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Key Points:

- Hydroacoustically derived methane flow rates from three areas offshore Svalbard range from 725 to 1,125 t CH₄/year
- Seasonal migration of the landward limit of the methane hydrate stability zone influences locations of bubble seepage
- Alternating CH₄-bubble seepage between two areas suggests geological interconnectivity

Supporting Information:

- Supporting Information S1
- Data Set S1

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Variability of Acoustically Evidenced Methane Bubble Emissions Offshore Western Svalbard

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Abstract Large reservoirs of methane present in Arctic marine sediments are susceptible to rapid warming, promoting increasing methane emissions. Gas bubbles in the water column can be detected, and flow rates can be quantified using hydroacoustic survey methods, making it possible to monitor spatiotemporal variability. We present methane (CH₄) bubble flow rates derived from hydroacoustic data sets acquired during 11 research expeditions to the western Svalbard continental margin (2008–2014). Three seepage areas emit in total 725–1,125 t CH₄/year, and bubble fluxes are up to 2 kg·m⁻²·year⁻¹. Bubble fluxes vary between different surveys, but no clear trend can be identified. Flux variability analyses suggest that two areas are geologically interconnected, displaying alternating flow changes. Spatial migration of bubble seepage was observed to follow seasonal changes in the theoretical landward limit of the hydrate stability zone, suggesting that formation/dissociation of shallow hydrates, modulated by bottom water temperatures, influences seafloor bubble release.

Plain Language Summary It has been speculated that the release of methane (a potent greenhouse gas) from the seafloor in some Arctic Ocean regions is triggered by warming seawater. Emissions of gas bubbles from the seafloor can be detected by ship-mounted sonars. In 2008, a methane seepage area west of Svalbard was hydroacoustically detected for the first time. This seepage was hypothesized to be caused by dissociation of hydrates (ice-like crystals consisting of methane and water) due to ocean warming. We present an analysis of sonar data from 11 surveys conducted between 2008 and 2014. This study is the first comparison of methane seepage-related hydroacoustic data over such a long period. The hydroacoustic mapping and quantification method allowed us to assess the locations and intensity of gas bubble release, and how these parameters change over time, providing necessary data for numerical flux and climate models. No trend of increasing gas flow was identified. However, we observed seasonal variations potentially controlled by seasonal formation and dissociation of shallow hydrates. The hydrate formation/dissociation process is likely controlled by changes of bottom water temperatures. Alternating gas emissions between two neighboring areas indicate the existence of fluid pathway networks within the sediments.

1. Introduction

Underwater methane bubble emissions are often thought to contribute significantly to global climate change (Hornafius et al., 1999; Kvenvolden, 1993; Shakhova et al., 2010, 2014), but recent evidence has challenged this suggestion. Numerical bubble modeling has shown that, except in water depths shallower than ~100 m below sea level (bsl), CH₄ in bubbles mostly dissolves (McGinnis et al., 2006; Vielstädte et al., 2015) and oxidizes before it reaches the atmosphere/ocean interface (Steinle et al., 2015). Additionally, CH₄ seepage may contribute to ocean acidification (Biaostoch et al., 2011; Pohlman et al., 2011) and deoxygenation (Boetius & Wenzhöfer, 2013; Yamamoto et al., 2014). Arctic marine sediments sequester large quantities of CH₄ in natural gas deposits, submarine permafrost, and gas hydrates (O'Connor et al., 2010;

Shakhova et al., 2014). Mechanisms for CH₄ release from these reservoirs are poorly constrained but likely comprise hydrate dissociation (Westbrook et al., 2009) triggered by ocean warming and pressure decrease from deglaciation and sea level change (Andreassen et al., 2017), or submarine permafrost thawing with increased anaerobic organic matter degradation due to ongoing bottom water warming (James et al., 2016).

