Continental Shelf Research 190 (2019) 104004

Contents lists available at ScienceDirect

Continental Shelf Research

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

Research papers

Response of marine methane dissolved concentrations and emissions in the Southern North Sea to the European 2018 heatwave

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ARTICLE INFO

Keywords:
European 2018 heatwave
North sea
Belgian coastal zone
Methane

ABSTRACT

During the European heatwave of 2018 that led to record-breaking temperatures in many countries across northern and central Europe, average seawater temperature in July was 2.5 °C higher than the mean from 2004 to 2017 for same month in the Belgian coastal zone (BCZ) (Southern Bight of the North Sea). The mean dissolved CH_4 concentration in surface waters in July 2018 (338 nmol L^{-1}) was three times higher than in July 2016 (110 nmol L^{-1}), and an extremely high dissolved CH_4 concentration in surface waters (1607 nmol L^{-1}) was observed at one near-shore station. The high dissolved CH_4 concentrations in surface waters in the BCZ in July 2018 seemed to be due to a combination of enhancement of methanogenesis and of release of CH_4 from gassy sediments, both most likely related to warmer conditions. The emission of CH_4 from the BCZ to the atmosphere was higher in 2018 compared to 2016 by 57% in July (599 versus 382 μmol m^{-2} d^{-1}) and by 37% at annual scale (221 versus 161 μmol m^{-2} d^{-1}). The European heatwave of 2018 seems to have led to a major increase of CH_4 concentrations in surface waters and CH_4 emissions to the atmosphere in the BCZ.

1. Introduction

Methane (CH_4) is the second most important long-lived anthropogenic greenhouse gas (GHG) after CO_2 (IPCC, 2013), and has numerous anthropogenic and natural sources and sinks in the three major Earth compartments (atmosphere, land and ocean) (Saunois et al., 2016). The open ocean is a very small source of CH_4 to the atmosphere (≤2 TgCH$_4$ yr^{-1}, Rhee et al., 2009; Weber et al., 2019) compared to other natural CH_4 sources (~220 TgCH$_4$ yr^{-1}) dominated by wetlands and to anthropogenic CH_4 sources (~350 TgCH$_4$ yr^{-1}) dominated by agricultural food production (cattle and rice paddies) (Saunois et al., 2016). The origin of CH_4 in surface waters of the open ocean is elusive, coined the "ocean CH_4 paradox", possibly related to several processes that are probably variable from one system to another such as the transformation of methylated molecules such as dimethylsulfoniopropionate or methylphosphonate (Karl et al., 2008; Florez-Leiva et al., 2013), production of CH_4 by phytoplankton itself (Lenhart et al., 2016), or methanogenesis in the guts of some species of copepods (Stawiarski et al., 2019). Coastal waters, and in particular estuaries, are more intense sources of CH_4 to the atmosphere (~10 TgCH$_4$ yr^{-1}) than open oceanic waters (Bange et al., 1994; Middelburg et al., 2002; Borges and Abril, 2011; Upstill-Goddard and Barnes, 2016). The CH_4 emissions from coastal waters are sustained by methanogenesis in sediments fueled by high organic matter deposition and in some regions by natural gas seeps, mud volcanoes or CH_4 hydrates (Dimitrov, 2002; Damm and Budeús, 2003; Mau et al., 2007; Malakhova et al., 2010; Shakhova et al., 2010). In coastal waters, the largest source of CH_4 seems to be sedimentary and leads to an enrichment of CH_4 in bottom waters, the fate of which depends on water column depth. Concentrations of CH_4 in surface waters and related CH_4 emissions to the atmosphere are higher in shallow regions of the continental shelf (Borges et al., 2016), and, in deeper areas, CH_4 in bottom waters is dispersed by lateral transport (advection or turbulent mixing) or removed by microbial oxidation, and is transported very slowly across the thermocline to surface waters (Schneider von Deimling et al., 2011; Mau et al., 2015; Graves et al., 2015). Overall, this leads to a negative relation between CH_4 concentration and depth (in absolute values) both locally (Borges et al., 2016, 2018) and globally (Weber et al., 2019).The future evolution of CH_4 emissions from coastal waters in response to warming and eutrophication (and related expansion of hypoxia) remains largely unconstrained and unquantified (Naqvi et al., 2010).

The response to natural oscillations (e.g. El Niño-Southern

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https://doi.org/10.1016/j.csr.2019.104004
Received 8 July 2019; Received in revised form 24 October 2019; Accepted 27 October 2019
Available online 6 November 2019
0278-4343/

