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TNO report
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Methane emission measurements of offshore oil and gas platforms

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Extended Summary

Background
Methane is a potent greenhouse gas with an equivalent greenhouse warming potential of 25-35 of CO_2 equivalents. There is an increasing regulatory effort to reduce methane emissions, including methane emissions from natural gas production. Oil and gas operators in the Netherlands report already for more than 20 years their annual methane emissions, using a combination of measurements, emission factors and process simulations. It appears that the reported emissions are significant lower than the assessment of the average loss of methane in oil and gas production worldwide. This has resulted in questions in the Dutch parliament in 2017 about the accuracy of the reported figures.

The purpose of this measurement program is to independently assess whether the emissions as reported accordance to requirements (e-MJV) meets the results obtained via concentration measurements.

The primary aim is to assess independently total methane emissions of both a selected group and that of a random group offshore oil and gas platforms in g/s by using concentration measurements at multiple distances from the source in combination with meteorological conditions and dispersion calculations.

Campaign concept
Gas released from a platform will travel with the wind and can be measured at the lee side as a gas plume similar to the smoke plumes observed from chimneys.
In general this plume will spread out in the horizontal and vertical direction and the width of the plume will increase with distance. Measurement of the concentration pattern downwind of the platforms makes these plumes visible. An atmospheric dispersion model is used to evaluate how much emission (in gCH_4/s) is needed to get the concentration levels (in ppb or in $\mu g/m^3$) observed downwind.

There is a lot of experience with mobile plume measurement campaigns over land (onshore), but meteorological conditions over sea expressed differently, leading to different dispersion characteristics at sea (offshore). Therefore the campaign in July 2018 planned N_2O release experiments at two platforms, the K5 (K5CC; Total) and K14 (K14-FA-1; NAM). For these plumes, that are measured with the same instrument and characterised as methane (CH_4) and ethane (C_2H_6), the source strength is known and the dispersion model can be “calibrated” to mimic the dispersion of the plumes over sea.

Before the start of the campaign, the tracer gas release set-up was send to the platforms (K5 and K14). Simultaneously with the measurements on the vessel, LDAR (Leak Detection And Repair) teams measured on the two release platforms (K5 and K14). The State Supervision of Mines (SSM), in charge of enforcement of environmental regulation of oil and gas sector emission legislation, witnessed the offshore experiments as an independent cross check of the methods and site selection.

Meteorological conditions have to be within a certain range with windspeeds between 2 and 20 m/s preferably. At very low windspeed the plumes do not develop but turn

into blobs of gas filling up the area around the platform. At 20 m/s the fear is that waves will be so high that either the scientists or their instruments might fail.
In addition to the methane (nitrous oxide and carbon monoxide) measurements for NOx were done, for benzene two analysers were tested.

First campaign (July 2018)

During the campaign of July 2018, 33 offshore installations were subject to methane emissions measurements. Twelve installations had been previously selected, 21 installations were visited unannounced, of which 12 only passed once downwind, the others at least 3 passages. Tracer gas emissions took place on K14-FA-1 and K5CC. On-board methane emission measurements took place on the latter two installations (performed by the Sniffers). A senior inspector of SSM witnessed the representativity of the process conditions on both offshore installations during the measurements. The inspector was on board K14-FA-1 during the measurements. The same inspector observed all relevant parameters of K5CC from the control room in the headquarters of Total in The Hague during the measurements at that installation.

The first night of measurements showed nice methane and ethane plumes downwind of the L platforms. In the early morning of day 2 (18 July 2018) when arrived at K14, plume measurements were performed while releasing the N_2O tracer. The data showed very variable results with N_2O showing up sometimes but not always, especially with the release through the high stack.
The interpretation on that day was that the amount of N_2O needed to get the whole release system in equilibrium (the big pipe going up to the stack exhaust) was misjudged. Before the experiment the release setup was discussed not realising well that the vents system volume in combination with the low and irregular vent gas flow would cause both a delay time for the N_2O release as well as an irregular emission pattern from the vent stack.

However, the re-evaluation of the meteorological data fields over the North Sea done by KNMI after the experiment campaign showed that the real problem was that a shallow boundary layer had formed with a temperature inversion as low as 30 meter. This means there was a two-layer build-up in the lower atmosphere, the methane and N_2O (high altitude) plume were released above this inversion layer and these plumes did not reach altitudes where the measurements were done. The methane plume (and the N_2O released) from the lower situated process area of the platform could sometimes be measured because these plumes were trapped below the inversion layer, reaching the altitude of the measurements.

The same problem persisted throughout the day and became even worse at the other platform K5CC where the tracer experiments took place in the afternoon of the same day. Being unaware of the low inversion layer at the time of measurements it was thought that the problems at K14 in the morning were because of the platform layout there. At K5 however it turned out that not any methane or N_2O plume was seen at all. An extensive discussion took place on board, several inlet and instrument tests were run, but 3 different instruments (2 QCL and 2 Picarro) all provided the same info: no trace of methane plumes.
Conclusion: The instruments were fine, the meteorological condition was the problem during this campaign.

For the rest of the campaign, the wind became stronger and the shallow inversion layer fortunately disappeared. Besides that**,** another 9 m mast was added on top of the ship mast, creating an inlet almost at platform height, 35 m above sea level (instead of 26 meters during the previous measurements). The plume measurements on day 3 looked good and compared well to what was used to be seen during onshore measurements, but unfortunately no N_2O tracer release was scheduled on any of the offshore installations visited under the more favourable condition.

After the campaign the data for all platforms were screened, calibration data were used and all data was made ready to be evaluated with the atmospheric dispersion model. An evaluation of the data for the platforms K5 and K14 was done showing vary variable emission results. At a discussion meeting with NOGEPA, UU, KNMI, SSM and the Sniffers it was concluded that the inversion layer issue had caused the problem.

The data from 10 installations cannot be evaluated in a useful manner due to the existence of a low inversion layer during the measurements.

It was concluded that the experiments during the first campaign had only partially delivered the expected results. NOGEPA then decided to do another experiment taking on board the lessons learned during the first campaign, and to stop data evaluation of that first campaign to wait for additional and reliable measurements data in order to have a calibrated model.