Sediments on the western Svalbard continental margin are influenced by the northward inflow of rapidly warming Atlantic water (AW). Therefore, gas hydrates, if present therein, are more susceptible to dissociation than elsewhere. West of Prins Karls Forland (PKF), numerous methane seeps were identified in 2008, and this area received additional attention because the seepage was attributed to ocean-warming-induced hydrate destabilization (Westbrook et al., 2009). Other authors have proposed that pressure changes due to isostatic rebound since 8 ka caused hydrate destabilization (Wallmann et al., 2018). The area has been investigated to reveal the gas origin (e.g., Gentz et al., 2014; Sahling et al., 2014), to describe subseabed migration mechanisms (e.g., Mau et al., 2017; Rajan et al., 2012; Sarkar et al., 2012), to determine the fate of gas released into the water column (e.g., Graves et al., 2015; Steinle et al., 2015), to determine the role of anaerobic oxidation in regulating methane flux at the sediment-seawater interface (Graves et al., 2017), to evaluate the warming potential due to CH₄ transfer to the atmosphere (e.g., Fisher et al., 2011; Pisso et al., 2016; Pohlman et al., 2017), and to elucidate a possible relationship between bubble release and ocean warming (e.g., Berndt et al., 2014; Mau et al., 2017).

Acoustic flares, the hydroacoustic expression of underwater bubble release, were first detected in the area in 2008 (Westbrook et al., 2009), and hydroacoustic evidence of bubble seepage has been reported repeatedly since (e.g., Berndt et al., 2014; Lund Myhre et al., 2016; Sarkar et al., 2012; Veloso et al., 2015). Our study comprises single-beam echosounder (SBES) data collected during 11 surveys, carried out between 2008 and 2014, by RV *Helmer Hanssen* and RRS *James Clark Ross*. The data allow the first spatiotemporal variability analysis of submarine bubble seepage offshore PKF and first quantitative comparison over several years using hydroacoustic information.

The study area is located west of Svalbard at the shelf offshore PKF (Figure 1), where flares are distributed in three active subareas (Figure 1) which we name Slope-Area (upper slope, 300–400 m bsl), SBreak-Area (shelf break, ~200 m bsl), and Shelf-Area (shelf, ~90 m bsl). Isotope analysis of CH₄ collected at the seabed in SBreak-Area and Slope-Area ($\delta^{13}\text{C}_{\text{CH}_4} = -55.7\text{‰}$; Mau et al., 2017; Sahling et al., 2014) and in sea surface waters in Shelf-Area ($\delta^{13}\text{C}_{\text{CH}_4} = -54.6\text{‰}$; Pohlman et al., 2017) suggest a microbial methane origin.

High-resolution seismic data acquired from the SBreak-Area and the Slope-Area suggest that fluids flow upslope along nearly seafloor-parallel permeable layers (Rajan et al., 2012; Sarkar et al., 2012). The main seepage locations may be determined by sediment permeability at the Slope-Area (Sarkar et al., 2012) and by the intersection with the seabed of the latest prograding glacial sequence at the SBreak-Area (Rajan et al., 2012). The sediments at the Slope-Area consist of diamictos, coarse ice-rafted debris, and hemipelagic material (Bohrmann et al., 2017; Riedel et al., 2018), plausibly causing heterogeneous sediment permeability. Similarly, glacial sediments with low permeability were found at a 340-m bsl drilling site, 50 m above the gas hydrate stability zone (GHSZ), which may inhibit vertical gas migration.

Seepage at the Slope-Area may be a consequence of hydrate dissociation triggered by bottom water warming since flares are aligned with the landward limit of the gas hydrate stability zone (LGHZ; Westbrook et al., 2009). Shallow hydrate has been recovered further downslope at 890 m bsl (Fisher et al., 2011), but recent drilling did not recover hydrate near the LGHZ (Riedel et al., 2018). Negative-polarity seismic bright spots that have been found at the base of the GHSZ at the Slope-Area may be caused by gas pockets (Sarkar et al., 2012) and/or iceberg scouring (Riedel et al., 2018). Anomalies in seismic velocity (Chabert et al., 2011) and electrical resistivity (Goswami et al., 2016) support the presence of shallow hydrate.

Seepage at the Shelf-Area has been attributed to hydrate dissociation triggered by ice sheet unloading after the last deglaciation, with the present-day seepage locations marking previous GHSZ pinch-out locations (Portnov et al., 2016). This hypothesis is supported by similar evidence from the formerly glaciated continental margin of the Barents Sea (Andreassen et al., 2017). Earthquakes related to extension of the nearby spreading ridge system (Figure 1) may influence bubble seepage indirectly (Plaza-Faverola et al., 2015). Pressure changes due to sea surface height fluctuations could modulate fluxes, as seen elsewhere (Römer et al., 2016).