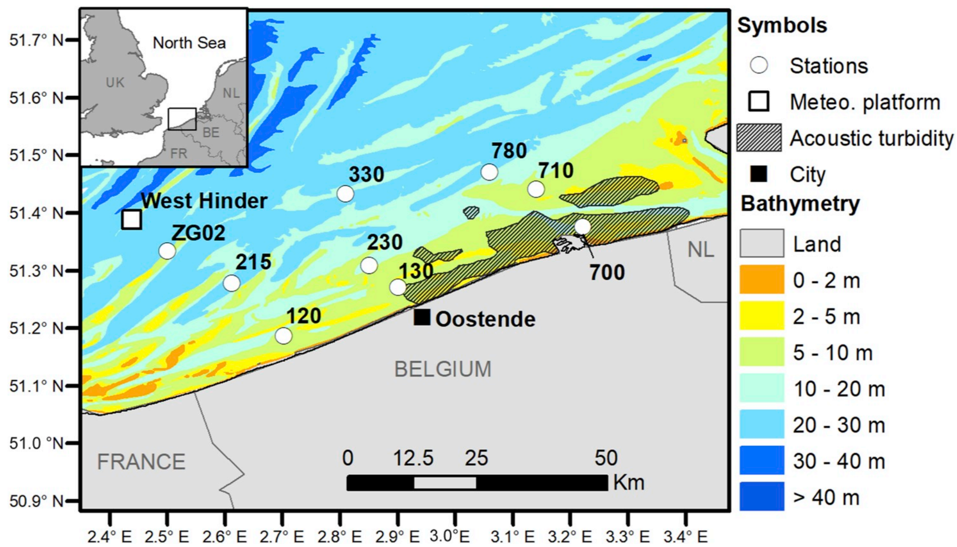

Fig. 1. Map of the nine sampling stations (circles), the West Hinder platform (wind speed measurements), bathymetry, and sediment acoustic turbidity in the Belgian coastal zone. Acoustic turbidity corresponds to gassy sediments (from Missiaen et al., 2002).

Oscillation, North Atlantic Oscillation) or extreme weather events (e.g. heatwave, very mild winter) can be used as a natural laboratory to determine how marine ecosystems might respond to climate change (e.g. warming, increased stratification, local change of wind intensity) (e.g. Le Quéré et al., 2002; Champenois and Borges, 2012, 2019). Furthermore, heatwave events are predicted to increase in frequency and magnitude as a consequence of global warming (Frölicher et al., 2018). Heatwaves have been shown to affect marine ecosystems worldwide, leading to mortality of some organisms, out-of-range species migrations, or outbreaks of undesirable organisms, in pelagic communities (McCabe et al., 2016; Cavole et al., 2016; Oliver et al., 2017), seagrass beds (Marbà and Duarte, 2010; Arias-Ortiz et al., 2018), coral reefs and reef-associated communities (Wernberg et al., 2013; Hughes et al., 2017), kelp forests (Wernberg et al., 2016), and rocky benthic communities (Garrabou et al., 2009). The effect of heatwaves on the marine sources and sinks of greenhouse gases such as CH_4 and on its emission to atmosphere have not been documented so far, to our best knowledge.

Borges et al. (2016, 2018) reported the distribution and seasonal variability of dissolved CH_4 in the Belgian coastal zone (BCZ) and hypothesized that warming would increase CH_4 concentrations in surface waters. This hypothesis builds on the fact that there are large quantities of organic matter from former peatlands (dating from the last glacial period) in near-shore sediments and the presence of gassy sediments, most probably pockets of CH_4 (Missiaen et al., 2002). Furthermore, the BCZ is an area of important deposition of sediment and organic matter compared to the rest of the North Sea (de Haas and van Weering, 1997), consequently near-shore sediments are muddy and rich in organic matter (Braeckman et al., 2014). Warming could stimulate the release of CH_4 from sediments either due to enhanced methanogenesis (mainly limited by temperature, given the high stock of sedimentary organic matter) and/or release of CH_4 from gassy sediments (ebullition/flaring). Furthermore, the water column in the BCZ is permanently well-mixed (no summer thermal stratification), so that inputs of CH_4 from sediments are efficiently mixed to surface waters; conversely, warming of surface waters propagates to an equivalent warming of surface sediments. The heat should then further propagate deeper into the sediment by diffusion and advection, depending on sediment porosity (Goto and Matsubayashi, 2009) and by pore-water pumping by surface waves (Savidge et al., 2016).

In the present study, we report dissolved CH_4 concentrations in surface waters at nine fixed stations in the BCZ during 2018 (Fig. 1) that are compared to an equivalent data-set obtained in 2016. We compare the data-sets obtained with the same analytical methodology in 2016 and 2018 at the same stations and using the same temporal resolution (monthly), to check for inter-annual changes. In particular, we investigate the response of marine CH_4 concentration to the European 2018 heatwave (WMO, 2018), in order to test the above mentioned hypothesis of enhancement of dissolved CH_4 concentrations in response to warming. The European 2018 heatwave led to record-breaking temperatures in many countries across northern and central Europe, and according to the European Center for Medium Weather Forecast, near-surface air temperature anomaly in Europe in the period of April to August, calculated with respect to the 1981–2010 average for those months, was nearly 2 °C in 2018, much larger than in any previous year since 1979 (Magnusson et al., 2018).