Preparation of the second campaign (November 2018)
For the second campaign carried out in November 2018, it was decided to perform an increased amount of measurements with tracer release and 5 platforms were selected K5 (K5CC; Total), K2 (K2b-A; Neptune), L8P4 (L08-P4; Wintershall), K14 (K14-FA-1; NAM) and K15 (K15-FB-1; NAM).

Lessons learned from the first campaign (July 2018) and steps taken:

- For November there was pre-campaign contact with KNMI to predict the inversion layer height. Minimum conditions were defined to prevent a repetition of the first campaign of events with the inversion layer. This worked out well as there was no inversion layer heights below 200 m for the November campaign.
- N_2O was not released through the vent stack itself but with a dedicated 1 inch hose that was hoisted up by the platform crane to 60 m above sea level and to platform height. In this way issue of high system volume with low exit flow is bypassed and a regular N_2O release is guaranteed. The disadvantage of this concept is the fact that the tracer gas will not follow the exact same pathway as the vent gas (height, slightly different location)
- For ease of logistics as well, the N_2O release sets were taken on board of the research vessel and hoisted on the platforms where tracers release experiments were performed (as opposed to sending N_2O sets to installations for the June campaign). Doing so the same tracer set could be used on all 5 platforms for the November campaign. N_2O cylinders were dedicated to each experiment to allow for accurate flow rate determination.
- Measurements inside the 500 m zone were added to better define the individual source areas downwind of the larger platforms.
- All measurements were done with the inlet at an altitude of 35m using a mast on top of the ship mast.

During the campaign of November 2018, 22 offshore installations were subject to methane emissions measurements. 5 installations had been previously selected, 17 installations were visited unannounced. Tracer gas emissions took place on K5-CC, K2-B, L8-P4, K14-FA-1 and K15-FB-1. During this campaign, no simultaneous on-board methane emission measurements took place.
The experiments went better during the second campaign, all instruments worked fine.

Measurements started at platform K5 (Total) where the first release experiment was performed. The release at the height of the process area (approximately 30 meters) went well showing nice N_2O plumes. The N_2O plumes for the release at 60 m (mimicking the high pressure vent stack) were detectable but much smaller than expected. For this reason, the release amount of N_2O was increased from 2 to 2.5 g/s for the next 4 platforms. Inversion layer height was not a problem.

During the evaluation of the data, in the months after the experiment, it was found that the 60 m release at K5 was subject to another unexpected issue. Large power generators and 3 large gas turbine driven compressors on the installation produce hot plumes of air. Cooler banks also produced vertical air flow. It appeared that at K5 the N_2O plumes released at 60 m travelled over the area with the platform power generation units and the gas compressors. These plumes seem to be affected by these hot plumes (flue gasses of the gas turbines is emitted at 40 m but with thermal plume rise in the order of 20 m). The methane released from the high pressure and low pressure vent stacks at 80 m height does not necessarily have the same interaction with the hot CO_2 containing flue gas plumes. This eventually leads to different dispersion mechanisms of the released tracer gas (h = 60 m) and the methane emission from the HP vent stack (h = 80 m), resulting in uncertainty of the measured concentrations.

Effect on the plumes known already
Prior to the whole measurement programme the release of gas plumes was simulated at different heights.

- With a plume released at 80 m, measurements in the distance range of 0 -500 m can completely miss that plume since it passes overhead. The wake of the “building” can bring the plume down occasionally but that will be intermittent and hard to interpret.
- So to evaluate the plume emitted at that height it needs to be measured > 1000 m, which was done.
- Measurements at distances > 2000 m become difficult because the concentration peak in the centre of the plume gets closer to the variations in the background concentrations.

The measurements indeed confirmed these effects. So the data obtained relatively close to the platforms do not provide the total emission level as they can miss part of the plume (with emissions from the HP/LP vent stack(s) passing overhead). Also the a priori idea that the best plumes for **total** emission quantification were to be expected between 1000 and 2000 m downwind of the platform is confirmed.

What was learned from the data evaluation

The first model calculations were done with the Gaussian plume model that was also used for onshore data evaluation. In general that model produces plumes that spread out significantly wider compared with plumes over land . The actual dilution over the sea surface is less than the calculated dilution, which is related to the lack of thermal convection over the relatively cool surface and the absence of objects like trees and houses that generate mechanical turbulence.

OCD model

To take into account the effect of the sea surface, a model developed for the USA-EPA from 1987, the OCD (Offshore and Coastal Dispersion) model was evaluated. This model confirms that dispersion of plumes is much less pronounced over sea when compared to land conditions. The plumes in general stay in a more confined cone of air. However the plume is seriously affected too by the leeside wake of the building, which acts as an initial mixer, setting the plume within both the horizontal and vertical direction.

The problem with the OCD model is that it works on hourly averaged data and thus not for plumes measured in 2-4 minutes. So it was impossible to use the OCD model as is to evaluate the measured data. Instead the Gaussian plume model was modified in order to provide narrower plumes in accordance with the OCD model, which are more representative for the offshore situation. Besides that, the effect of the wake of the platform on the plume was also incorporated using the equations provided in the OCD model. The OCD model implementation seems to give a more consistent set of emission numbers when looking at the platforms for which N_2O plumes were available. With the improved dilution modelling, it was possible to better fit the measured tracer gas concentration with the source strength. With that, the calculation of the source strength of methane emissions from the installations also has become more reliable.

November tracer experiment results

For the 5 platforms where the N_2O tracer experiments took place in November all available plumes were evaluated. Whereas the model implementation gives reasonable agreement when evaluating the release of N_2O at the height of the process area ($h \approx 35$ m) data sets, it shows strongly underestimated N_2O emission levels when used for the releases at the high altitudes ($h \approx 60$ m) at K5 and L8P4 and K14.

At K5, L8P4 and K14 it seems that the N_2O plumes released at 60 m height were extra diluted by the large thermal sources (turbines, cooler banks, glycol regeneration units). At K2 and K15 the experiments with release at higher level (40 and 60 m respectively) seem to be successful. For K2 and K15 the model can reproduce the low and high release plumes reasonably well with the same model setting.