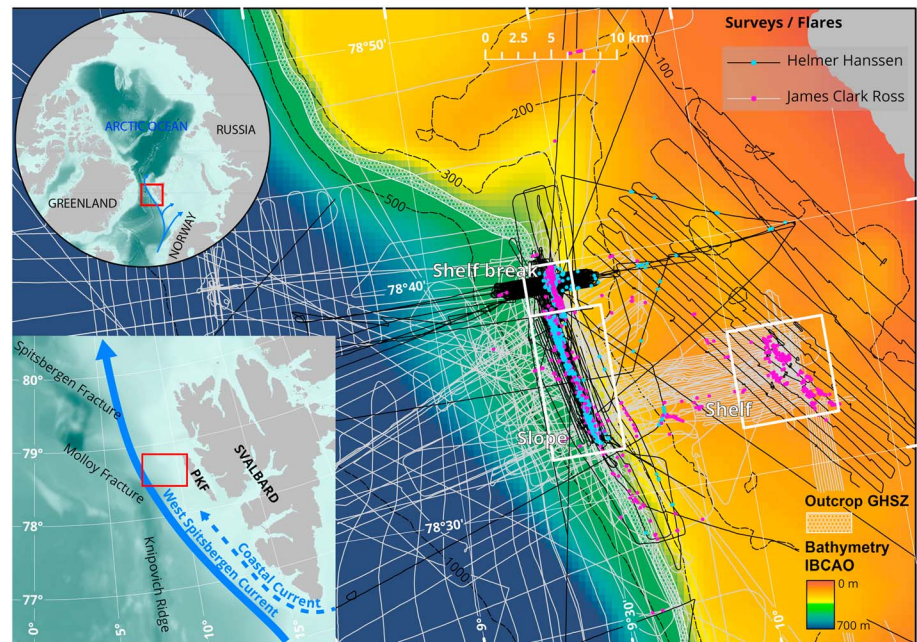


Figure 1. Bathymetric map of the study area. Black tracks with blue flare locations mark RV *Helmer Hanssen* surveys, and gray tracks with pink flare locations mark RRS *James Clark Ross* surveys. White hex pattern marks migration of the landward limit of the gas hydrate stability zone (360- to 410-m isobaths; Westbrook et al., 2009). PKF = Prins Karls Forland. Rectangles indicate the different survey areas. GHSZ = gas hydrate stability zone; IBCAO = International Bathymetric Chart of the Arctic Ocean.

Two ocean currents control the water properties in the area. The West Spitsbergen Current introduces warm and saline AW from the south, and the Coastal Current contributes fresher and colder transformed AW to the northward flow (Graves et al., 2015; Nilsen et al., 2016). Bottom water temperature (BWT) changes on seasonal to decadal time scales have been proposed to cause shallow hydrate formation and dissociation in the Slope-Area, yielding a positive correlation between ocean temperature and bubble release (Berndt et al., 2014; Westbrook et al., 2009). However, the hydrate occurrence zone is expected to be thinner than the GHSZ because hydrate formation is limited by the supply of water and CH_4 in excess of its solubility and by the thickness of the sulfate reduction zone in which methane concentrations are too low to allow hydrate formation (Mestdagh et al., 2017; Ruppel & Kessler, 2017). Shallow hydrate formation may occur within gas conduits, where focused gas advection overcomes downward sulfate diffusion (Riedel et al., 2018).

2. Materials and Methods

2.1. Hydroacoustic Detection of Gas Venting

We analyzed hydroacoustic water column data from 11 surveys conducted during 2008–2014: S1 (08/2008); S2 (07/2009); S3 (10/2010); S4 (07/2011); S5 (08/2011); S6 (07/2012); S7 (07/2012); S8 (07/2013); S9 (10/2013); S10 (06/2014); S11 (10/2014); see supporting information (SI); Table SI 1. Data were acquired with an EK60 SBES (Kongsberg), which are calibrated routinely, using moving spheres (Foote, 1987), allowing for unbiased comparison of absolute target-strength values (TS; logarithm of ratio between scattered and incident acoustic intensities; dB re 1 m^2). We used the 38-kHz frequency for this study because it is common between the two vessels and provided the best backscattering response of bubbles, with the highest signal-to-noise ratio at depths relevant to the study area (Figure SI 1). We identified 3,145 acoustic flares (Figure SI 2) and selected flares that could be traced clearly from the seabed and were well above (10 dB TS) the background noise of ~ -70 dB-TS. For each selected flare, we extracted a representative TS value from a layer 5–10 m above seafloor, using the FlareHunter graphical user interface (FH-GUI; <http://www.geomar.de/en/research/fb2/fb2-mg/deepsea-monitoring/software/flarehunter-and-fluxmodule/>). Georeferenced footprint areas of the flares and their corresponding centers were obtained from the motion-compensated beam coverage,