2. Material and methods

Data were collected in the BCZ on board the *RV Simon Stevin* at nine fixed stations (Fig. 1) in 2017, 2018 and 2019 during 23 cruises of one or two days duration (28/29-03-17; 26-04-17; 23/24-05-17; 05-03-18; 21/22-03-18; 04/04-04-18; 24/25-04-18; 02/03-05-18; 29/30-05-18; 25/26-07-18; 27/29-08-18; 25/27-09-18; 24/25-10-18; 21/22-11-18; 18-12-18; 29/30-01-19; 20/21-02-19; 26/27-03-2019; 08/08-04-2019; 23/24-04-2019; 06/08-05-2019; 20/21-05-2019; 04/05-06-2019). Sampling was carried out in surface waters (3 m depth) with a 4L Niskin bottle mounted on a six bottle rosette connected to a conductivity-temperature-depth (CTD) probe (Sea-bird SBE25). Sampling was only made in surface waters because we previously showed that there are no major vertical gradients (between surface and bottom waters) of salinity, temperature and CH_4 in the BCZ which is a permanently well-mixed area due to its shallowness and strong tidal currents (Borges et al., 2016). Duplicate water samples for the determination of dissolved CH_4 concentration were collected in borosilicate serum bottles (50 mL) with silicone tubing, left to overflow, poisoned with a saturated solution of $HgCl_2$ (200 µL), sealed with a butyl stopper and crimped with an aluminum cap. The concentration of CH_4 was determined with the headspace equilibration technique and a gas chromatograph (GC) equipped with a flame ionization detector (SRI 8610C) calibrated with CH_4:CO_2:N_2O:N_2 mixtures (Air Liquide Belgium) of 1, 10 and 30 µatm CH_4. The method is described in detail by Borges et al. (2018), and was inter-calibrated with other laboratories in the first large-scale international inter-calibration of marine CH_4 and N_2O measurements (Wilson et al., 2018). Precision was about ±3% for CH_4 based on analysis of 159

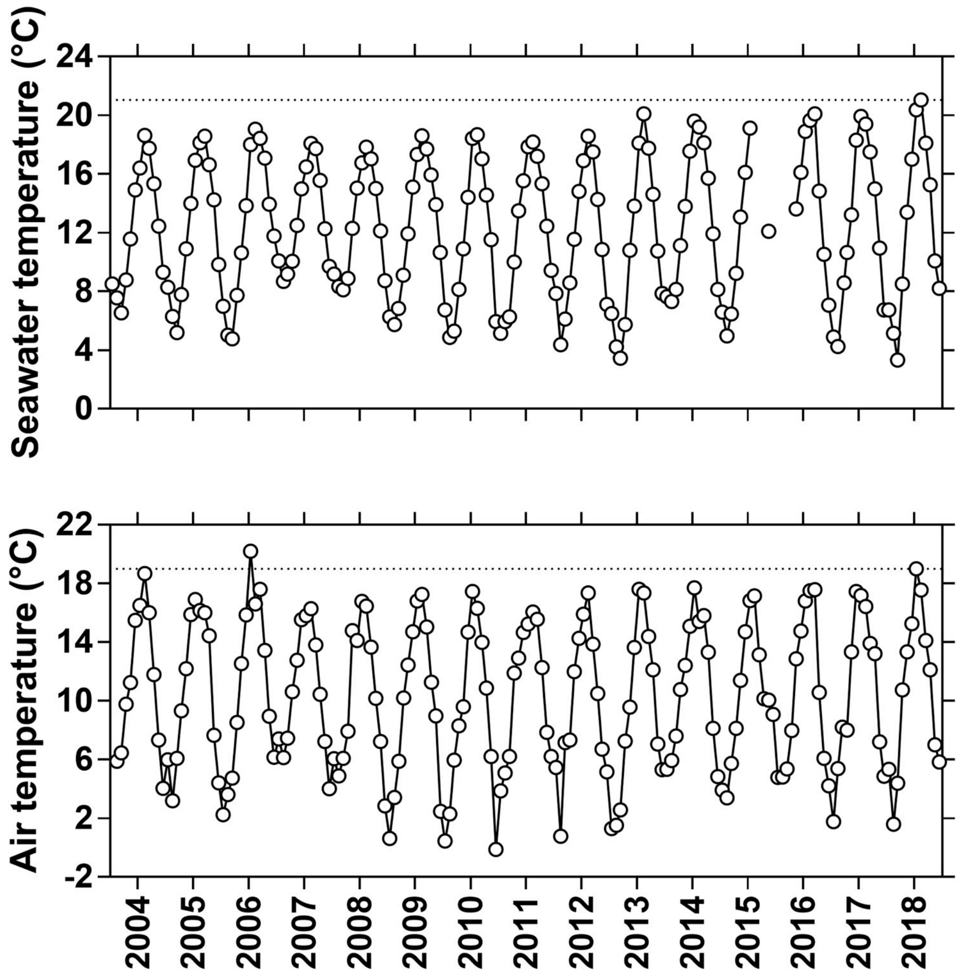

Fig. 2. Time series of monthly seawater temperature (°C) in the Belgian coastal zone and monthly air temperature (°C) in the city of Oostende from 2004 to 2018. Horizontal dotted line indicates the value of July 2018.

duplicate samples. The air-sea flux of CH_4 (F_{CH4}) was computed using the gas transfer velocity parameterization as a function of wind speed of Nightingale et al. (2000), and the Schmidt number of CH_4 in seawater computed from temperature according to Wanninkhof (1992), using daily wind speed data from the Westhinder platform (2.4378°E 51.3883°N) acquired by the Meetnet Vlaamse Banken (MVB) and retrieved from the Vlaams Instituut voor de Zee (VLIZ) data-center (http://www.vliz.be/en/measurement-network-flemish-banks). We used a constant atmospheric value of the partial pressure of CH_4 (pCH_4) of 1.9 µatm. The typical variability of atmospheric pCH_4 of ±0.2 ppm leads to a small error in the computation of F_{CH4}, on average of <±0.5% for our data-set because the observed dissolved CH_4 concentrations in the BCZ were always distinctly above the saturation value.

