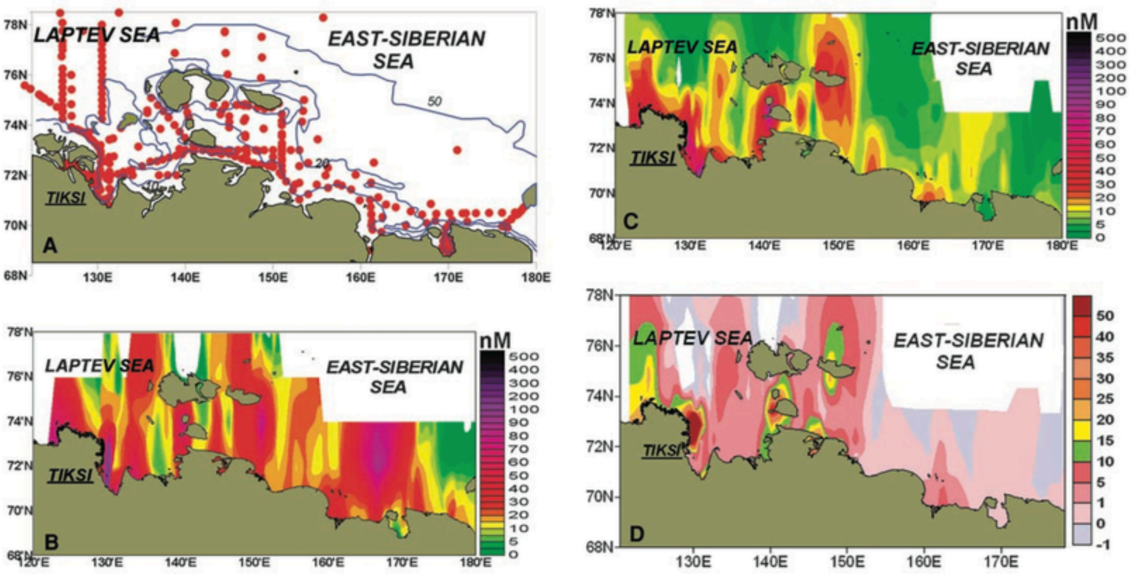

Figure 13: These images represent summertime observations of dissolved methane on the East Siberian Arctic Shelf. A: The position of oceanographic stations on the shelf from which observations were made. B: Dissolved methane in bottom water. C: Dissolved methane in surface water. D: Fluxes of methane venting into the atmosphere over the shelf. These images reveal that methane is actively venting from the shelf into the atmosphere, confirming that hydrate dissociation here has already begun (Shakhova et al., 2010).

As demonstrated by documented methane emissions from both the West Spitsbergen Continental Margin and the East Siberian Arctic Shelf, Arctic hydrates are already beginning to dissociate as a result of present day climate change. These emissions also signify that future accelerating greenhouse warming in the Arctic could have considerable consequences manifest by larger releases of hydrate methane. These sites are among the first locations discovered to harbor dissociating hydrates, and have released relatively minor amounts of methane compared to the emissions potential of the hydrates of the entire Arctic Ocean. It is likely hydrate dissociation will spread to other areas of the Arctic as temperatures continue to rise. These locations constitute canaries in the coal mine for hydrate dissociation in the Arctic, and should be heeded as a clear warning that anthropogenic climate change has already begun to have effects on Arctic hydrate stability. These sites likely represent only a small fraction of the hydrate deposits currently dissociating in the Arctic Ocean, and are also indicative that this dissociation will increase if Arctic temperatures continue to rise. The Russian research team investigating hydrates at the East Siberian Arctic Shelf declared potential hydrate dissociation resulting from climate warming a matter of national safety (Shakhova, 2010). This concern stems from the possibility that a large scale hydrate dissociation could dramatically increase atmospheric concentrations of methane. This increased methane has the potential to dramatically accelerate the progress of climate change. While it is clear atmospheric methane concentrations in such a dissociation scenario would rise, to understand the climatic effects of such an increase, we must look into a time period in Earth history in which such hydrate dissociation has occurred.

Chapter 3: Hydrate Dissociation at the PETM

Through instances of hydrate dissociation discovered in the Arctic, it has been determined that hydrate destabilization in the near future could release considerable quantities of methane into the atmosphere. With temperatures in the arctic rising due to anthropogenic climate change, the risk of dissociation from polar hydrates could intensify in the coming years and decades. Yet even more significant than the potential for hydrates to emit massive quantities of methane into the atmosphere are the consequences these emissions could have for global climate change. In conjunction with models being developed to predict the effects of increased greenhouse emissions on climate warming, an effective means of determining the impacts of a future hydrate methane release is an examination of a geological instance of hydrate dissociation. Intriguingly, the hydrate destabilization transpiring in the arctic today is not the first time methane hydrates have dissociated in Earth history. In the late Paleocene Epoch, hydrates dissociated on a large scale, resulting in substantial impacts on global climate. Geologic records of hydrate release at the Paleocene-Eocene Thermal Maximum 56 million years ago can provide insight into the climate impact of a potential large-scale hydrate dissociation in the 21st century. Such a hydrate methane release would have far reaching implications for both natural ecosystems and human society.

3.1 Hydrate Dissociation at the Paleocene-Eocene Thermal Maximum

Abbreviated as the PETM, this climatic event was discovered in the 1990's. Since that time, the PETM has generated considerable interest from the scientific community. This is because the sharp temperature increase during the event was fueled by a rapid release of carbon into the atmosphere. As such, the PETM may serve as the only natural instance that parallels the carbon releases transpiring as a result of modern anthropogenic climate change. At the time of the PETM, the dinosaurs had only been extinct for ten million years. The supercontinent Pangea was breaking up, beginning to split into the continental positions of the present. The planet was much warmer than today's climate as a result of increased concentrations of atmospheric CO2, rendering it without ice caps.