projected at the layer average depth (SI 1). Subsequently, CH₄ flow rates (volume per time unit) for individual flares were calculated, using the inverse hydroacoustic method embedded in the FH-GUI (Velooso et al., 2015, 2019). A bubble size distribution was derived from video observations made in cruises S2 and S3, as seen in SI 2 and Figure SI 4 (McGovern, 2012; Velooso et al., 2015). Various bubble rising speed models (BRSMs) for “clean” and “dirty” bubbles (Leifer et al., 2000; Leifer & Patro, 2002; Mendelson, 1967; Woolf, 1993; Woolf & Thorpe, 1993), which are all included in the FH-GUI, were used (SI 3 and Figure SI 5). Ambient water properties and gas and environmental constants used for CH₄ flow rate quantification are specified in Table SI 2.

2.2. Areal Flow Rates

Areal flow rates were calculated for the three areas by integrating over all surveys. Flares were clustered if their footprints overlapped, to avoid overestimating flow rates if vent clusters were insonified repeatedly. Equivalent cluster fluxes were calculated by averaging the individual fluxes (flare flow rates normalized by their respective virtual footprint area) of flares within a cluster. Cluster flow rates were derived by multiplying the cluster fluxes by the cluster areas (Velooso et al., 2015; SI 4). Finally, areal flow rates were derived by summation of cluster flow rates and isolated flare flow rates (no overlap with other flares) for the three subareas individually (Table 1).

2.3. Temporal Flux Variation

Each acoustic data set results in a unique insonified area. Even if the tracks of multiple surveys are identical, the insonified areas at the seafloor will very likely not be identical, due to vessel motion. Therefore, flow rates derived from different surveys cannot be directly compared. Such a temporal analysis would inevitably suffer from spatial biases. However, bubble fluxes can be used for variability analysis. We developed a common area flux (CAF) method (SI 5) based on the comparison of fluxes from bubbling areas that were repeatedly insonified (including clustered and isolated flares and their respective flux values). The method follows the technique described in section 2.2, but only flares from the same survey are clustered. The georeferenced flare and cluster areas were gridded on a regular survey matrix with flux values for each cell. A common bubbling area was extracted from the survey matrices (Figure SI 9), and a representative flux (Q_{RF}) was calculated, using the arithmetic mean of fluxes in the common area (Figure 2a).

No flare-related grid cell was covered by all 11 surveys, but small areas were covered by up to eight surveys. Our analysis includes multiple combinations of survey matrices with a minimum of two overlapping surveys for the SBreak and Slope-Area (Figure 1). Several Q_{RF} s were obtained for each survey from different combinations of surveys (Tables SI 3 and SI 4), and the average Q_{RF} of each survey (\bar{Q}_{RF}), is shown in Figure 2a. The Shelf-Area was not included in this analysis since it was only surveyed once. Since flux magnitudes and their changes are similar when using different clean and dirty BRSMs, we only show the results for clean bubbles using the “Leifer” rising speed model (Leifer et al., 2015).

2.4. BWT and Evolution of LGHZ

Mean BWTs from the SBreak-Area and Slope-Area were extracted from conductivity-temperature-depth data collected during the surveys and from the World Ocean Database (SI, Excel file). Additionally, we created a synthetic BWT function (Text SI 8) based on MASOX observatory data (Berndt et al., 2014) and a 0.05 °C yearly BWT increase observed by Ferré et al. (2012). Mean BWTs from conductivity-temperature-depth casts and values from the synthetic BWT function showed good correlation ($\rho = 0.84$; Figure 2b). From the synthetic BWT series, we calculated the expected depth of the LGHZ using the formulae suggested by Tishchenko et al. (2005). This depth is presented together with observed flare depths (FDs) and mean flare depths (MFDs) for each survey (Figure 2c). Flares located within the Slope-Area and at 350–400 m bsl were included in this comparison.