Samples for the determination of chlorophyll-*a* (Chl-*a*) were filtered on Whatman GF/F glass fiber filters (47 mm diameter) and stored frozen (−20 °C). The concentration of Chl-*a* was determined on acetone (90%) extracts by fluorimetry (Holm-Hansen et al., 1965) using a Kontron SFM25 fluorimeter. Samples for the determination of total suspended matter (TSM) were filtered on pre-weighted Whatman GF/F glass fiber filters (47 mm diameter) and data retrieved from the VLIZ data-center (http://www.vliz.be/en/lifewatch-0).

Hourly seawater temperature data from 2004 to 2018 were acquired at the two platforms (Westhinder (2.439°E 51.389°N) and Wandelaar (3.047°E 51.395°N)) by the MVB and retrieved from the VLIZ data-center (http://www.vliz.be/en/measurement-network-flemish-banks). Seawater temperature from the platforms compared satisfactorily with the CTD measurements from the cruises (Fig. S1). Daily average air temperatures were acquired at the Oostende airport (2.870°E 51.204°N, < 1km from the seashore) and were retrieved from Weather Underground data-base (https://www.wunderground.com/).

Statistical tests were carried out at 0.05 level, using GraphPad Prism® software. Normality of the distribution was tested with the D'Agostino-Pearson omnibus normality test, and differences were tested with the Wilcoxon matched-pairs signed rank test.

The georeferenced and timestamped data-set from 2017 to 2019 of dissolved CH_4 concentration, salinity, water temperature and Chl-*a* is publicly available (Borges and Gypens, 2019). The data-set from 2016 is also publicly available as a Supplemental File of Borges et al. (2018).

3. Results and discussion

Seawater temperature in the BCZ in July–August 2018 was exceptionally high compared to the last 13 years (Fig. 2). The monthly average of seawater temperature in the BCZ in July 2018 (20.4 °C) was 2.5 °C higher than the mean from 2004 to 2017 in July (17.9 °C), and the monthly average of seawater temperature in August 2018 (21.0 °C) was 2.3 °C higher than the mean from 2004 to 2017 in August (18.8 °C). The monthly average seawater temperature in 2018 was higher by 1.5 °C in July and by 1.4 °C in August compared to 2016. Monthly air temperature in Oostende in July 2018 (19.0 °C) was 2.3 °C higher than the mean from 2004 to 2017 in July (16.7 °C). The monthly average air temperature in 2018 was higher by 2.2 °C in July and by 0.1 °C in August compared to 2016. The time-series of air temperature since 2004 shows that two other heatwaves occurred in August 2004 (18.7 °C) and July

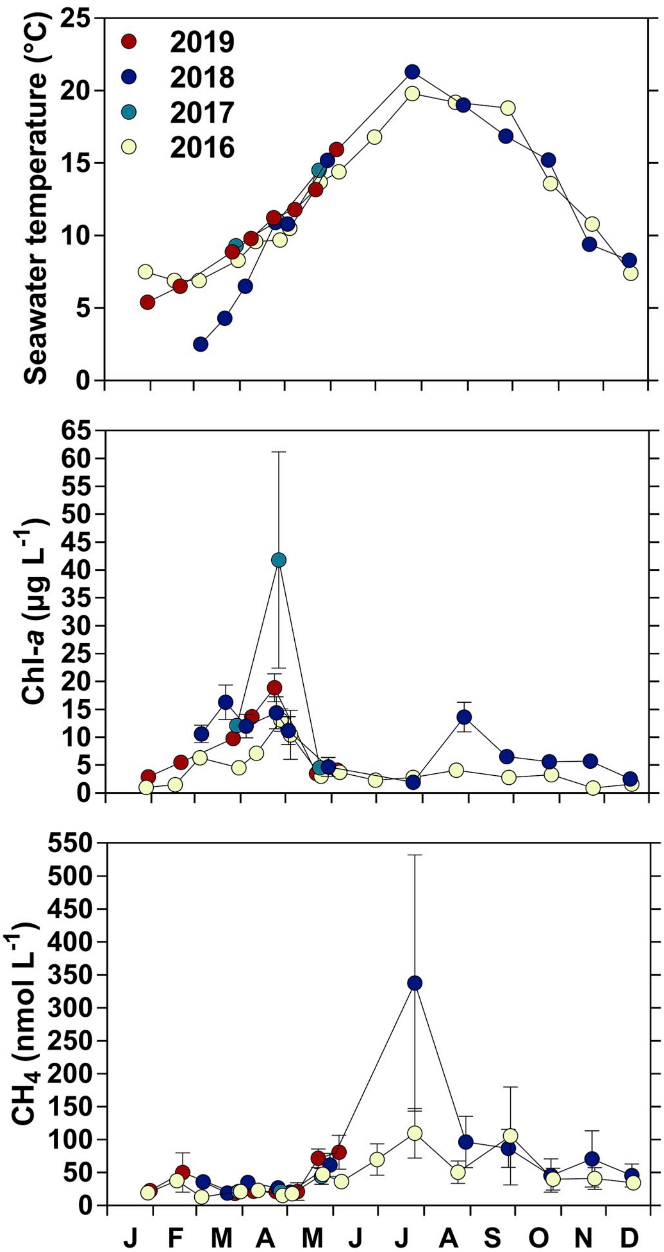

Fig. 3. Average of the nine sampled stations in the Belgian coastal zone (Fig. 1) of seawater temperature (°C), chlorophyll-*a* concentration (Chl-*a* in µg L^{-1}), and dissolved CH_4 concentration (CH_4 in nmol L^{-1}) in 2016, 2017, 2018 and 2019. Error bars represent the standard error (that in some cases are smaller than the symbol and do not appear on the plot).