The effect of an extra dilution in the N_2O plume due to interaction with the plumes generated by thermal sources, is inconvenient and results in wrongly calculated methane emissions. When N_2O plumes released at maximum crane height are subject to more dilution than the CH_4 plumes (released from the HP/LP ventstack(s) at 80 to 100 m instead of the 60 m for N_2O) the result is that the emission derived for CH_4 can get extremely high (the emission is calculated by dividing the integral of

the methane plume by the integral of the N_2O plume. If the N_2O integral is too small, the emission level will become extremely large).

With the tables shown in the report for each of the tracer release experiments it was shown how the emission from a platform can be obtained in different ways, either using:

1. the ratio of the measured CH_4 and N_2O tracer plume
2. the ratio of the measured and modelled CH_4 plume using the gaussian model calculation (two different model versions used)
3. the gaussian model calculation but calibrated with the N_2O plume data

When these three methods provide the same emission level, it is assumed that the resulting emission estimate is robust. When these different paths lead to different answers it was attempted to understand and to explain these differences and to choose the estimate that is most plausible.

Plume by plume analyses

The different issues mentioned above have made progress in the data evaluation slower than anticipated. During this project part of the data interpretation, plume integration, plume location selection etc. were automated, in order to make the calculations transparent and reproducible. In the end the calculations turn out to be an iterative procedure showing that that plume by plume corrections are still required after the automated calculations. Furthermore, when evaluating the model for one platform , new insights were gained in how to improve the model runs, which then required a re-run of the model for all other platforms too.

- The measurements of July 2018 are extra tricky because of the inversion layer effect.
- The methane plumes are on top of a background concentration (in the order of 2000 ppb). This is a smooth line for many platforms (with variation of 1-10 ppb in 15 minutes), but for some platforms the incoming airmass apparently had a significant effect from (land based?) sources showing significant variations (20-200 ppb on top of the 2000 ppb level). These (local) background concentration variations are on the 15 minute time scale, the plumes are shorter in time and show as 2-3 minute peaks on top of the changing background concentration. For data with such a variable baseline it is important to do the baseline fit well and subtract the right amount of methane from the plume. Otherwise the emission will be either over- or underestimated.
- The wind data from automated measurements on board the vessel were used for the first model run. However when the wind direction in the area between the platform and the vessel is (only) 1-10 degrees different from the wind direction data that was used (which is really good), the model plume will not be on top of the measured plume and the ration of the measured and modelled integrated plume can provide wrong emission data. The effect of this in principle leads to overestimation of the emission, because the plume integration window is determined by the measured plume. If the model plume misses a part in that window, it was divided by a number that is too small.
- Some platforms consist of multiple connected sub-platforms and some platforms have other platforms in the vicinity. These sets need separate modelling to be able to derive the different sources.

- The hot CO/CO_2 plumes interact with the "cold" N_2O and CH_4 plumes. At some locations this interaction is the same for N_2O and CH_4 and there is no problem. But for other platforms the CH_4 and N_2O plume are affected in different ways which creates a bias in the emission estimates using the N_2O tracer.

Getting there

Extensive evaluation was done for the 5 main platforms were the N_2O tracer release experiments were performed in November 2018. The results are summarised in Table 1.

Table 1 The five platforms for November emissions are split into all (vent emissions including fugitive emissions) and fugitive emissions only.

Platform	Operator All gCH_4/s	Via N_2O meas All (diffuse) gCH_4/s	Via Model All (diffuse) gCH_4/s	Via CO_2 All gCH_4/s	Remark
K5 (Total)	13.6	70 (1.4)	14 (2.4)	32	Hot plume interaction
K14 (NAM)	25.8	54 (2	35 (2.5) 24*	48	Hot plume interaction
L8P4 (Wintershall)	2.6	20 (10)	26 (1.1)	10	Hot plume interaction
K2 (Neptune)	1.6	5.1 (3.9)	2.9 (4.2)	4.8	OK
K15 (NAM)	18.9	20 (5.0)	18 (4.9)	8.3	OK

*ventstack on outrigger

For these platforms the emission as determined by the operator through its emission registration system and the emission as determined by the measurements are compared. Beware that both are valid for the day of measurement only and are thus not per se valid throughout a year.

Based on the evaluation of the tracer gas experiments it was decided to run the model using the OCD building effect for all other platforms that have no tracer release. Also the modified dispersion parameters that make the plumes narrower in the horizontal direction were used. Main missing parameter in the model evaluation is how the plumes disperse in the vertical direction. Experiments that would give that information can be of great help to improve the emission estimates for these calculations.
In theory, when measurements at multiple distances from a platform are available, the unknown vertical dispersion could be solved. However, the problem is that the emission is also not per se constant in time and the wind pattern will cause concentration variation in time and space. Given all these uncertainties an agreement within a factor of 2 between the ship-measurement and estimate provided by the operator should be considered a success. When the measurements indicate an emission level that is a factor 10 above or below the operator estimate, there was a reasonable reason to doubt one of the two.

For platforms without tracer and only as single pass a difference of a factor 3 should be considered to be "the same within the error margin". Also it should be clear that what was measure now, was in general with "normal operation" at the platforms.

Of course there are major overhaul events that can generate high pulse emissions (e.g. blown-down). For such days relatively large quantities of gas can be expected to be emitted, but these emissions are relatively well quantified (the released volumes should be known), when compared to the representative operation condition emission levels.

The cooperation between the research team and the operators was a crucial step in getting a scientific well documented dataset. With this cooperation it was possible to enter the 500 m safety zone, and the emission levels reported by the operators were available for the comparison. The discussion in joined project meetings between different operators about the high or low emission levels found by the TNO measurement analyses has facilitated exchange of knowledge on various types of leaks and their relative importance.

The tracer release experiments with N_2O that were performed from several platforms were unique. This is the first time that this type of release experiments were done offshore.

Results July experiments

Table 2 Results CH_4 measurements July campaign.