2.5. Hydroacoustic Data Confidence Related to Spatial Analysis of Flares

We defined two parameters to assess the confidence of the SBES data, relating to spatial seepage migration: (a) the relative areal coverage of the SBES footprint (R_{AC}), representing the area covered by the SBES footprint relative to the total analyzed area, and (b) the Complement of the relative quadratic deviation of the SBES depth distribution (C_{RCD}), representing the similarity between the SBES-mapped depth distribution and the depth distribution (bathymetry histogram) of the region. Both values were

Table 1
Volumetric and Mass Flow Rates of CH₄ Calculated Using Merged Hydroacoustic Information of SBreak-Area, Slope-Area, and Shelf-Area Using Different BRSMs

	Clean bubble models			Dirty bubble models			
	M1C	M2C	M3C	M1D	M2D	M3D	M4D
SBreak-Area							
Flow rate, volumetric (L/min)	30.74	39.57	30.74	25.33	31.73	39.60	34.08
Flow rate mass (t/year)	258.01	332.14	258.01	212.60	266.30	332.38	286.08
Area with acoustic data (m ²)				646,234			
Mean annual flow rate (t/year)	306.13			274.34			
Standard deviation flow rate BRSM (t/year)	41.72			49.61			
Relative standard deviation flow rate BRSM ^a (%)	±13.63			±18.08			
Slope-Area							
Flow rate, volumetric (L/min)	37.62	48.79	48.23	31.00	39.12	48.82	42.02
Flow rate mass (t/year)	487.31	632.07	624.76	401.56	506.69	632.42	544.33
Area with acoustic data (m ²)				1,466,867			
Mean annual flow rate (t/year)	581.38			521.25			
Standard deviation flow rate BRSM (t/year)	81.55			95.62			
Relative standard deviation flow rate BRSM ^a (%)	±14.03			±18.34			
Shelf-Area							
Flow rate, volumetric (L/min)	15.20	19.63	19.40	12.53	15.74	19.65	16.91
Flow rate mass (t/year)	138.99	179.62	177.53	114.53	144.00	179.74	154.71
Area with acoustic data (m ²)				507,447			
Mean annual flow rate (t/year)	165.38			148.24			
Standard deviation flow rate BRSM (t/year)	22.88			27.01			
Relative standard deviation flow rate BRSM ^a (%)	±13.84			±18.22			

Note. Supporting information, Figure SI 5; M1C: “Leifer” clean; M2C: “Mendelson” clean; M3C: “Leifer and Patro” clean; M1D: “Leifer” clean; M2D: “Leifer and Patro” dirty; M3D: “Woolf93”; M4D: “Thorpe 91” dirty. BRSM = bubble rising speed models.

^aRelative standard deviation = $\frac{\sigma}{\bar{x}} \times 100$; σ = standard deviation; \bar{x} = mean.

calculated for each survey within a band delimited by the 350-and 400-m isobaths at the Slope-Area (Figure 2c) as presented in SI 9.

3. Discussion

3.1. Quantifying Bubble Emissions

Assuming continuous release of pure CH₄ bubbles, we estimate yearly emissions of 210–330, 400–630, and 115–180 t for the SBreak, Slope, and Shelf Area, respectively. These results are similar to CH₄ seepage areas elsewhere (Römer, Sahling, Pape, Bahr, et al., 2012; Römer et al., 2014; Römer, Sahling, Pape, Römer, Sahling, Pape, Bohrmann, et al., 2012; Sauter et al., 2006; Schneider von Deimling et al., 2011; Torres et al., 2002) as seen in Table SI 5. Previously obtained flow rates from a subsection of the SBreak-Area using the same hydroacoustic method (Veloso et al., 2015, 2019) are half of the values presented here. This difference can be attributed to the difference in SBES areal coverage. The risk of missing bubbling areas is reduced by increasing the SBES coverage. Therefore, flow rates derived from our larger data set (merging of nine surveys) is likely a better estimate for the SBreak-Area (~210–330 t CH₄/year from ~13.4 km²) than those determined by Veloso et al. (2015), who used only two surveys. Variations can also be introduced by inaccurate flare locations, resulting in flow rate overestimation if the same flare is considered multiple times. The transient nature of bubble release generates another uncertainty since short-term variability is neglected when data from different surveys are combined.

