Continental Shelf Research 31 (2011) 867–878

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Research papers

Quantification of seep-related methane gas emissions at Tommeliten, North Sea

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ARTICLE INFO

Article history:
Received 14 December 2010
Received in revised form
12 February 2011
Accepted 16 February 2011
Available online 23 February 2011

Keywords:
North Sea Tommeliten
Gas seepage
Methane
Gas bubbles

ABSTRACT

Tommeliten is a prominent methane seep area in the Central North Sea. Previous surveys revealed shallow gas-bearing sediments and methane gas ebullition into the water column. In this study, the in situ methane flux at Tommeliten is re-assessed and the potential methane transport to the atmosphere is discussed, with regards to the hydrographic setting and gas bubble modeling. We have compiled previous data, acquired new video and acoustic evidence of gas bubble release, and have measured the methane concentration, and its C-isotopic composition in the water column. Parametric subbottom sonar data reveal the three-dimensional extent of shallow gas and morphologic features relevant for gas migration. Five methane ebullition areas are identified and the main seepage area appears to be 21 times larger than previously estimated. Our video, hydroacoustic, subbottom, and chemical data suggest that ~1.5 × 10^6 mol CH_4/yr (~26 tons CH_4/yr) of methane gas is being released from the seepage area of Tommeliten. Methane concentration profiles in the vicinity of the gas seeps show values of up to 268 nM (~100 times background) close to the seafloor. A decrease in $\delta^{13}C$-CH_4 values at 40 m water depth indicates an unknown additional biogenic methane source within the well oxygenated thermocline between 30 and 40 m water depth. Numerical modeling of the methane bubbles due to their migration and dissolution was performed to estimate the bubble-derived vertical methane transport, the fate of this methane in the water column, and finally the flux to the atmosphere. Modeling indicates that less than ~4% of the gas initially released at the seafloor is transported via bubbles into the mixed layer and, ultimately, to the atmosphere. However, because of the strong seasonality of mixing in the North Sea, this flux is expected to increase as mixing increases, and almost all of the methane released at the seafloor could be transferred into the atmosphere in the stormy fall and winter time.

1. Introduction

1.1. CH_4 in the atmosphere

Methane is the most abundant hydrocarbon in the atmosphere and is influencing the global climate. Compared to carbon dioxide, the global warming potential (GWP) of methane is about 25–40 times higher on a 100 yr timescale (Shindell et al., 2009). The atmospheric methane concentration growth rate per year has decreased from 1% in the early 1980s (Blake and Rowland, 1988) to close to zero at the turn of the millennium. Following this period of little change, Rigby et al. (2008) present measurements showing renewed growth in early 2007. The reasons for this observation are still under debate, but Arctic wetlands, thawing permafrost, and fires in the high latitudes are among the most favored explanations.

1.2. Marine methane seepage

The net atmospheric methane emission is currently estimated to be 592 Tg CH_4/yr and predominantly consists of anthropogenic contributions (>60%, e.g. agriculture, gas flaring; Reeburgh, 2007). Emissions of submarine methane from mud volcanoes, faults and seepage have been neglected in previous IPCC reports, but were suggested as a potentially important source ranging between 15 and 60 Tg CH_4/yr (Etiope, 2004; Kvenvolden and Rogers, 2005). However, the atmospheric input of this geologic marine methane remains unknown. Methane from marine sediments enters the water column either dissolved in the pore

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0278-4343/$ - see front matter
doi:10.1016/j.csr.2011.02.012

waters (fluid flow) and/or as free gas in form of rising gas bubbles or gas-bubble-plumes. Given the fact that seawater is extremely undersaturated in methane, a rising methane gas bubble partially dissolves during its ascend through the water column (McGinnis et al., 2006). However, by rapid bubble-mediated vertical transport, methane may enter the upper mixed ocean layer (Solomon et al., 2009) and eventually reach the atmosphere via air–sea exchange (Schmale et al., 2005).

Gas seeps are a globally widespread phenomenon (Judd and Hovland, 2007) and the number of direct flux measurements and studies about their temporal variability are steadily increasing. Fluxes from single seep holes (here termed 'vents') are mostly small (e.g. 3.5 mL/min; Leifer and MacDonald, 2003), but can reach up to >10 L/min (e.g. Leifer and Boles, 2005).

At our study site, Tommeliten, previous studies have documented significant seepage of thermogenic methane associated with a doming salt diapir (Hovland and Sommerville, 1985; Niemann et al., 2005) causing elevated methane concentrations in the water column and at sea surface (Niemann et al., 2005; Schneider von Deimling, 2006, 2009, Fig. 4).

Here, we combine acoustic, hydrographic and geochemical data from previous as well as new field studies to investigate the seepage at Tommeliten, and we use these data to re-assess methane emission, its fate in the water column, and transfer to the atmosphere.

1.3. Study area

1.3.1. Geology and seepage

Tommeliten is located on the European shelf in the Central North Sea (Fig. 1), which is characterized by strong seasonal forcing and shallow water depth (average 74 m). This area has a complex buried graben structure containing Permian to Tertiary source rock from which oil, gas, and fluids migrate and are potentially stored in shallow hydrocarbon reservoirs. The sub-seafloor of Tommeliten is characterized by three underlying salt diapirs (Alpha, Gamma, and Delta). The Delta structure has domed and pierces the overlaying sediments; it therefore lacks a proper seal (Hovland and Judd, 1988). Seismic studies indicate shallow gas and gas seepage distributed over an area of approximately 120,000 m^2. Single subbottom echosounder profiles presented by Hovland and Sommerville (1985) and Niemann et al. (2005) indicate a dome-like structure in shallow sediment depth interpreted as gas front. Where this gas front comes very close to or even intercepts with the seafloor, gas ebullition is commonly observed. The bathymetry of the Tommeliten seep area is flat with a gentle slope from 72.6 m in the northeast to 73.4 m in the southwest (Fig. 2). Small, 3 m-wide depressions of $\sim$0.2 m depth occur irregularly inside and at the boundary of the seepage area.