JULY	Platform	Distance	Avg gCH4/s	Stdev gCH4/s	N	std err	Operator estimate	Class
17-7-18 22:26	L11-B	637 - 1560	2.7	2.1	9	27%	14	
17-7-18 23:36	L08-Hotel	750	0				0	
18-7-18 00:47	L08-P4	901 - 1603	0.9	0.5	2	39%	2.3	
18-7-18 02:14	L08-Alpha	906	11	11	1		0	
18-7-18 03:12	L10-B	2028					0	
18-7-18 03:18	L10-E	684					0	
18-7-18 03:19	L10-D	2032					0	
18-7-18 03:38	L10-A complex	1429 - 1940					29	
18-7-18 05:40	K15-FG-1	663 - 1404					0.008	
18-7-18 05:51	K15-FB-1	750 - 1500					6.9	
18-7-18 06:54	K15-FC-1	560 - 663					0.005	
18-7-18 07:14	**K14-FA-1**	750 - 2000					16	
18-7-18 12:15	K08-FA-3	1200					0.7	
18-7-18 14:58	**K5CC**	550 - 3500					14	
18-7-18 20:18	K4-BE	783			1		0.023	
18-7-18 21:37	J6-A-Markham	929 - 2137	0.9	1.4	9	51%	9.9	
18-7-18 23:58	K4-BE	802 - 1303	0.1	0.0	2	19%	0.023	
19-7-18 02:02	K4-A	4503	2.6	2.6	1		0.04	
19-7-18 06:42	K13-A	825	0.5	0.5	1		12	
19-7-18 12:37	P11b-De Ruijter	1000 - 1600	0.15	0.055	4		1.8	
19-7-18 14:35	P11-E	652 - 817	1.1	1.1	1		6	
19-7-18 15:57	P15-D	1123 - 1776	2.1	1.3	7	23%	4	
19-7-18 18:52	P09c-A	565 - 1333	0.6	0.3	4	22%	0	
19-7-18 20:23	P06-D	736	0.3	0.3	1		0	
19-7-18 20:44	P06-A	669 - 2391	3.9	4.0	6	42%	0.02	
19-7-18 22:43	Q01-Helder	909 - 3113	9.6	8.2	8	30%	0.4	
20-7-18 00:05	Q1-D	1942 - 7188	0.8	0.8	1		0	
20-7-18 03:20	Q04-C	679 - 1942	1.4	1.2	4	41%	0.2	

*the red platform labelled indicate the set of platforms for which the inversion layer height turned out to be too low during the experiment.

Results November experiments

Table 3 Results CH_4 measurements November campaign.

NOVEMBER	Platform	Distance	Avg gCH4/s	Stdev gCH4/s	N	std err	Operator estimate gCH4/s	Class
15-11-18 02:30	K15-FG-1	500-1000	1.9		1		0.005	
15-11-18 02:36	K12-B	500-1000	1.1	0.3	3	20%	6.16	
15-11-18 07:00	K5CC	100-2500	14	13	12	27%	14	
15-11-18 10:59	K4-A	500-1300	2.0		3		0.04	
15-11-18 13:00	K2b-A	100-2000	6	2	22	8%	1.6	
15-11-18 19:35	K6-D	750	0.6		1		0.08	
15-11-18 20:01	K6CC	500-1100	3.6	5	5	62%	26	
15-11-18 21:44	K09c-A	2782	42		1		1.45	
15-11-18 21:44	L4-A	500-1000	19	19	5	45%	2.8	
15-11-18 23:56	L05-FA-1	500-800	1.7		1		2.6	
16-11-18 01:41	L5a-D	500-1000	9.8		2		0.04	
16-11-18 13:50	L08-P4	100-2000	17	5	3	16%	2.6	
16-11-18 15:43	L10-B	1000	0.6	13	1		0.03	
16-11-18 16:30	L10-E	500-1000	0.2		1		0.03	
16-11-18 16:59	L10-A	500-1000	21	19	5	40%	28	
16-11-18 19:20	L10-M	700	0.01		1		0.01	
16-11-18 19:47	K12-G	600	0.01		1		0.01	
16-11-18 20:23	K12-B	500-1000	0.8		3		4.57	
17-11-18 10:09	K14	100-2000	35	10	16	28%	26	
17-11-18 16:39	K15-FB-1	100-2000	18	9	10	16%	19	

Benzene

A part of the benzene measurements data are available (Table 19). For the July campaign, benzene concentrations taken with gas flasks and measured with a BTX monitor ranged from 0.03 µg/m^3 to 1.21 µg/m^3. The background concentrations ranged between 0.03 µg/m^3 and 0.06 µg/m^3. For the second campaign, mixed samples taken with TENAX tubes resulted in benzene concentration of 1.3 µg/m^3 to 5.1 µg/m^3 within the 500 m zone and 1.2 µg/m^3 to 2.6 µg/m^3 outside the 500 m zone. Next to these samples, data of the mini-DOAS providing open path benzene measurements were collected, but this method is still in a developing phase. Further study is needed to process these data.

Conclusions

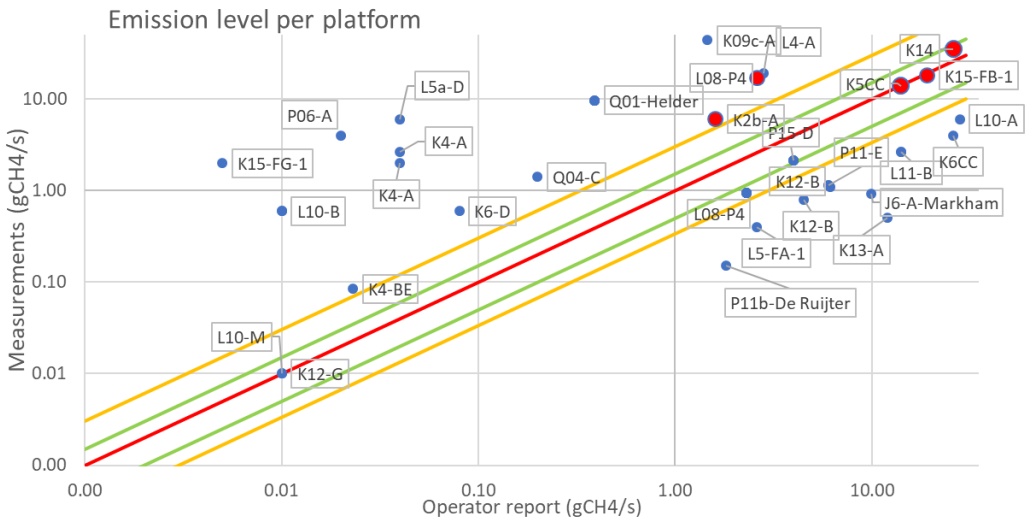

Figure 1 Platforms methane emission measurement versus operator methane emission calculation.