A survey offshore PKF combining multibeam echosounder (MBES) and a ROV-based visual inspection (Sahling et al., 2014) suggested that 433 and 417 t CH₄/year are emitted from areas comparable to SBreak-Area and Slope-Area, respectively. This is 0.7–1.3 times our estimates (~290 and ~550 t CH₄/year), which indicates remarkably good agreement from different methods by different research teams in the same

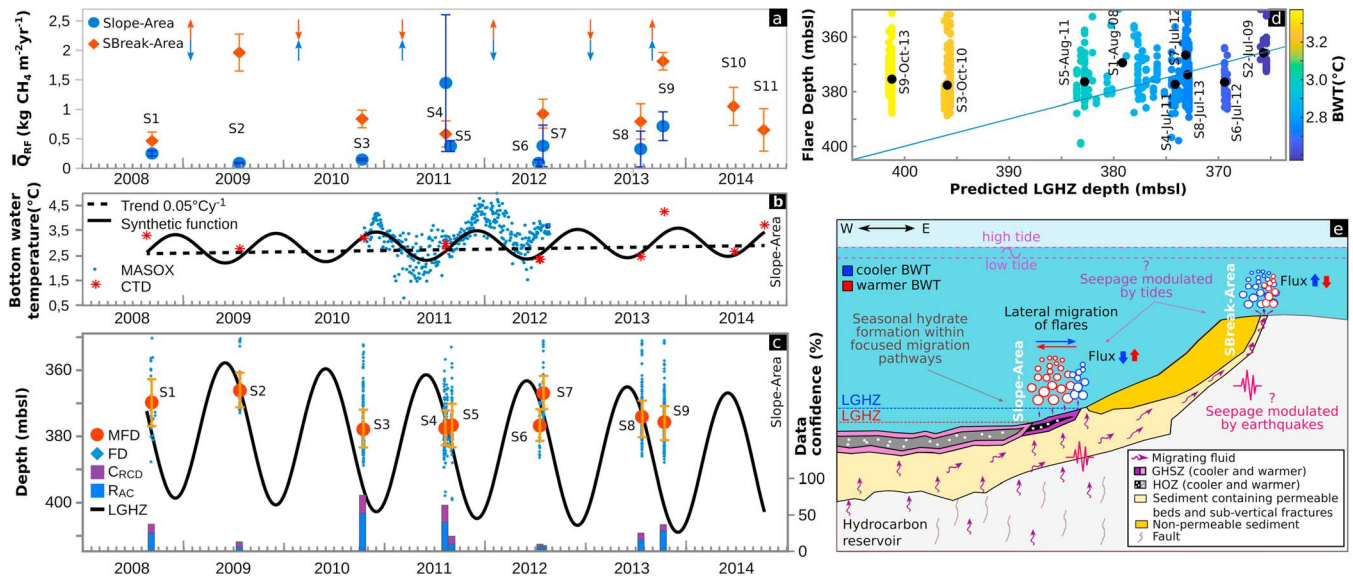


Figure 2. (a) Temporal variability of CH₄ fluxes in SBreak-Area and Slope-Area derived with the common area flux method using bubble rising speed model M1C. Blue dots and orange diamonds represent mean \bar{Q}_{RF} s for the Slope-Area and SBreak-Area, respectively; error bars show the standard deviation of fluxes from common areas used to calculate the mean \bar{Q}_{RF} . Blue and orange arrows indicate changes in fluxes between surveys for the Slope-Area and SBreak-Area, respectively. (b) Time series of BWTs. The red stars indicate BWTs from conductivity-temperature-depth information and from the World Ocean Database, and the blue dots show digitized values of mean BWTs per day, extracted from Berndt et al. (2014). The black dashed line depicts the 0.05 °C yearly increase in BWT observed by Ferré et al. (2012), while the black continuous line represents the synthetic BWTs described in the text. (c) Time series of FDs and MFDs, for flares located between 350 and 400 m below sea level at the Slope-Area. Blue dots indicate individual flares, while the red dots with error bars indicate the mean depth and the corresponding standard deviation for each survey. Black line indicates the expected depth of the LGHZ, derived from the synthetic BWT function. Blue and violet bars indicate the confidence parameters R_{AC} and C_{RCD} , described in section 2.5. (d) Observed FDs versus predicted depth of the LGHZ. Small dots indicate individual flares (in total 1,016 flares), colored by the synthetic BWT. Black dots indicate the MFDs for each of the surveys. Blue line depicts a perfect 1:1 relation between FD/MFD and the predicted LGHZ depth. (e) Conceptual model of bubble seepage offshore Prins Karls Forland, illustrating the suggested flux changes in the Slope-Area and SBreak-Area, the spatial shift of bubble seepage, and the lateral migration of the LGHZ and the HOZ during cooler and warmer BWTs. The image also indicates the suggested interconnectivity between Slope-Area and SBreak-Area (light yellow patch and curved arrows). Earthquakes and tides are proposed as plausible control mechanisms of bubble seepage. BWT = bottom water temperature; FD = flare depth; MFD = mean flare depth; LGHZ = landward limit of the gas hydrate stability zone; GHSZ = gas hydrate stability zone; HOZ = hydrate occurrence zone.