2006 (20.2 °C), but there was not a corresponding increase of seawater temperature, probably reflecting less extensive and more local heat-waves, and/or of shorter duration.

The mean seawater temperature measured at the nine fixed sampling stations (Fig. 1) was 1.5 °C higher in July 2018 (21.3 °C) than in July 2016 (19.8 °C) (Fig. 3). Higher seawater temperatures were observed at all nine stations, with differences ranging between 0.7 °C at stations 700 and 780 and 2.3 °C at station 215 and ZG02 (Fig. S2). There was an onshore-offshore gradient of seawater temperature in July 2018, with lower temperatures offshore (20.8 °C on average for stations ZG02, 330 and 780) than onshore (22.0 °C on average for stations 120, 130 and 700) (Fig. S2).

Summer-time CH_4 concentrations (July–August) were significantly higher in 2018 than 2016 (Wilcoxon matched-pairs signed rank test $p = 0.0432 < 0.05$). The mean CH_4 concentration in surface waters in July 2018 (338 nmol L^{-1}) was three times higher than in July 2016 (110 nmol L^{-1}) (Fig. 3). Higher CH_4 concentrations in July 2018 than July 2016 were observed at seven of the nine individual stations (Fig. 4 and S3). The differences of CH_4 concentrations in July 2018 compared to July 2016 were particularly marked at stations 130 and 700, with extreme CH_4 concentrations of 1074 and 1607 nmol L^{-1}, respectively. Such dissolved CH_4 concentration values are much higher than those typically reported in estuarine polyhaline regions, as maximum CH_4 concentrations are observed mostly in the oligohaline estuarine regions with values typically <500 nmol L^{-1} (Borges and Abril, 2011). These dissolved CH_4 concentration values were higher than any other previous report in natural surface waters of the North Sea, and equivalent to the maximum concentration reported above an abandoned borehole in the Northern North Sea (CH_4 concentration of 1453 nmol L^{-1}, Rehder et al., 1998). Such high dissolved CH_4 concentrations are extremely uncommon in continental shelves in general (typically $CH_4 \leq 10$ nmol L^{-1}) (e.g. Bange et al., 1994; Bange, 2006; Weber et al., 2019), and are only observed in areas of shallow and intense gas seeps such as near Coal Oil Point in Santa Barbara Channel (Mau et al., 2007) or the bays in the Black Sea around Sevastopol (Malakhova et al., 2010). The dissolved CH_4 concentrations in the BCZ in late winter and spring (January–May) were similar in 2016, 2017, 2018 and 2019 (Fig. 3), even if the late winter (January–March) seawater temperatures were particularly low in 2018 (Figs. 2 and 3). The dissolved CH_4 concentrations in the BCZ in early winter (October–December) were also similar as those in 2016 and 2017 for the monthly averages of all stations (Fig. 3). At station 130, the shallowest among the nine sampled stations, high values of dissolved CH_4 concentrations were observed in September 2016 and November 2018 (Fig. 4) possibly in relation to transient increases in relation sediment resuspension due to autumn storms. Indeed, in November 2018, TSM values were higher in the most coastal stations (700, 130, 120) (50.0 ± 19.0 mg L^{-1}) than the most off-shore stations (ZG02, 330, 780) (13.0 ± 10.4 mg L^{-1}), indicative of vigorous sediment resuspension, and the highest TSM value among the nine sampled stations was at stations 130 (69.0 mg L^{-1}). In conclusion, the major difference among years of dissolved CH_4 concentrations in the BCZ was observed in July 2018 compared to 2016, except for small-scale variations in autumn due sediment resuspension at the shallowest station (130).

The concentration of CH_4 in estuarine environments depends on the balance of source terms (riverine and lateral inputs and sedimentary fluxes) and loss terms (emission to the atmosphere and microbial oxidation). Salinity values in July 2018 were lower in most stations than in July 2016, but values were within the range typically observed at each station (Fig. S4). However, at station 700 where the highest CH_4 concentration was observed, salinity was higher in July 2018 than in July 2016. Furthermore, Borges et al. (2018) showed using a simple model that CH_4 brought from the Scheldt estuary is rapidly lost during transport in the BCZ mainly due to emission to the atmosphere, and that inputs of CH_4 from the Scheldt do not contribute significantly to the observed high CH_4 values in the BCZ. We conclude that the difference in dissolved CH_4 concentration in the BCZ between July 2018 and 2016 was unrelated to differences in estuarine inputs of CH_4 from the Scheldt.