In Figure 1 all methane emission results are plotted in one graph with the emission level derived from the measurements plotted versus the value reported by the operators. The red line shows the 1:1 ratio, points above this line indicate that the measured emission is higher compared to the operator estimate, below the red line the measured emission is lower compared with the operator estimate. The green lines show a plus or minus 50% difference between the two estimates. The orange lines show a difference of a factor of 3.The conclusion from Figure 1 is that there are both platforms with higher methane emissions and platforms with lower emissions when operator and measured estimates are compared (Figure 1).
Another way to assess the same data is to add up all emissions estimated from the measurements and compare that with the same data for the operator estimated values. This is shown in Figure 2.The total estimated emission for 32 platforms for both cruises ends up at 152 gCH_4/s based on the measurements and 139 gCH_4/s using the estimates provided by the operators. Given the uncertainty in the measurement bases emissions (10-40% random error and a potential non-random error in the order of +/- 50%) the conclusion is that these two levels are similar.

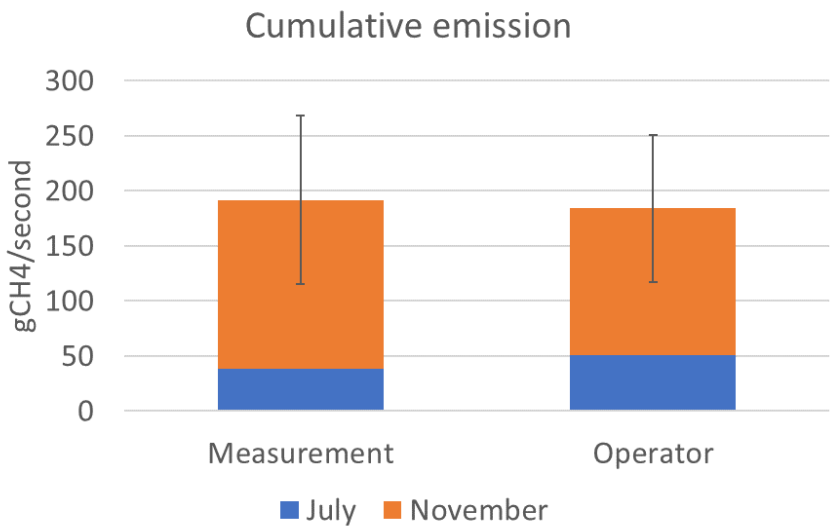

Figure 2 Emission for all platforms together for July (blue) and November (orange) campaign added up using the measurement based estimated (left and the operator provided estimates (left).

There are some considerations to take into account while making this statement:

- It has to be noted that with the measurements a plume can be missed (passing over the ship for example) but will not be generated in the data when there is no plume. In other words, the measurement dataset shows a minimum level for the emission rather than a maximum level.
- The measurement based estimates require the atmospheric dispersion model to translate the measured concentration levels in the atmosphere (in ppb or ng/m^3 CH_4) into emissions (in gCH_4/s). Sets of plumes together using different conditions (mainly different distances) show that this method has a random uncertainty in the order of 30% (for >3 plumes). This however does not cover systematic (non-random) errors that can be made when setting the constants and factors used in the dispersion parametrisation calculation. The N_2O tracer experiments were designed to overcome that problem. Successful tests show that the emission can be under- or overestimate somewhere in the order of 40% for a platform. Where concentration at valves and the emission numbers can result in a factor 10 uncertainty, 40% uncertainty is reasonably good. When adding up results for multiple platforms that error can be different per platform and thus become a random issue again. With only 5 release tests there were not enough statistics to make that claim.
- The “unsuccessful” tracer experiments (the ones that seem to be messed up when hot CO_2 plumes mix with the cold N_2O tracer plumes) can show a mismatch between measured and modelled plumes that can easily be in the order of a factor 10. That implies that when the CH_4 plumes obtained from the measurements are evaluated as cold plumes but were in fact modified by the hot CO_2 plumes, the measurement based emission could be significantly higher. This problem might occur for a subset of all platforms measured (the ones with significant fuel use and CO_2 generation and a wind direction that makes the hot and warm plumes overlap.

Contents


PL-K2b-PA

1 Introduction

1.1 Background

Methane is a potent greenhouse gas with an equivalent greenhouse warming potential of 25-35 of CO_2 equivalents. There is an increasing regulatory effort to reduce methane emissions, including methane emissions from natural gas production. Also under the CCAC Oil & Gas Methane Partnership actions are taken to accelerate the reduction of methane emissions.

One of these actions is the quantification of the methane emissions, including the contribution of oil and gas production. Oil and gas operators in the Netherlands report their annual methane emissions already for more than 20 years, using a combination of measurements, emission factors and process simulations. It appears that the reported emissions are significant lower than the assessment of the average loss of methane in oil and gas production worldwide. This has resulted in questions in the Dutch parliament in 2017 about the accuracy of the reported figures.

Therefore NOPGEPA has started a methane reduction project, which consists of several sub-projects:

1. Update methane reporting guideline;
2. Emission measurement to verify independently methane emissions;
3. Methane emission reduction.

Independent measurements were commissioned in 2016-2017 by SSM (State Supervision of Mines) on land locations, using vehicle based measurement equipment to measure the methane concentration in the air down wind and up wind of a gas production/processing site (ECN-E--18-032 and TNO 2019 R10332). Using this data the actual methane emission in kg/s can be calculated based on the concentration difference in the air. This method is internationally used to measure the methane emissions of all kind of sources. Recently a NGO (Environmental Defense Fund (EDF)) has started a measurement campaign on the North Sea, using an airplane equipped with similar measurement equipment.