area, given the uncertainties in both methods. While flow rates calculated from optical methods are more precise than those derived from SBES data inversion, uncertainties arise when extrapolating flow rates from a few visual observations to a larger number of MBES-detected flares. SBES-data inversion may decrease these uncertainties by using the backscatter heterogeneity of all detected flares to derive flow rates, but it incorporates other uncertainties inherent in the backscattering model, the BRSMs, the bubble size distributions, and limited SBES footprint coverage compared to MBES (Veloso et al., 2015). Future surveys should consider using a combination of both methods to improve flow rate assessment for large seepage areas.

3.2. Seepage Variability

Our results show that CAF values in SBreak-Area vary between 0.5 and 2 kg CH₄·m⁻²·year⁻¹ with a standard deviation of 0.15–0.35 kg CH₄·m⁻²·year⁻¹ (Figure 2a), indicating that common areas have similar gas emissions over several surveys. Fluxes fluctuate around a mean of 0.75 kg CH₄·m⁻²·year⁻¹, except during S2 and S9, when higher fluxes (~1.9 and ~1.8 kg CH₄·m⁻²·year⁻¹, respectively) were observed. In the Slope-Area, fluxes ranged from 0.09 to 1.4 kg CH₄·m⁻²·year⁻¹ with a mean of ~0.4 kg CH₄·m⁻²·year⁻¹. A peak flux was observed for survey S4, with a standard deviation of ~1.16 kg CH₄·m⁻²·year⁻¹, which is perhaps high due to spatial separation of the common areas involved in the mean \bar{Q}_{RF} calculation. All other mean \bar{Q}_{RF} values exhibit lower standard deviations (<0.35 kg CH₄·m⁻²·year⁻¹).

No clear increase in both bubble seepage and BWT over the investigation time is evident (Figures 2a and 2b). However, the empirical BWTs are well correlated with values from the predictive BWT function, which includes a yearly rising trend. Long-term BWT monitoring with better temporal resolution would be

required to rigorously assess bottom water warming. Increasing BWTs coincide with increased fluxes at the Slope-Area, except for the period between surveys S3 and S4. We tentatively attribute this observation to shallow hydrate formation/dissociation due to BWT fluctuations, although available data limit documentation of this mechanism. Gas seepage may be controlled also by hydrostatic pressure changes (e.g., Schneider von Deimling et al., 2011) and tectonic activity since the area is close (~40–50 km) to the tectonically active Molloy-Knipovich ridge system and the Hornsund Fault zone (Mau et al., 2017; Plaza-Faverola et al., 2015). We analyzed the relationship between seepage activity, tidally induced pressure changes (SI 6) and earthquake activity in the region (SI 7). Because we lack continuous hydroacoustic records, we were unable to tie seepage variability to these two trigger mechanisms.

3.3. Seepage Migration at the LGHZ

A seasonal BWT-driven lateral LGHZ shift of approximately 2 km at the Slope-Area was predicted between summer 2011 and winter 2012 (Berndt et al., 2014) and geothermal modeling of the GHSZ suggests that only the upper 6 m of sediments is affected significantly by seasonal fluctuations at the Slope-Area within the time frame of this study (Riedel et al., 2018). In order to verify whether a seasonal shift of the LGHZ drives migration of bubble seepage, MFDs were compared to the predicted LGHZ depth (Figure 2c). The comparison revealed a correlation coefficient of 0.48. MFDs from four surveys (S2, S4, S7, and S8) out of nine show excellent agreement with the predicted depths of the LGHZ (Figure 2c), which supports the hypothesis of spatial seepage migration driven by BWT modulation. Nevertheless, we recognize that our data have insufficient temporal resolution of BWT and SBES data, and SBES coverage, as seen in the data confidence (Figure 2d). Hence, the observed relationship between bubble stream locations and the predicted LGHZ awaits confirmation in future studies. From the observed flares, ~70% occur at depths shallower than the predicted LGHZ (Figure 2d), consistent with blockage of vertical gas migration pathways in the area by shallow hydrates.