Borges et al. (2018) showed that CH_4 at the different stations of the BCZ behaved differently to inputs of phytoplankton organic matter and to seasonal temperature change, depending on the organic matter content of sediments (sandy and organic matter poor versus muddy and organic matter rich). At stations with organic poor and sandy sediments (stations 215, ZG02 and 330), CH_4 production in sediments seemed to rapidly increase in response to the sedimentation of organic matter from the spring phytoplankton bloom, and then declined by the start of summer. This is in line with the observation of a peak of CH_4 production in the sediments that follows the spring phytoplankton bloom with a time lag of 1 month in Eckernförde Bay in the Baltic Sea (Bange et al., 2010; Steinle et al., 2017). In the stations of the BCZ with sandy sediments, the time lag between the CH_4 peak and the phytoplankton bloom

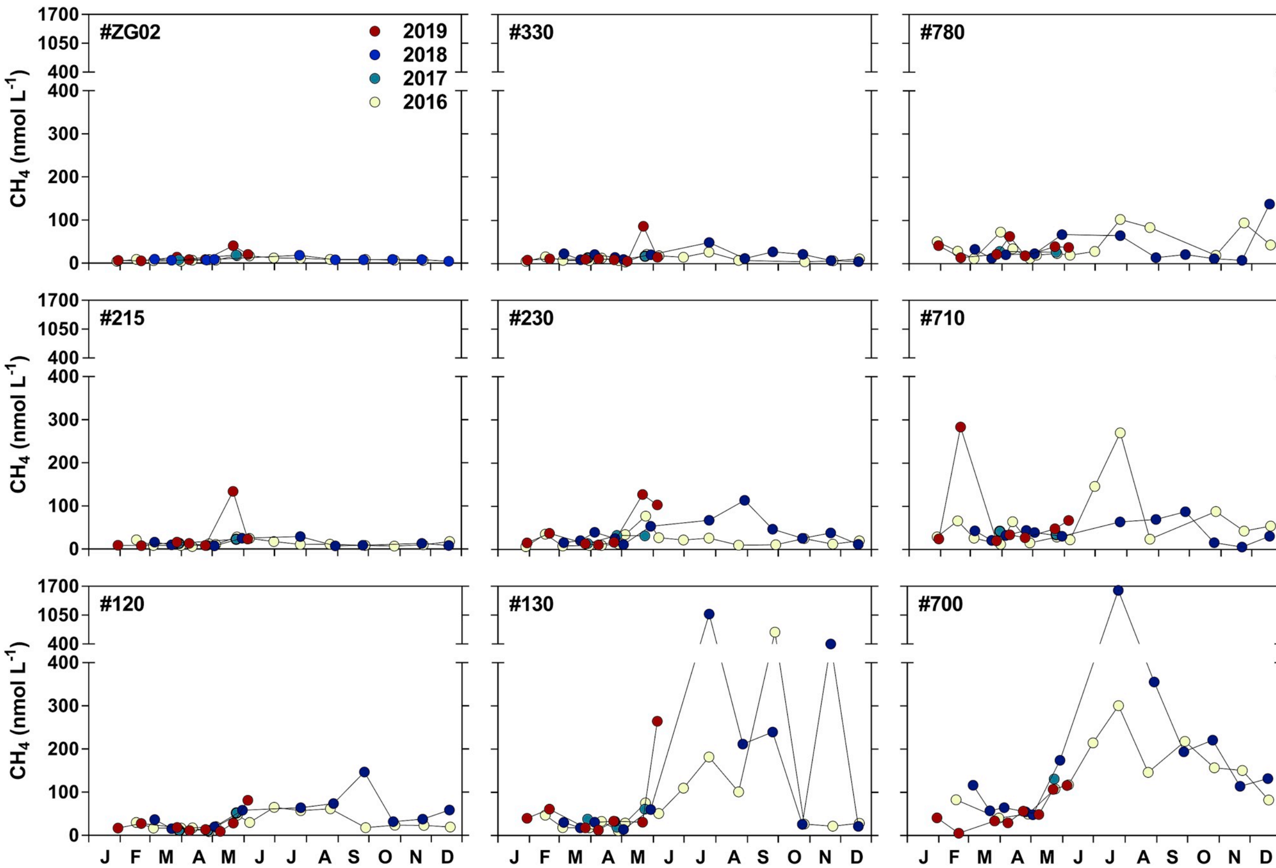

Fig. 4. Seasonal variations of dissolved CH_4 concentration (CH_4 in nmol L^{-1}) at nine stations in the Belgian coastal zone in 2016, 2017, 2018, 2019. The plots are arranged to correspond to the spatial distribution of the stations (Fig. 1), left to right corresponding to West to East, and top to bottom corresponding from off-shore to near-shore. The same data are presented in Fig. S2 with Y-axis individually scaled for each station.

seemed to be shorter (14–21 d) because more shallow (Borges et al., 2018). Consequently, it seems unlikely that changes in the intensity of the spring phytoplankton bloom might explain changes in CH_4 production in the BCZ several months later, either in summer or fall. Indeed, the most off-shore western stations (ZG02, 330, 215 and 230) showed in 2019 distinctly higher peaks of CH_4 in mid-May compared to the other years (Fig. 4 and S3). This was probably in response to the higher delivery of freshly produced organic matter from the phytoplankton bloom. Indeed, average Chl-*a* at stations ZG02, 330, 215 and 230 in April was higher in 2019 ($11.7 \pm 3.6\ \mu g\ L^{-1}$) than 2016 ($4.1 \pm 2.1\ \mu g\ L^{-1}$) and 2018 ($10.3 \pm 7.1\ \mu g\ L^{-1}$) (the higher mean value in 2018 compared to 2016 was driven by the values at station 230, the mean value in 2018 excluding this station was $6.9 \pm 3.0\ \mu g\ L^{-1}$). At these stations, CH_4 peaked in Mid-May 2019 in response to higher spring-time Chl-*a* but decreased again by early June 2019, confirming that the response of CH_4 to the spring phytoplankton bloom is fast (<1 month) and short-lived.