Based on these experience, a vessel based methane measurement campaign was commissioned by NOGEPA on the Dutch sector of the North Sea.

1.2 Aim of measurements

The purpose of this measurement program is to independently assess whether the methane emissions as reported in accordance with requirements (e-MJV) are in line with the results obtained via concentration measurements.

The primary aim was to independently assess total methane emissions of a, partially selected, partially ad random, group offshore oil and gas platforms in g/s using concentration measurements at multiple distances from the source in combination with meteorological conditions and dispersion calculations.

Secondary aims are:

- Compare the overall methane emission in g/s: the reported methane emissions obtained from the operators to the calculated methane emission of the platforms during the measurements;
- Assess differences in overall platform emissions and effectiveness of already implemented methane reducing measures;
- Assess contribution of methane emission from sea water, including screening of potentially leaks from sea bottom;
- Measurements of other relevant emissions (NOx, benzene, PM)

As the purpose of the measurements is independent verification of the methane figures, SSM has requested NOGEPA to conduct the study. NOGEPA has assigned TNO as contractor to carry out the measurements in line with methane measurements carried out near onshore gas production locations in 2016-2017.

The former ECN team that performed the experiments has a long track record for greenhouse gas emission studies. The program for this campaign builds on the expertise collected over the last 20 years. ECN has carried out this kind of studies for several national and international projects looking at landfills, farm methane emissions. The ECN team became part of TNO by April 2018. The program is developed in cooperation with and with input from representatives from NOGEPA and operators which is essential in order to have access to the platforms, being able to enter the 500 m safety zone when necessary etc.

- NOGEPA has provided for the vessel for the measurements.
- During the measurements the platforms had to be in normal representative operating mode, this was coordinated with the different operators.
- All research methods and equipment were prepared and arranged by TNO with additional equipment provided by University Utrecht and KNMI.
- During the first campaign the platforms were selected to provide a spread of offshore installations (main platforms and satellites, oil producing installations and gas producing installations, installations with and without major refurbishments for methane emission reductions). The route was developed to allow for as much as possible measurements within the defined time frame of three days, at random platforms were visited along the main route depending on the actual wind direction and ship track.
- For the second campaign the selected platforms were five main gas producing installation, where tracer gas releases could take place. The route was developed to allow the possibility to do the measurements of the five main platforms in different order, depending on the weather conditions.
- In addition to the TNO crew, the independent cross check of the methods and site selection is done by SSM, in charge of enforcement of environmental regulation of oil and gas sector emission legislation. A PhD student from University Utrecht/TNO has participated and will use the data for publishing. The Environmental Defense Fund (EDF) was also invited to provide input in the setup of this proposal. SSM has verified the conditions under which the measurements are taking place.
- The results of both measurement campaigns will be published in a peer reviewed report.

1.3 Emission sources and measurement techniques

Methane emissions from offshore facilities originate from different types of sources:

- HP stack, usually high sources (45-100 m above sea level)
- LP stack, usually high sources (35-80 m above sea level)
- Local vents (seal gas, glycol units) are deck level (25-35 m above sea level)
- Fugitive emissions (spread over the process area, 15-25 m above sea level)

Based on literature, there is no easy technique to establish the overall methane emissions from the combination of this type of sources. Several measurement method can be used to quantify the emission from a complex source like a platform. Using a combination of different emission measurement and modelling tools allows for a reduction of the uncertainties in the final reported emission. The following techniques are used in this project:

1. Flow meters inside plant;
2. Modelling;
3. LDAR program (Leak detection and repair program);
4. Emission measurements combined with dispersion calculations.

NOGEPA has developed a Protocol for the determination of methane emissions (Table 4). For each emission source, methods for the determination of methane emissions are listed (in order of preference). Operators use the Protocol to determine the methane emissions of offshore platforms. These emissions are recorded in emission registration systems (a legal requirement). SSM supervises the implementation of the emission registration systems by the NL operators. Operators are also required to report methane (and other) emissions to authorities annually. SSM also supervises these annual reports (electronic annual environmental report, e-MJV).

The methods applied by operators to establish methane emissions can be summarized as listed in Table 4.

Table 4 Methods to establish methane emissions.

e-MJV category	Reporting method sequence	Description
CH_4 emissions from combustion installations	Measurement	Measurement of CH_4 in flue gas
	EPA emission factors	EPA 42 tables 4-7/4-9
CH_4 emissions from flaring (flow measurement – feed to flare stack)	NL national guideline on emissions	Design efficiency 99%
	EPA emission factors	EPA 42 table 4-11
CH_4 emissions from venting (channeled gas flows to vent)	Measurement	Thermal metering, pressure difference measurement, ultrasonic
	Modelling	Modelling based on operator specific programs or Pro II / Unisim
	Calculation	Calculation based on volume, pressure and locally determined gas composition
CH_4 emissions from diffuse emissions	Leak-no leak approach	Dedicated maintenance program
	Differentiation based on emission factors	Emission factors for different types of equipment
	Measurement	E.g. FLIR-camera, ultrasonic. TVA

The measurement program will assess whether the methane emissions as determined by the NL operators, using the CH_4 emission protocol (bottom up approach), are comparable with the emission levels established on the basis of concentration measurements (top down approach).

1.4 Two campaigns

This report will describe the set-up and results of two measurement campaigns. The first campaign was from 17 to 20 June 2018 and the second campaign was from 14 to 17 November 2018. Lessons learned from the first campaign were taken into account to improve the second campaign.
The measurement campaigns were developed using the experience of SSM and TNO and were based on the methane emission measurement program of oil and gas production or storage facilities carried out onshore in 2016-2018 (ECN-E--18-032 and TNO 2019 R10332) and earlier projects for different source types like landfills and dairy farms.