3.4. Subseafloor Fluid Network

Fluxes at the SBreak-Area are weakly anti-correlated with fluxes in the Slope-Area, except for surveys S8 and S9 as seen in Figure 2a. Although the correlation is low ($r = -0.22$), the alternating CH₄ bubble seepage suggests connectivity between the two areas through a common subseafloor fluid migration system. Flux alternation between the two areas may be caused by transient hydrate formation and dissociation that blocks and opens gas conduits feeding the upslope seepage areas. When vertical pathways are open in the Slope-area, less gas will be supplied to the SBreak-Area. Alternatively, the observed alternating flux could be a result of changing resistance/capacitance of fluid migration pathways due to tectonic activity.

3.5. Conceptual Model

We propose that temporal, spatial, and quantitative variations of bubble seepage are controlled by a combination of factors: shallow hydrate formation and dissociation due to seasonality, heterogeneity of sediment permeability, hydrostatic pressure changes, and earthquakes. Available observations suggest that seepage in the Slope-Area is influenced by rapid formation and dissociation of hydrates in shallow sediments containing permeable beds and subvertical fractures, but other factors also may be involved. The temperature control mechanism can be described as follows (Figure 2d). If focused gas advection overcomes downward sulfate diffusion, shallow hydrate formation could be possible. Seasonal BWT variations of ~1.5 °C may affect stability of this shallow hydrate. Gas conduits within the affected zone could partially or completely open due to hydrate dissociation in warm conditions and seal again by hydrate formation during cold conditions. Open conduits may allow vertical migration of CH₄ from deeper hydrocarbon reservoirs toward the seafloor, while blocked conduits could force lateral migration. Spatial migration of CH₄ seepage therefore takes place due to permeability changes (partial or complete blocking) of the fluid conduit system. Under the assumption of interconnectivity between areas, seasonal hydrates at the Slope-Area may force CH₄ to migrate upslope, which increases gas emission in the SBreak-Area. Conversely, seasonal dissociation could release gas earlier along the lateral migration pathways, closer to the Slope-Area, and consequently decrease fluxes at the SBreak-Area.

4. Conclusions

Analyses of hydroacoustic data from 11 surveys offshore PKF during 2008–2014 showed no significant trend toward increased seepage. Assuming steady gas flow, the total average CH_4 free gas fluxes were $0.75 \text{ kg CH}_4 \cdot \text{m}^{-2} \cdot \text{year}^{-1}$ at the Shelf break and $0.38 \text{ kg CH}_4 \cdot \text{m}^{-2} \cdot \text{year}^{-1}$ close to the LGHZ. These fluxes average over short natural fluctuations (days to weeks), and may contribute to future modeling of CH_4 budgets in the Arctic Ocean. However, care must be taken when extrapolating over longer periods because we lack data between November and May. Variations in gas fluxes can be linked to warming and cooling of BWT at the Slope-Area. In our study, the majority (70%) of the observed flares occur at depths shallower than the BWT-controlled LGHZ. Additionally, a correlation was observed between observed MFDs and the predicted depth of the LGHZ. These observations support the hypothesis of temperature-controlled hydrate buildup within the shallow sediments, which modulates both the amount and distribution of gas seepage. The inferred interconnectivity between seepage areas supports the interpretation that seepage is controlled by flow-focusing migration pathways (Rajan et al., 2012; Sarkar et al., 2012), consistent with the proposed seasonal formation and dissociation of shallow hydrates. Our model may be further validated using data of higher spatial and temporal resolution. Since our data were acquired from moving vessels, the echosounder beam only intermittently covered the same seepages. Therefore, we cannot assess the impact on gas seepage intensity of changing seafloor pressure or earthquake activity.

Our data analysis shows that ship-based hydroacoustic methods are an efficient tool for repeated monitoring of bubble release. Applied in a standardized way they will help to establish the response of gas-rich sediments to internal and external forcing mechanisms in the Arctic and elsewhere. Increasing water temperatures are likely to have a long-term impact on gas release and seep distribution offshore PKF. For a more conclusive study, long-duration observations are required.

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