Average Chl-*a* was higher in March and early April 2018 than 2016 (Fig. 3). This seemed to be a generalised feature at all nine stations (Fig. S5) suggesting better light conditions in early 2018 than 2016, as winter-time dissolved inorganic nutrients were similar in 2018 and 2016 (not shown). However, average Chl-*a* concentrations in the BCZ were similar from late April to July in 2016 and 2018 (Fig. 3). Furthermore, the highest CH_4 concentrations in July 2018 were observed at stations 130 and 700 where sedimentary CH_4 production does not respond to inputs from the spring phytoplankton bloom, but, instead is a function of seasonal temperature variations because they have muddy sediments rich in organic matter (Borges et al., 2018). We conclude that the difference in CH_4 concentration in the BCZ between July 2018 and 2016 was unrelated to marginal differences in the early spring phytoplankton bloom in particular in the near-shore muddy stations (130 and 700) where the highest CH_4 concentrations were observed, although it might have played a small role in the off-shore sandier stations (ZG02 and 330).

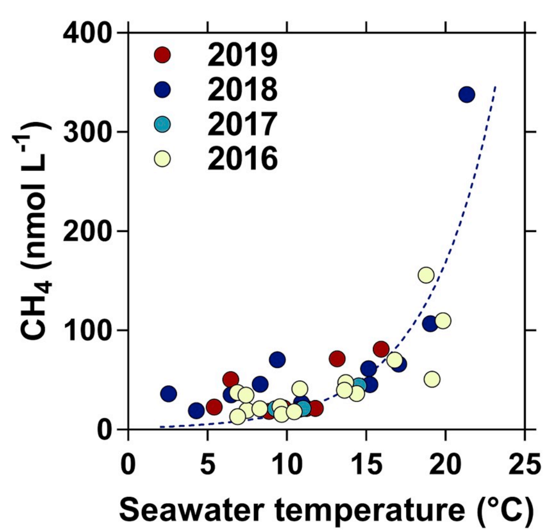

Fig. 5. Dissolved CH_4 concentration (nmol L^{-1}) as function of seawater temperature (°C) averaged for the nine stations (Fig. 1) in the Belgian coastal zone in 2016, 2017, 2018 and 2019. The dotted line shows the exponential fit for data with seawater temperature (T) > 10 °C: $CH_4 = 1.7527\ \exp(0.2283{*}T)$ ($r^2 = 0.93$), where CH_4 is in nmol L^{-1} and T in °C.

Table 1
Average at nine stations in the Belgian coastal zone (Fig. 1) of dissolved CH_4 concentration in surface waters (nmol L^{-1}), wind speed (m s^{-1}), gas transfer velocity (k_{600} in cm h^{-1}) and air-water CH_4 flux (FCH_4 in μmol m^{-2} d^{-1}). The date corresponds to the last day of the cruise (duration 1–2 days). Wind speed was averaged over the 15 days prior to the last day of the cruise to provide seasonally representative values and smooth out transient weather events (windy or calm spells). Data of CH_4 were not acquired in January and February 2018, so to provide annual averaged FCH_4, the yearly cycle was completed with data acquired in January and February 2019. Only the cruises of 2016 concurrent in the yearly cycle with those of 2018/9 were used.

Dates		CH_4		Wind speed		k_{600}		FCH_4	
		nmol L^{-1}		m s^{-1}		cm h^{-1}		μmol m^{-2} d^{-1}	
		2016	2018/9	2016	2018/9	2016	2018/9	2016	2018/9
28-01-16	29-01-19	20	23	10.9	9.5	33.8	25.9	90	79
16-02-16	21-02-19	38	50	11.2	8.8	34.7	22.4	192	167
04-03-16	05-03-18	13	36	9.9	10.2	28.5	28.3	47	131
31-03-16	22-03-18	21	19	8.9	9.6	22.7	24.5	70	58
11-04-16	04-04-18	23	35	8.4	7.3	21.3	14.6	76	75
27-04-16	24-04-18	15	27	8.6	6.4	20.4	12.6	45	56
04-05-16	03-05-18	18	20	8.6	8.9	21.0	22.7	58	73
25-05-16	30-05-18	48	61	7.0	6.8	14.3	13.5	126	163
26-07-16	26-07-18	110	338	7.3	5.1	15.4	7.5	382	599
24-08-16	27-08-18	51	96	8.3	8.2	19.3	18.8	209	391
27-09-16	26-09-18	156	87	7.3	8.0	15.7	19.0	530	543
26-10-16	24-10-18	40	45	8.4	7.2	19.8	14.8	142	207
23-11-16	22-11-18	41	71	10.5	10.1	30.6	27.5	208	313
19-12-16	18-12-18	35	46	7.2	11.2	14.3	34.8	74	245
Average		**45**	**68**	**8.8**	**8.4**	**22.3**	**20.5**	**161**	**221**