The event began as a result of volcanism fueled from the tectonic activity driving the supercontinent Pangea apart. This volcanic activity emitted thousands of gigatons of carbon dioxide into the atmosphere. This increased concentration of greenhouse gasses began warming the planet. This warming disrupted weather patterns, reducing precipitation. This dearth of rainfall gave way to drought in numerous regions worldwide, drying out vegetation. These widespread drought conditions enabled large wildfires to burn significant areas of land, emitting considerable quantities of carbon dioxide into the atmosphere. The warming due to volcanism also initiated the thawing of permafrost in Arctic latitudes, releasing large quantities of carbon dioxide and methane into the atmosphere. Greenhouse gasses from the thawing permafrost and burning wildfires added to the greenhouse gas burden already present due to volcanism, warming the planet at the start of the PETM. The warming then began to affect the stability of shallow water Arctic hydrate deposits. This transpired due to the effects of warming temperatures on current systems channeling water to marine hydrate deposits. When the climate began to warm, currents funneling water to hydrate deposits at the poles shifted their sources from higher latitudes to lower latitudes. This shift occurred primarily in the Atlantic Basin. These new current patterns channeled warm water from lower latitudes to hydrate deposits in polar waters. The warmer water increased Arctic bottom water temperatures in the Arctic Ocean basin by 4-5 degrees Celsius at the start of the PETM. This increase brought water temperatures around hydrate deposits located on continental shelves to above freezing, causing the hydrates to rapidly dissociate. Methane emissions from melting hydrates began to warm the atmosphere further than the volcanism, wildfires, and thawing permafrost had. The additional warming augmented the shift in ocean current systems. This channeled more warm water from lower latitudes toward the poles, resulting in more hydrate dissociation. The cycle of polar water temperature increase, hydrate dissociation, atmospheric warming, and ocean current disruption formed a positive feedback loop that lasted eight thousand years. After this time, all hydrates susceptible to warmer ocean water from the equator had dissociated (Mcnerney and Wing, 2011). This 8000-year period represents the largest hydrate dissociation recognized in the geologic record. Roughly half of the global hydrate reservoir dissociated, releasing between 2000 and 4000 gigatons of methane into the atmosphere (Dickens, 2001). The tremendous methane release had far reaching impacts on climate warming. Following this emission, global temperatures warmed between 5 and 8 degrees Celsius over the pre-PETM baseline. The warming of the PETM was so protracted this temperature increase persisted for 200,000 years (Katz, 1999). After this period, natural processes removed the greenhouse gasses from the atmosphere and the planet cooled. The ensuing lower water temperatures at the poles facilitated hydrate formation. After several million years, the hydrate reservoir was replenished. The phenomenon of climate driven hydrate dissociation and re-formation is referred to by researchers as the Clathrate Gun Hypothesis (Kennet et al., 2003). Note that clathrate is an alternative term for hydrate. Initial hydrate dissociation due to warming temperatures represents a firing of the Clathrate Gun, resulting in a period of warming for Earth's climate. After several hundred thousand years, cooling conditions represent a reloading of the Clathrate Gun as hydrates re-form in lower water temperatures. After the Clathrate Gun is reloaded, hydrates are once again susceptible to "firing" if climate warming surpasses a certain threshold (Huntley, 2006). Evidence of the Clathrate Gun firing in the late Paleocene is recorded in abrupt Carbon 13 spikes in the fossil record. This Carbon 13 spike denotes a sharp increase in the concentration of greenhouse gasses in the atmosphere (Dickens, 2011). Carbon dating is a tool employed by geologists to assess the age of a given fossil specimen. Because the Carbon 13 nucleus is unstable, it decays over time. To determine the age of a given specimen, geologists use instrumentation to detect the fraction of Carbon 13 that is present as opposed to the fraction that has decayed. In this instance, Carbon 13 is used to indicate the concentration of greenhouse gasses present in the atmosphere at the time of the PETM. A spike in Carbon 13 signifies an increase in these atmospheric greenhouse gas concentrations. The 5-8 degree Celsius warming of the PETM reveals evidence of a significant and rapid change to the climate system. While this warming was not entirely caused by methane releases due to hydrate dissociation, these hydrate methane releases were responsible for a significant fraction of this temperature increase. The event demonstrates that when all hydrates susceptible to increasing polar water temperatures dissociate, the atmospheric warming that takes place has the potential to be five to eight times greater than the current anthropogenic global warming since the industrial revolution.

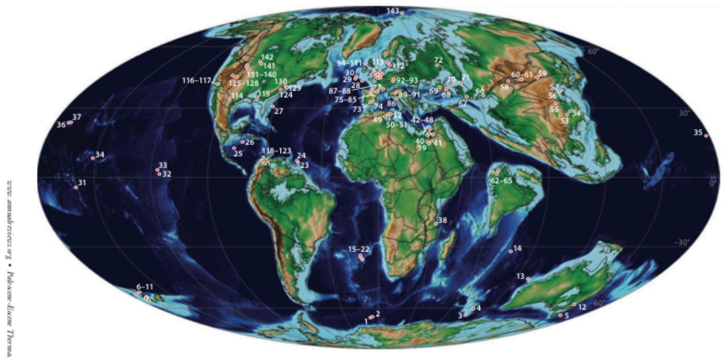

Figure 14: This figure represents the global position and shape of the tectonic plates at the time of the PETM, 56 million years ago. Red dots and corresponding numbers are sites at which the PETM has been studied. The map's colors show continental elevation and depth (Katz et al., 2009).