According to the investigations of Hovland and Sommerville (1985) the seeps are concentrated in an area of 6500 m^2 which they termed the area of 'main seepage'. Within this area, 22 vents with an average release of one 10 mm diameter bubble every 6 s were reported and a total number of 120 vents for the entire area were estimated (Hovland and Sommerville, 1985). Based on these data, a gas flux of 24 m^3/d (at 75 m water depth) was derived (Hovland and Sommerville, 1985); this figure is also quoted in more recent publications (Judd and Hovland, 2007). However, we cannot confirm this frequently cited number from a simple re-calculation (120 vents $\times$ 86,400 s/day $\times$ 1/6 s $\times$ bubble volume $=$ 0.9 m^3/d) and it is unclear how the total estimate was made. The cited figure seems to be the total daily flux issuing from the whole gas-charged main seepage area. This estimate has, however, been more clearly stated as a flux per m^2 per year by Hovland et al. (1993). In Judd (2004) a re-calculated number of 41 t/yr is presented, but no indication is given how the calculation was performed.

Niemann et al. (2005) report flares that reach the transducer depth during their observations in 2002 and they estimated a gas ebullition area of 3500 m^2. The same authors report indications for an additional seep area at 56°29.56′N, 2°59.25′E. This was subsequently confirmed by Wegener et al. (2008) and Schneider von Deimling et al. (2010).

In accordance with previous observations (Hovland and Sommerville, 1985), our video surveys in 2006 reveal the presence of funnel-shaped craters, approximately 10 cm deep and 20 cm in diameter, forming around each vent hole in the sandy seafloor. The release holes are typically $\sim$1 cm wide. Occasionally, these craters

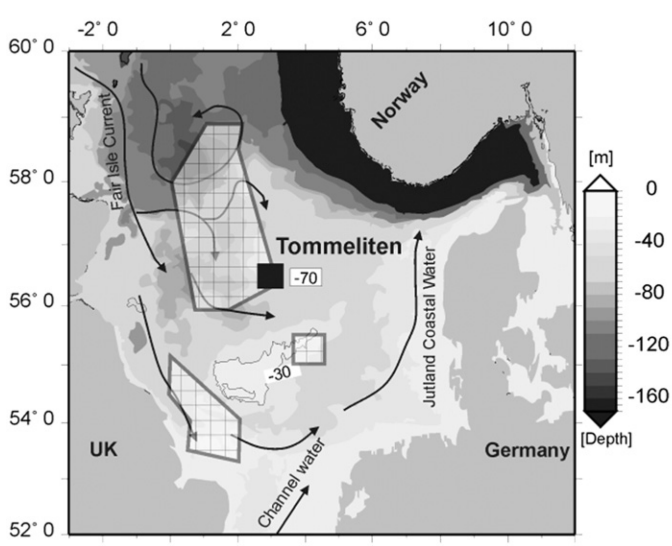

Fig. 1. North Sea bathymetry from the GEBCO grid (http://www.gebco.net), together with main current patterns adapted from Turrell et al. (1992). Hatched areas represent areas of methane gas seepage in the vicinity of Tommeliten. Areas of methane gas seepage from Judd and Hovland (2007), Judd et al. (1997), Judd (2001), and Schroot et al. (2005).

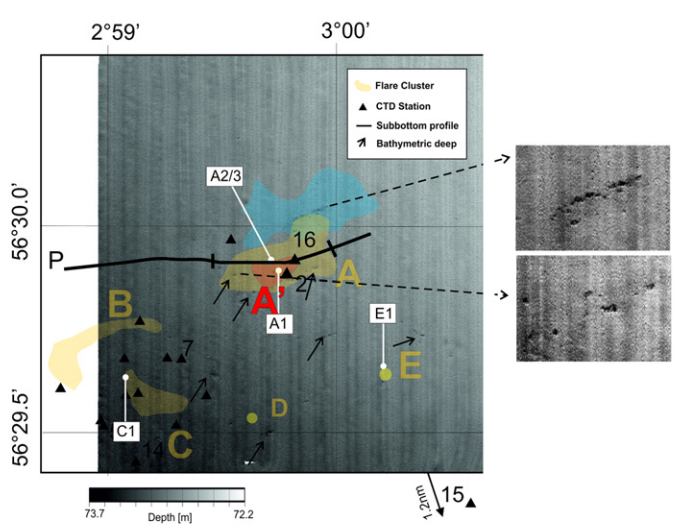

Fig. 2. Map showing multibeam bathymetric data of the Tommeliten area (illumination is from the North). Arrows indicate shallow seafloor depressions; close-ups of some of these are shown on the right. Formerly reported gas-charged upper sediment area (Hovland and Sommerville, 1985) and free gas bubble ebullition (Niemann et al., 2005) plot as blue and red area (*A*′). Gas seepage areas defined in this study are shown in yellow and labeled A to E. Individual flares discussed in the text are labeled *A*1–*A*3, *C*1, and *E*1. Black triangles indicate the locations of CTD casts. The black line P shows the location of the subbottom profile shown in Fig. 4.