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2 Offshore Methane Emission Campaign

2.1 Plume measurements method - theory

Methane sources like platforms have a complex spatial distribution of the source strength within a confined area. These sources can be evaluated with plume measurements techniques. These techniques evaluate the concentration plume that originates at the source and is transported with the wind (Czepiel et al., 1996, 2003, Tregoures et al. 1999). On a transect crossing the wind direction the concentration is measured. Meteorological data (wind speed, wind direction, turbulence) and a transport model are used to calculate the emission level from the observed concentration pattern. Using the tracer release (see from within the source area, enable a dual tracer measurement or to calibrate the transport model (Hensen et al, 2012).
When the spatial distribution of a tracer source can be made “sufficiently” similar to the source distribution of the actual source, the dispersion function in both the equation for the tracer and for the source are equal. The limitation of this method lies in the term “sufficiently similar”. If the tracer only originates from a particular place within the source other parts of that source, not in the vicinity of the tracer might experience different dispersion effects. This problem decreases when the distance between source and measurement transect increases. The atmospheric dispersion model can help to provide a correction for a non-ideal tracer source distribution on the site. Drawback of the plume technique is that meteorological circumstances and logistics (availability of a measurement transect in a specific wind direction) dictate when measurements can take place (Hensen et al, 2012). For the platforms at sea, wind direction is not a problem, as the platform can be passed at all sides. Here the heat sources dictate when measurements can take place.

The measured concentrations in the plume transects were compared with the output of a multiple gauss plume model (Figure 3). Reflection of the plume at the ground level and the inversion layer were taken into account. The emission strength of the platform is equal to the source strength needed in the model to obtain an agreement between the integral of the concentration along the transect for the modelled and the measured plume (Hensen and Scharff, 2001).
The meteorological data (heatflux, wind speed, cloud cover) indicate the Pasquill stability class, but a check on this choice is recommended. Especially because the dispersion parameters over land might differ from the ones over sea.

A tracer, N_2O released from a gas cylinder on selected platforms, was used to evaluate the performance of the dispersion models. The QCL measured both the N_2O and CH_4 plume simultaneously. For the N_2O source, both position and source strength are known, and the horizontal dispersion σ_y is obtained. The model calculation for this plume can be used to check and if necessary to adapt, the dispersion parameters (Hensen and Scharff, 2001).

The uncertainty in the CH_4 concentration measurements is about 1-5% due to instrument noise, drift of the laser and uncertainty in the background concentration level. Changes in wind direction (on a timescale of 5-10 min) are the main cause for variation in the set of emission estimates. Furthermore, the emission of the platforms

is not constant over time and in order to obtain an annual average emission level, multiple measurements should be taken over the year (Hensen and Scharff, 2001).

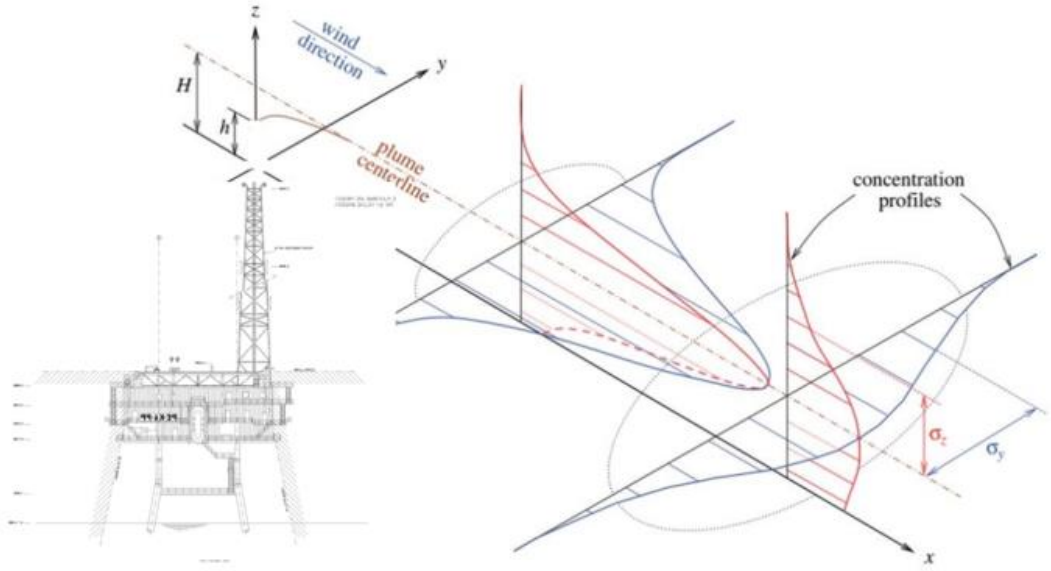

Figure 3 Schematic view of plume used for model.

The reported emission level at a particular platform is the average of a set of emission estimates for individual plume transects. Between 1-10 plumes are available for individual platforms. For the platforms with a tracer release > 10 plumes were measured for each of the two release tests done per location (see below). The standard deviation error of the estimates is reported (=standard deviation divided by the square root of the number of plumes used) this value is generally about 25% of the obtained emission with a range between 10 and 100% depending on the reproducibility of the plume measurement (and thus depending on platform layout etc.)

2.1.1 OCD model

The OCD model was developed in 1989 by Donald C. DiCristofaro and Steven R. Hanna. This Offshore and Coastal Dispersion (OCD) model was developed to simulate the effect of offshore emissions from point, area, or line sources on the air quality of coastal regions. The OCD model was adapted from the EPA guideline model MPTER (EPA, 1980). Modifications were made to incorporate overwater plume transport and dispersion as well as changes that occur as the plume crosses the shoreline.

The model runs on an hourly timescale and can thus not be used directly for the interpretation of the plume measurements obtained in this project, as a plume measurement takes a few minutes and is not a static measurement that allow for hourly averages. This model is a Gaussian dispersion model and parts of the model were incorporated in the Gauss-plume model that TNO is using. The model and the evaluation in the OCD documentation clearly shows that plumes over sea are more stable compared to plumes over land. This is well in line with what was observed. The measured plumes are slim (the plume stays in a small area

perpendicular to the wind), when compared what was expected when running the model as used over land.
Apart from modifications of the dispersion the OCD model describes the effect of plume rise and of the wake that occurs downwind of the platform. The model has a parametrization in which the effect of the building is parametrized as an extra contribution to sigmaZ and sigmaY of the gaussian dispersion formula. This effect depends on the building size versus the height of the stack from which the main emissions occur.