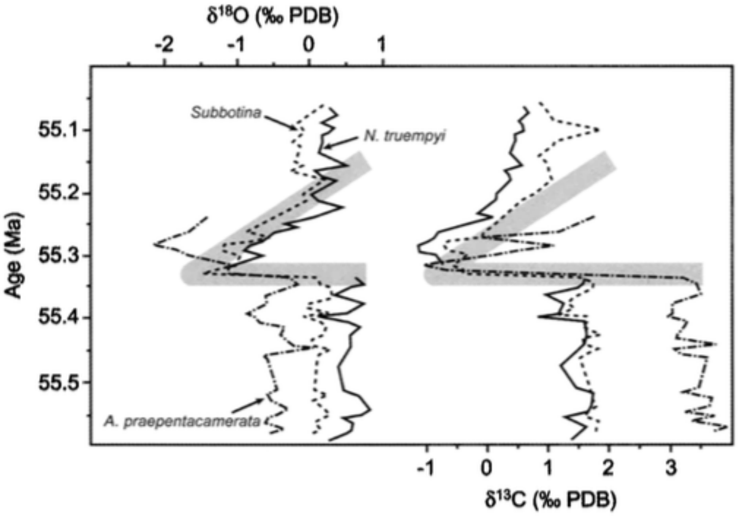

Figure 15: These represent Oxygen 18 and Carbon 13 isotope spikes during the PETM. The spikes indicate sharp rises in atmospheric methane concentrations. This increase is due to large scale hydrate dissociation at the end of the Paleocene (Kennett et al., 2003).

3.2 Climatic Effects of Hydrate Dissociation at the PETM

When the Clathrate Gun fired in the late Paleocene, methane emissions effected far-reaching changes to the planet's environment and had permanent impacts on the planet's biological systems. The massive methane releases at the start of the PETM rendered the climate considerably warmer. The climatic instability inherent in this rapid temperature increase was manifest through significantly further disruptions in global precipitation than were present due to the initial volcanism. Regions which once received steady rains now received precipitation only from highly intermittent storms. Increased concentrations of water vapor ensured that when these storms did occur, they were much more powerful and damaging. Large swaths of the planet experienced extreme drought during this time, likely exacerbating the wildfires (Kennet and Scott, 2001). The sharply increased carbon in the atmosphere also resulted in dramatic acidification of the oceans. Ocean temperatures spiked by 5 degrees Celsius, enabling aquatic organisms in higher latitudes to migrate northward. Rising water temperatures impaired the activity of oxygen-producing plankton. Due to the oxygen depletion of deep-water areas, Benthic foramnifera, a species of deep-water microorganism, became extinct during the PETM (Kennet and Scott, 2001). On land, myriad species were forced to undergo considerable physical and behavioral adaptation to cope with the rapidly shifting climate. Mammals experienced enormous evolutionary adaptation during the PETM. In fact, mammalian adaptation during the PETM was so considerable that it laid the foundations for diversity and dominance of mammalian orders in the present day. Once exhibiting massive body sizes, mammals rapidly shrank during this period. Because smaller organisms are able to dissipate body heat more easily, smaller mammals were able to better survive in warmer conditions. During the PETM, mammalian orders also greatly diversified. Orders containing the smaller ancestors of giraffes, zebras, horses, and elephants arose due to the selection pressures of this period. Most significantly, the earliest primates first evolved as a result of the evolutionary forces of this time (Katz et al., 2001). As such, the PETM was so significant that we as humans may owe our existence to widespread hydrate dissociation. Although the climate cooled and re-stabilized after 200,000 years, the PETM had transformative impacts on the planet's organisms.

In the instance of the firing of the Clathrate Gun at the Paleocene-Eocene Thermal Maximum, massive methane emissions from melting hydrate deposits resulted in abrupt and profound climate warming. From this geologic event, the effects of a large-scale hydrate methane release in the 21st century can be estimated. At present, the Clathrate Gun remains loaded through the vast quantities of methane stored in hydrate deposits in the Arctic. Due to the cooler temperatures at the poles in the present day than during the PETM, the polar hydrate reservoir is 2.3 times larger today than it was at the end of the Paleocene (Dickens, 2001). As such, hydrate dissociation in the modern day could potentially result in an even greater methane release than transpired during them PETM. As with the start of the PETM, initial emissions of greenhouse gasses are warming the globe, albeit from anthropogenic instead of volcanic sources. Feedback loops in the Arctic are dramatically augmenting this warming, leaving Arctic hydrates vulnerable to dissociation. Warming of Arctic waters is approaching a critical threshold beyond which the Clathrate Gun may fire again. At the present day, this firing would entail the release of between 200 and 2000 gigatons of methane from Arctic marine hydrates. While the present day climatic system is not the same as that of the PETM, the PETM can be used to gain insight into the level of environmental transformation that would transpire when the Clathrate Gun fires. If the Clathrate Gun were to fire today, global temperatures could rise up to 8 degrees Celsius. This increase would result in the melting of a significant fraction the world's polar ice caps. The melting of a significant fraction of the world's ice sheets would result in considerable sea level rise. Globally, such a rise would inundate low-lying areas such as the Netherlands, Bangladesh, India and parts of the United Kingdom. In America, the rise would submerge states such as Virginia, Florida, Louisiana, and parts of California. The human costs of a sea level rise of between 30 and 80 meters, which is possible with large scale hydrate dissociation, would be staggering. Up to forty percent of the world's population would be displaced. At mid-century demographic projections, these 4 billion refugees would represent one of the worst humanitarian crises in world history (Nicholls and Cazenave, 2010). For the biosphere, the impact of an eight degree temperature increase would be catastrophic. The climatic shift would dwarf the existing anthropocene extinction, resulting in the loss of over 50% of the world's biodiversity. As was the case in the PETM, atmospheric weather conditions would destabilize. Precipitation would become highly irregular, often falling in the midst of superstorms or not at all. Massive droughts would occur, potentially precipitating large-scale crop failures. Such decline in agricultural yields could result in mass starvation and enormous geopolitical tensions (Meehl et al., 2005). A recent financial estimate determined the economic impact of a 50 gigaton methane release from hydrates on the East Siberian Arctic Shelf would be 60 trillion dollars over the next century (Whiteman et al., 2013). This is equivalent to the entire annual GDP of the world, and does not account for larger releases of methane from the Shelf or elsewhere in the