The average dissolved CH_4 concentration for each cruise was positively correlated to water temperature (Fig. 5), as previously reported in the area (Borges et al., 2016, 2018), although extending markedly the upper bounds of the range of variations of both dissolved CH_4 concentration and seawater temperature values. This might possibly be explained by the optimum temperature for methanogenic archaea around 35–40 °C for mesophiles and 60–65 °C for thermophiles (Zeikus and Winfrey, 1976; Schulz et al., 1997; Yvon-Durocher et al., 2014). The most common lineages of methanogenic archaea in marine sediments are *Methanoculleus* and *Methanosaeta* followed by *Methanolinea,* and organisms from all three groups are either mesophiles or thermophiles (Wen et al., 2017). Psychrophile methanogenic archaea (optimum growth at 15–20 °C) have only been reported in cold deep lake sediments but not in marine sediments (Blake et al., 2017), although psychrotolerant methanogenic archaea (optimum growth temperature similar to mesophiles but capable of survival at temperatures of 0–5 °C) have been reported in Arctic marine sediments (Kendall et al., 2007). Below the optimum temperature and in an environment rich in organic matter, a positive relationship between methanogenesis and temperature is expected (Yvon-Durocher et al., 2014). Indeed, warming has been shown experimentally to increase CH_4 production in freshwater sediments (Yvon-Durocher et al., 2017; Comer-Warner et al., 2018).

Although station 120 is characterized by muddy sediments rich in organic matter (Braeckman et al., 2014), the increase of CH_4 in July 2018 compared to 2016 was not as spectacular as in stations 130 and 700 (Fig. 4 and S3). Stations 130 and 700 are located above a zone of gassy sediments (Missiaen et al., 2002). Release of CH_4 from gassy sediments is enhanced in warmer conditions due the decrease of the solubility of CH_4 and thermal expansion of gas pockets (Martens et al., 1998; Wever et al., 1998). We conclude that the increase of temperature related to the heatwave of 2018 most likely led to a general increase of CH_4 in surface waters (at nearly all stations) due to enhancement of methanogenesis (stimulation of microbial metabolism), and that, in addition, the higher temperature also most likely led to enhanced CH_4 release from gassy sediments (in particular at stations 130 and 700 situated in the area of acoustic turbidity indicative of gassy sediments).

However, the above interpretation of the CH_4-temperature relation given in Fig. 5 requires that the extra heat in the water column during the heatwave of 2018 partly propagated into the sediments, and presumably also led to higher sediment temperatures. The BCZ is shallow (<30 m deep) and experiences strong tidal currents, consequently, the water column is permanently well mixed so that the surface of sediments should have experienced warmer conditions in 2018 compared to the other years, and we assume that this extra heat propagated deeper in the sediment. The extent of additional warming of sediments should depend on the sediment thermal diffusivity that increases with porosity and is highest in sandy sediments (Goto and Matsubayashi, 2009). Furthermore, in sandy and permeable sediments such as those present in the BCZ, surface gravity waves may drive advective pore-water exchange that can increase 50-fold the fluid exchange between sandy sediment and overlying water relative to the exchange by molecular diffusion (Precht and Huettel, 2003), and should also increase heat propagation in sediments (Savidge et al., 2016). In shallow and sandy sediments of the Gulf of Mexico, Jackson and Richardson (2001) showed that temperature within the sediment down to 1 m below surface tracked closely seasonal changes of the overlying water at time-scales compatible with the long-lasting heatwave experienced in Europe in 2018.

The FCH_4 in July 2018 was 202% higher at station 130 (1935 versus 639 μmol m^{-2} d^{-1}) and 165% higher at station 700 (2845 versus 1070 μmol m^{-2} d^{-1}) than in July 2016. The overall average of FCH_4 for the nine stations in July 2018 was 57% higher than in July 2016 (599 versus 382 μmol m^{-2} d^{-1}) (Table 1). The yearly average of FCH_4 for the nine stations was 37% higher in 2018 than 2016 (221 versus 161 μmol m^{-2} d^{-1}), showing that the European heatwave of 2018 most likely had a major impact on the CH_4 emissions from the BCZ.

4. Conclusion

The European heatwave of 2018 most likely led to a major increase of the emissions to the atmosphere of CH_4 from the BCZ both in summer and at annual scale. This indicates that emissions of CH_4 to the atmosphere in coastal environments similar to the BCZ (shallow and with organic rich sediments) should most likely increase in future because heatwave events are predicted to increase in frequency and magnitude as a consequence of global warming (Frölicher et al., 2018). Also, the response of the BCZ to the European of 2018 heatwave seems to have provided a natural in-situ experiment of the response to future warming of CH_4 emissions from shallow marine areas.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We are grateful to the crew of the *RV Simon Stevin* for assistance during the cruises, to André Cattrijsse and Jonas Mortelmans (VLIZ) for organizing the schedule of cruises, to Thibault Lambert for producing Fig. 1, to Marc-Vincent Commarieu and Adriana Anzil for help with laboratory analysis, and to two anonymous reviewers and associate editor for constructive comments on the previous versions of the manuscript. CTD and TSM data were provided by VLIZ and acquired in the frame of LifeWatch. The GC was acquired with funds from the *Fonds National de la Recherche Scientifique* (FNRS) (2.4.598.07). CR has a PhD grant from the FRIA (Fund for Research Training in Industry and Agriculture, FNRS). JLM has a PhD grant from the International Training Network MIxITiN funded by European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 766327. AVB is a research director at the FNRS.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.csr.2019.104004.

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