Arctic Ocean. If the Clathrate Gun were to fire, the significant climate impacts would transpire within decades of the initial methane release, rendering this climate shift an event which could take place within our lifetimes. While it is not known when the Clathrate Gun could fire, sites at the West Spitsbergen Continental Margin and the East Siberian Arctic Shelf demonstrate that limited-scale hydrate dissociation in the Arctic has already begun. At present, it is necessary to assess the realistic risk the Clathrate Gun will fire in the near future to determine the probability of the severe climatic shifts of the PETM transpiring within our lifetimes.

Chapter 4: Risk Assessment of Hydrate Dissociation

It has been demonstrated that large scale hydrate releases have transpired in Earth's geologic past. Such releases prove that when hydrates dissociate on a large scale, sufficient quantities of methane are emitted into the atmosphere to significantly affect climate warming and lead to large scale environmental shift. That the Clathrate Gun could fire again at some point in Earth's geologic future is a certainty. The question with respect to human society is whether the Clathrate Gun will fire as a result of anthropogenic climate change in the 21st century. Despite the considerable evidence that hydrate dissociation will likely transpire in the coming decades, there are contentions that such a methane release cannot be triggered by anthropogenic climate warming and will thus be unlikely. These arguments maintain that initial perspectives on the immediate risk of methane hydrate dissociation were overreactions and that the bulk of the evidence suggests that destabilization will not occur. However, findings from recent field expeditions advance the opposite conclusion, that near term hydrate dissociation is not only possible but is already beginning. Complicating the contention are uncertainties regarding the true amount of methane stored in shallow polar marine hydrates and how rapidly these hydrates could in fact dissociate. It is critical to examine both arguments while acknowledging the uncertainty of presently available information to assess the realistic risk that hydrate dissociation will occur in the coming decades. Given both contentions, it appears it is realistic to expect some degree of hydrate dissociation in the next ten to twenty years. Such a destabilization would have at least moderate impacts on global climate change.

4.1: Percent of the Hydrate Reservoir Susceptible to Climate Change

A critical aspect of the argument that hydrate dissociation will not take place as a result of 21st century climate change is that an insufficient portion of the global hydrate reservoir is susceptible to the effects of climate warming. As discussed in Section 2.2, vulnerability of hydrates to climate induced destabilization is dependent on the conditions in which they are formed. Hydrates that form in shallow water due to the low temperatures of polar environments are susceptible to climate induced dissociation when this polar environment warms. However, hydrates that form in deep water as a result of the low temperatures afforded by high depths are not susceptible to surface temperature shifts due to anthropogenic warming. Those that argue significant hydrate dissociation will not occur articulate that an insufficient quantity of methane is stored in polar shallow water hydrates to trigger significant increases in atmospheric greenhouse gasses. This is because 90-95% of the global hydrate reservoir occurs in deep water hydrates (Ruppel et al., 2011). Investigators who argue this perspective cite the lower end of the estimate for the amount of methane in the global hydrate reservoir at 2500 gigatons. They contend that based on this estimate the 125-250 gigatons of methane present in shallow water polar hydrates is insufficient to trigger significant increases in atmospheric warming (Beauchamp, 2004). While 125-250 gigatons is substantial, they argue a much smaller subset of this would be emitted in hydrate dissociation at any given time. While this theory is correct in contending that 90-95% of the hydrate reservoir is not susceptible to climate warming, it relies on the assumptions that there are in fact only 2500 gigatons of methane in the global hydrate reservoir and that only a small subset of the methane in the Arctic would be released at any given point (Archer, 2007).

Proponents of the school of thought that hydrate dissociation is indeed possible in the near future contend that the 5-10% of the global hydrate reservoir in shallow polar waters is more than enough to cause meaningful greenhouse warming. These individuals maintain that up to 10,000 gigatons of methane could be present in the global hydrate reservoir. This denotes that up to 1000 gigatons of methane may be present in hydrates in the Arctic Ocean, four times larger than the estimate of the other side of the argument (Harvey and Huang, 2005). Other estimates posit there are between 250 and 2000 gigatons of methane in the arctic ocean, suggesting the possibility of an even larger reservoir of hydrate carbon vulnerable to climate change (Dickens, 2003). This signifies a meaningful increase in the potential of polar arctic hydrates to cause climate warming. Researchers studying hydrate deposits in the East Siberian Arctic Shelf propose that the amount of methane residing in Arctic Ocean hydrates may be even larger. Russian researcher Natalia Shakhova and her colleagues have concluded that between 100 and 1000 gigatons of methane are present in hydrates on the East Siberian Arctic Shelf alone. This estimate does not account for hydrate deposits elsewhere in the Arctic Ocean, which would be significantly larger. It appears that the amount of methane present in shallow Arctic waters may be more than is thought to exist by those proposing methane hydrates will not dissociate. As shown in Figure 2, a release of even 50 gigatons of methane would result in an increase in temperature rise resulting from anthropogenic climate change by 25% (Whiteman et al., 2013). As such, there is more than enough hydrate methane vulnerable to climate change to at least moderately impact global greenhouse warming.

4.2 Amount of Emitted Methane that Enters the Atmosphere

A second postulate made by those arguing that substantial hydrate dissociation will not occur in the 21st century is that a diminutive fraction of methane released into ocean water from melting hydrates is actually emitted into the atmosphere. This camp argues that hydrate methane releases in deep water do not reach the surface, but that releases from shallow water can reach the surface and be emitted into the atmosphere. This group articulates that methane emissions from deep water sources do not reach the surface due to both methane dissolving in the ocean water and the vented methane's oxidation by bacteriological organisms. When methane is emitted due to dissociating hydrates, it is released into the ocean as gaseous bubbles. However, methane does not remain in these bubbles for long. As the bubbles rise through the water column, many fracture into smaller and smaller bubbles until their constituents no longer rise through the ocean water but remain suspended in the water column. From here, the methane dissolves in the ocean water and is never emitted into the atmosphere (Youxue, 2003). As such, this methane never contributes to greenhouse warming and has no effect on climate change. Only larger bubbles survive the ascent through the ocean water column to make contact with the surface. However, as the bubbles rise through the water column, their methane content is replaced by oxygen and nitrogen from the surrounding water. Methane is lost through the bubbles' surfaces and is released into the ocean water where is dissolves (Rehder et al., 2009). This dissolved methane is never emitted into the atmosphere. Additionally, vented methane is uptaken and oxidized by bacteriological organisms in the ocean water. When methane is emitted from dissociating hydrates, bacteria requiring methane for their biological processes absorb the compound from both the ocean water and the rising gaseous bubbles. The organisms then convert the methane to CO2, which is released into the ocean water. From here, the CO2 is not emitted into the atmosphere, having no effect on greenhouse warming. The amount of methane oxidized by bacteria is directly proportional to the depth through which the methane must rise to reach the surface. As such, a smaller percentage of shallow emissions are oxidized than deep water emissions. As a result of the combined effect of dissolution, oxygen and nitrogen replacement, and bacterial oxidization of methane rising through the water column, any methane emission from hydrates greater than 100 meters does not reach the surface (Kerr, 2010). As a result, only methane emissions from hydrates shallower than 100 meters has any contribution to greenhouse warming.

Proponents of the argument that hydrates are likely to dissociate in the near future acknowledge that methane emitted from hydrates deeper than 100 meters does not reach the surface. However, they contend that hydrates most susceptible to climate warming in the Arctic have formed in shallow water, typically less than 100 meters in depth. This is a result of low polar temperatures ideal for hydrate formation (See Section 2.2). Because the bubbles of vented methane rise through the water column at the same rate regardless of depth, there is not as much time for the methane to be dissolved, replaced, or oxidized in shallow water as there is in deep water (Are, 2001). Because of this dynamic, supporters of this argument maintain that a significant fraction of methane vented from dissociating hydrates shallower than 100 meters reaches the surface in spite of dissolution, replacement, and oxidation. As such, destabilizing hydrates shallower than 100 meters can contribute to climate warming. This phenomenon is evidenced by hydrate dissociation on the East Siberian Arctic Shelf. On the shelf, hydrates are present at an average depth of 5-50 meters (Shakhova et al., 2010). As shown in Section 2 Figure 6, these shallow hydrates have facilitated substantial documented methane emissions into the atmosphere (Shakhova et al., 2010). While dissolution, replacement, and oxidation reduces the amount of the global hydrate reservoir that can contribute to climate warming, more than enough methane is stored in Arctic shallow water hydrates below 100 meters in depth to meaningfully impact climate change.

Figure 16: This figure depicts bubbles of methane rising through sediments. Such methane emission has been documented in the West Spitzbergen Continental Margin, the East Siberian Arctic Shelf, and the Beufort Sea Shelf (Whiteman et al., 2013).

4.3 Timescales of Hydrate Dissociation

A third argument made by those contending hydrate dissociation is not relevant for human society is that hydrate destabilization is gradual enough that it can be dealt with by future generations. As a result, this group contends that it is not of concern to present society and that the threat of hydrate dissociation need not be reflected in policy. This school of thought posits that rather than dissociating immediately, hydrates melt over a period of several hundred to several thousand years. Proponents of this school point out that while hydrates are dissociating in the present day, they are doing so at a comparatively gradual rate. This suggests that full melting may transpire over centuries to millennia. Geological evidence of this dissociation rate is presented through hydrate destabilization during the PETM. During this time, hydrates released methane over a period of 8000 years (Dickens, 2001). Even if the rate of hydrate melting was ten times faster than that of the PETM, it would still take eight centuries to achieve the same level of warming as was present at the end of the Paleocene. This timescale is long enough that hydrate dissociation can be dealt with by future generations, and thus suggests that the risk of hydrate methane release may be irrelevant with respect to present day policymaking. In addition to this, gradual releases of methane are mitigated by the rate of oxidation of methane in the atmosphere. After 12 years in the atmosphere, methane gas is oxidized into carbon dioxide. As CO2 is only 1/25 as potent a greenhouse gas as methane, this considerably curtails the climate effects of methane emissions after 12 years. As such, in order for methane concentrations to meaningfully increase in the atmosphere, the rate of methane emission must exceed the rate of its oxidation (McGinnis, 2006). Due to this, methane emissions that are too gradual are oxidized before they can impact climate warming. Not only do hydrate emissions take place on timescales not relevant for anthropogenic to the present generation, the gradual emissions on this scale may be oxidized before they can impact climate warming.

Proponents of the theory that hydrate destabilization is indeed relevant for the present generation cite significant differences between the 21st century and the PETM and the potential of hydrates to emit methane abruptly. One critical difference is the presence of the Arctic ice cap in the 21st century and the lack of polar ice at the end of the Paleocene. Because hydrates rely on cold temperatures to form, when temperatures are lower, more hydrates form. As a result of the considerably colder temperatures present in the Arctic in the 21st century than at the end of the Paleocene, there is 2.3 times more carbon stored in Arctic hydrates than there was during the PETM (Charles et al., 2007). As a result, present day hydrates have the potential to effect considerably greater impacts on atmospheric greenhouse gas concentrations. The presence of an Arctic ice cap also influences the depth at which modern day hydrates are found. Depth of present day marine hydrates in the ocean water is notably shallower than it was during the PETM. This is a result of the lower temperatures of the Arctic that enable hydrates to form in comparatively shallow water versus warmer temperatures at the PETM that caused the formation of hydrates in deeper water (See Section 2.3). As a result of the shallower depths of hydrates in the present day, these hydrates are more susceptible to climatic shift than those in the PETM. The Arctic ice cap also warms considerably faster due to greenhouse warming than other regions in lower latitudes. This is due to Arctic feedback loops such as the ice albedo effect that work to amplify anthropogenic climate change in a non linear fashion not present at the PETM (see section 2.3), further accelerating the rate of hydrate destabilization. Additionally to the presence of an Arctic ice cap, another distinction between the PETM and the present day is the comparative rapidity of anthropogenic climate change due to human carbon emissions. While the initial warming due to volcanism, wildfires, and permafrost that triggered the firing of the Clathrate Gun in the late Paleocene took place over millennia, anthropogenic carbon emissions have only transpired over the last century and a half (Lamarque, 2008). The rapid warming that has ensued as a result of these abrupt increases in greenhouse gasses has the potential to thaw hydrate deposits considerably faster than their rate of melting at the end of the Paleocene. These critical distinctions between the PETM and the 21st century are reflected in the findings of the research team investigating hydrate dissociation on the East Siberian Arctic Shelf. The team found that as a result of warming conditions on the shelf stemming from anthropogenic climate change, an abrupt release of up to 50 gigatons of methane is possible at any time (Shakhova et al., 2010). If this release were to transpire, it would increase climate warming caused by anthropogenic climate change by 25% (Whiteman et al., 2013). The team estimated 50 gigatons only accounts for between 5 and 50 percent of the carbon stored on the shelf. As such, an augmentation of climate warming by 25% does not take into account if more carbon is released from the shelf, or if hydrate dissociation takes place from the 250-2000 gigatons of methane stored elsewhere in the Arctic Ocean (Dickens, 2003). Through a combination of the larger amount of hydrate carbon due to the presence of the Arctic ice cap, the more rapid rate of anthropogenic climate change, and the significant amount of methane determined to be susceptible to immediate release, it is clear there is at least a fair risk that hydrate dissociation is relevant to present policymaking.

In response to the arguments that gradual methane release could not overcome the rate of methane oxidation in the atmosphere, advocates of the theory that hydrate dissociation is relevant for modern society articulate that significant climate change still transpired due to dissociating hydrates in the PETM. In the environment of the late Paleocene, hydrate dissociation took place at a considerably slower rate than is possible today. However, even in the PETM, the rate of methane emission from dissociating hydrates exceeded the rate of its oxidation in the atmosphere to warm the climate between 5 and 8 degrees Celsius (Dickens, 2001). As such, the PETM demonstrates that even gradual hydrate methane emissions have the potential to affect significant climate warming.

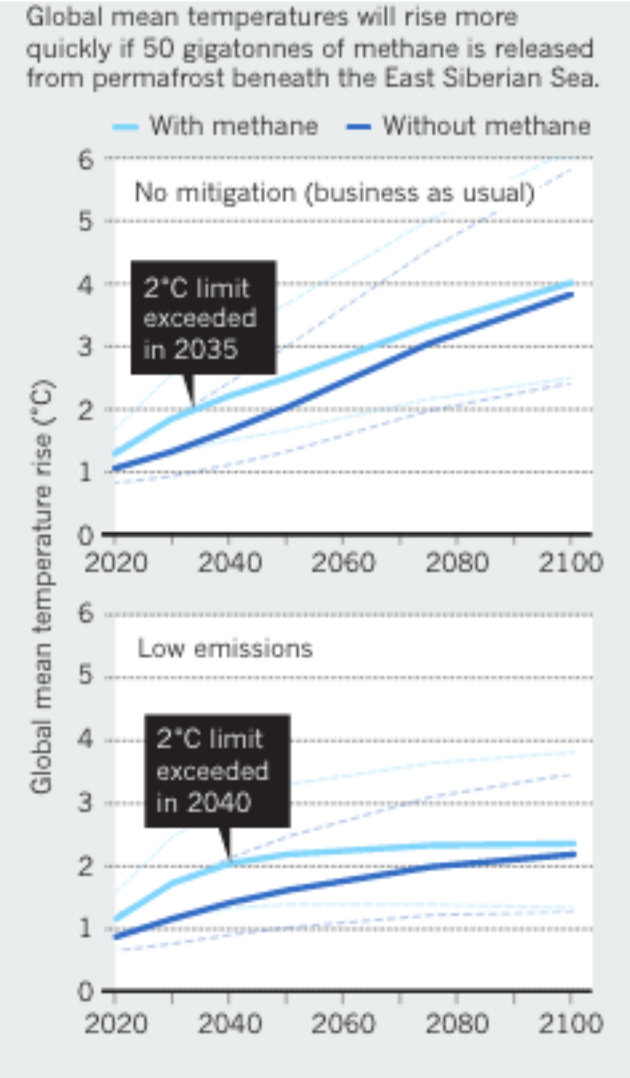

Figure 17: This figure illustrates the projected climate effects of a 50 gigaton methane release from the East Siberian Arctic Shelf. The light blue line indicates the climate warming if the 50 gigaton release takes place. The dark blue line indicates the warming if the 50 gigaton emission does not take place. The top panel shows projected climate warming if no mitigation efforts are implemented. The bottom panel shows projected climate warming if emissions are modestly reduced. This only applies to initial methane emissions from the East Siberian Arctic shelf and does not take into account later emissions from the Shelf or from the Arctic Ocean as a whole. For reference, there is between 100 and 1000 gigatons of methane present on the shelf and between 250 and 2000 gigatons present in the Arctic Ocean. This figure articulates the effects of the release of only 50 gigatons (Whiteman et al., 2013).

4.4 General Risk Assessment

Given the arguments of both sides of the discourse over the likelihood that hydrate dissociation could meaningfully impact global climate change, there remains considerable uncertainty over the exact risk this dissociation will occur. In order to exactly characterize the possibility large scale hydrate dissociation will affect climate warming, additional research must determine two additional pieces of information. The first is the exact amount of methane present in shallow water Arctic hydrates vulnerable to climate warming. Current estimates vary between 250 and 2000 gigatons. This gap is highly significant and does not permit accurate assessment of the risk that Arctic hydrate dissociation will impact the climate. The second is the percentage of this methane that is susceptible to rapid versus gradual dissociation. While Arctic methane hydrates have begun to dissociate gradually, none have yet dissociated rapidly on a large scale. As a result, this piece of information is not currently known. The present uncertainty in the size of the methane reservoir in shallow Arctic waters and how much of this methane is vulnerable to rapid dissociation makes predicting the holistic risk that hydrate destabilization will impact the climate very difficult (O'Connor et al., 2010). In order to address the considerable gaps in accurately assessing the risk of hydrate dissociation, improvements in the technologies to assess the location, size, and methane concentration of hydrate deposits are necessary. Additional research utilizing these improved technologies to clarify the amount of methane stored in shallow Arctic waters and how much of this methane is susceptible to rapid dissociation should be undertaken as soon as possible. Numerous scientific papers have dismissed the threat of dissociating hydrates with respect to the present generation of policymakers without acknowledging the benefit of additional research (Beuchamp, 2004, Archer, 2007, Ruppel et al., 2011). This perspective could be very hazardous, as it permits the dismissal of this critical problem without characterizing its exact risk. This leaves modern society open to discovering the threat of large-scale hydrate dissociation too late to engage in mitigation solutions.

While considerable uncertainties are present in determining the risk of present day hydrate dissociation, the information currently available can be used to form a general characterization of this risk. As a result of the large amount of methane potentially present in shallow Arctic waters, and the considerable amount of methane potentially vulnerable to rapid dissociation, the downside risk to the argument that hydrate dissociation is not a credible threat is enormous. The demonstration of the climatic effects of hydrate dissociation at the PETM, the increased amount of methane present in the Arctic in the present day compared to the PETM, the faster rate of anthropogenic climate change in the Arctic compared to the Paleocene, and the findings of researchers at the East Siberian Arctic Shelf and the West Spitsbergen Continental Margin suggest at least a moderate risk of hydrate dissociation that could significantly impact modern day climate change. If enough methane is present in shallow Arctic waters to cause climate warming, and if enough of this methane can dissociate rapidly, initial methane emissions that would effect larger climate change would begin in the next 1-2 decades. Beyond this, the full effect of these emissions would take between 1-3 decades to manifest (Whiteman et al., 2013). If such a scenario is credible, sharp reductions in anthropogenic carbon emissions are essential to prevent this contingency. Among researchers closely studying hydrates at the East Siberian Arctic Shelf and the West Spitsbergen Continental Margin, geoengineering has also been suggested (Westbrook et al., 2009, Shakhova et al., 2010). Through either engaging in additional research or through large scale hydrate dissociation itself, it is likely modern society will more accurately determine the risk of hydrate methane emissions in the next one to two decades.

Conclusion

While not enough is known about hydrate dissociation to determine the exact risk this destabilization will transpire, hydrates have been studied in nature for the last three decades. During this time, significant knowledge on hydrates has been acquired which can be used to assess the gravity of the threat melting hydrates pose to society. Based on information presently available, it can be determined that there is a moderate risk hydrates will dissociate in the coming decades. At first glance the term “Moderate” seems general and broad. This is a reflection of the fact that the specific risk of hydrate destabilization is not known. The most important definition of the term “moderate” in this case is that it is greater than “minimal”. This distinction is critical in characterizing the implications of hydrate dissociation for society. While a minimal risk would permit both researchers and policymakers to dismiss the risk of hydrate dissociation as a long term contingency, a moderate risk does not allow this dismissal. Instead, it demands recognition of the problem of hydrate dissociation as an immediate threat that warrants purposeful and meaningful action on the part of society. This action would involve additional measures to combat climate change undertaken specifically as a result of the discovery of this potential climatic tipping point. Additionally, a moderate risk entails that the threat of the Clathrate Gun firing again in the coming decades is significant enough that societies should prepare contingency scenarios for situations in which the

Clathrate Gun actually fires. These situations are identical to the worst effects of climate change already projected, signifying that these efforts could be integrated into any existing climate change preparation. While there is not a one hundred percent chance large scale hydrate dissociation will occur, if this contingency does transpire, societies around the world must be prepared.

In assessing that societies must be prepared for the environmental effects of large scale hydrate dissociation, it is critical to determine what these effects will be. Such global impacts can be extrapolated from hydrate dissociation at the Paleocene Eocene Thermal Maximum. If a large scale methane release from hydrate destabilization were to occur in the present day, accelerated greenhouse warming would begin immediately, with the full effects transpiring after roughly two to three decades (Whiteman et al., 2013). As was the case with the PETM, a triggering of the Clathrate Gun in the present day would result in warming of 5 to 8 degrees Celsius (Mcnerney et al., 2011). This would melt a significant fraction of the world's ice caps, resulting in sea level rises of between 100 and 250 feet. Such a sea level rise would displace up to 40% of the world's population (Nicholls and Cazenave, 2010). A 5 to 8 degree temperature increase would also result in unpredictable precipitation, leading to crop failures. Increased moisture in the atmosphere would also lead to much more powerful hurricanes (IPCC, 2014). The cost of these environmental impacts to society would be significant. A recent study published in the journal nature declared that even a 50 gigaton release of methane would cost the world 60 trillion dollars over the next half century (Whiteman et al., 2013). This does not account for additional releases of methane caused by the dissociation of all hydrates susceptible to climate warming. As 60 trillion dollars represents the annual economic productivity of the entire planet, it is likely that in many cases societies will be unable to adequately cope with the effects of large scale hydrate dissociation. This suggests that a considerably more feasible course of action than addressing the consequences of hydrate dissociation after they have occurred is to prevent these environmental impacts from transpiring in the first place.

At present, not only are societies around the world not working to prevent a substantial release of methane from dissociating hydrates, they are actively accelerating the process of anthropogenic climate change. There are currently 404 parts per million of Carbon Dioxide in the atmosphere (Moss et al., 2010). A NASA study concluded that atmospheric levels of CO2 in excess of 350 parts per million is fundamentally incompatible with existing societal structures over the next century (Hansen et al., 2008). This does not account for an acceleration of climate change due to a methane release from dissociating hydrates. NASA researchers have concluded that in order to preserve societal structures as they exist today, atmospheric levels of CO2 must be reduced to 350 ppm as soon as possible (Hansen et al., 2008). However, instead of reducing the concentrations of carbon dioxide in the atmosphere, societies around the world are increasing atmospheric CO2 levels by 2 ppm per year (Moss et al., 2010). The amount of annual increase is itself increasing, as economies in the developing world are growing their use of electricity and transportation. This trend, combined with the first world's failure to demonstrate serious and meaningful implementation of alternative energies, suggests that it is probable CO2 emissions will continue to accelerate in the near future.

Since the industrial revolution, human carbon emissions have raised global temperatures by 1 degree Celsius. Projections regarding realistic points at which the temperature increase can stabilize vary widely. The Intergovernmental Panel on Climate Change predicts that global temperatures will rise between 2.5 and 10 degrees Celsius by the end of the century (IPCC, 2014). It is significant that temperatures rise disproportionately to the global average in shallow polar waters due to ice albedo feedbacks. As such, even a small temperature rise beyond existing levels could result in dramatically accelerated hydrate dissociation. It is not presently known how high global average temperatures can rise before the Clathrate Gun is triggered and climate change begins to accelerate out of human control.

It is possible that larger awareness of the potential firing of the Clathrate Gun could help guide policy decisions regarding significant implementation of alternative energies. In societies worldwide, leaders and policymakers are presently largely unaware of the existence, degree, or implications of hydrate dissociation risk. Such ignorance is partially due to lack of communication from the scientific community. As a result of the debate between researchers as to the severity of the threat of hydrate dissociation, policymakers are able to dismiss the phenomenon as controvertible and make no additional effort to reduce carbon emissions. Despite the existence of a debate within the scientific community, enough evidence is presently available to warrant immediate and meaningful climate mitigation measures from policymakers. The lack of urgency regarding this and climate change as a whole is epitomized by the anticipated US withdrawal from the Paris Climate Accords reached in 2015.

In perhaps the most critical period to mitigate climate change and prevent large scale hydrate dissociation, it appears that leaders in both the United States and around the world will implement policies compatible with increasing carbon emissions. This is transpiring in light of the fact that the firing of the Clathrate Gun due to destabilizing hydrates is not the only tipping point present that could lead to accelerated climate change. Other tipping points include methane emissions from organic matter in thawing permafrost, the changing albedo of the Arctic sea ice and the Greenland ice sheet, and the destabilization of the West Antarctic Ice Sheet (Lenton, 2011). All of these tipping points represent scenarios in which climate change is dramatically accelerated. Moreover, these scenarios are not accounted for in Intergovernmental Panel on Climate Change projections (IPCC, 2014).

While a debate exists in the scientific community as to the risk posed by dissociating hydrates, human discussion does not affect the objective likelihood large scale hydrate dissociation will occur. We will know in the next one to two decades whether the Clathrate Gun is firing. At present we have a possible but small window to respond. To prevent a large scale release of methane from dissociating hydrates that could meaningfully impact climate change, substantially accelerated conversion to alternative energies and geoengineering solutions should be considered.

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