2.1.2 Procedure of the emission calculations

The plume evaluation procedure has several steps

- For all measurement data a running 10 percentile value is subtracted from the data to obtain the concentration - background level values.
- Raw data are processed, calibration corrected and shifted in time versus the GPS data in order to account for the delay of the gas in the inlet line system from the inlet to the measurement cell.
- In that data peaks are auto located that are above the selection criterion, for most platforms ethane is the best tracer to identify the plumes because the ethane background levels are more smooth compared to the methane background levels.
- The timeseries around the peaks is split into plume data blocks that each cover a single plume measurement.
- The plume model calculates a modeled concentration value assuming a source of 1 g/s at the position of the platform upwind of the measurement transect.
- This data is checked. If the measured and modelled plume show up at different locations, the model either used a wrong source location (the wrong platform, but this hardly ever occurs) or the wind direction as obtained from the general circulation model zoom-in needs adjustment.
- Wind direction is adjusted manually. Both model and measured plume are integrated. The ratio provides the emission in gCH_4/s.
- Important parameters in the model are the width and height of the plume, which are expressed in the sigma-Y (horizontal) and sigma-Z (vertical) variables used in the gaussian formula. Sigma-y is available from the measurements because the width of the plume is actually observed. (except for those cases when the plume is split into different small sub-plumes, see below). What is missing is the info on sigma-Z, the distribution of the plume concentration in the vertical. In normal conditions there is a more or less constant ratio between sigma-Y and sigma-Z. Both sigma-Y and sigma-Z depend on the distance and in theory with multiple plumes downwind of a platform sigma-Z can be partially solved. The other option is the N_2O tracer releases (see above).
- Effect of a mismatch
- When the model and measurement data are not correctly interpreted the calculation scheme will end up with an emission factor that is wrong.

2.1.3 Two examples of a plume measurements and calculation.

An example of the procedure is shown in Figure 4 for a plume originating from the K14 platform during the second campaign.

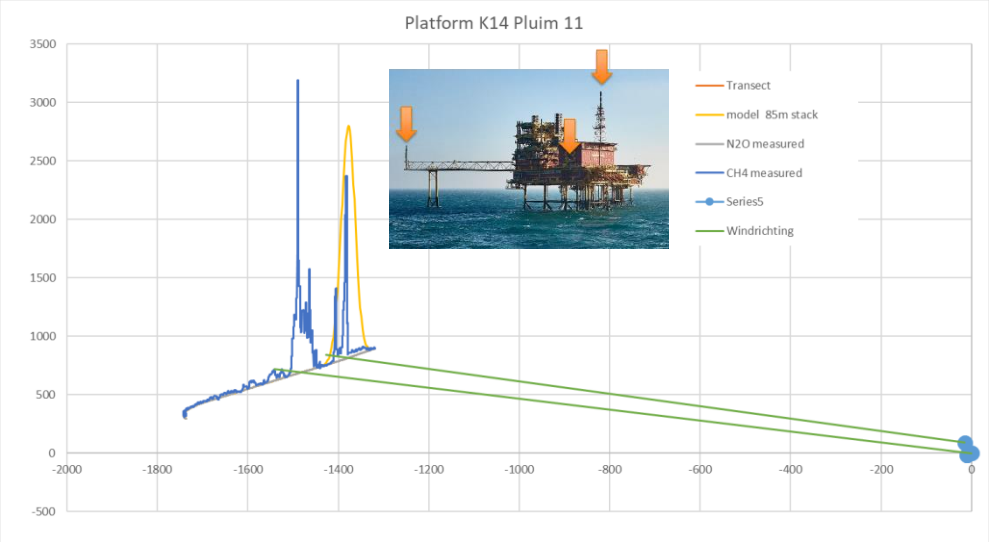

Figure 4 Example of a plume measurement at the K14 during the second campaign.

In this case the plume (blue line) shows two parts, one originating from the main platform and a second part from the vent on the boom extending in the sea. The green lines show the wind path on the map connecting the blue dots (platform) with the observed data. The blue line shows CH_4 measured, the orange line the model output for the vent stack using an emission level of 1 g/s.

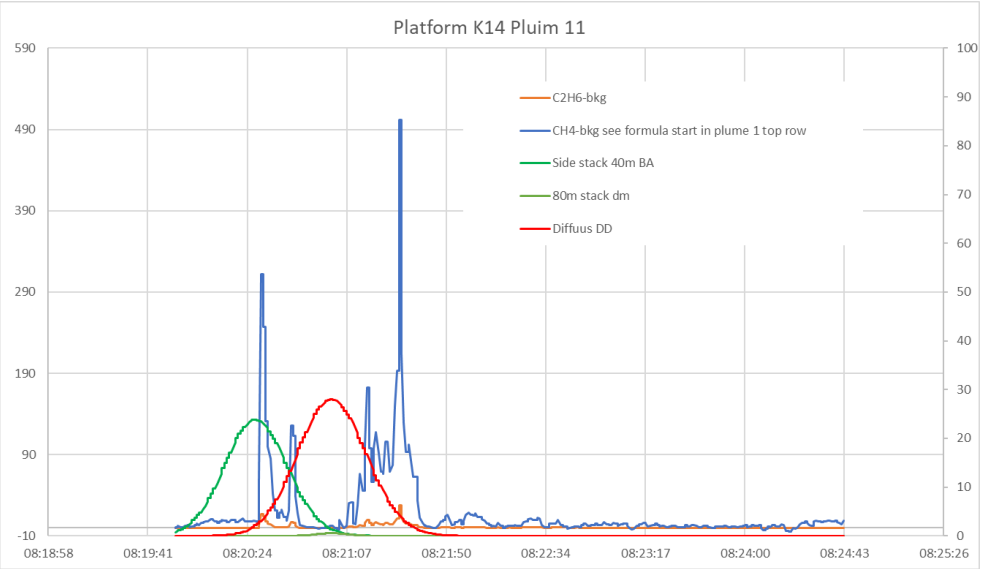

Figure 5 The same plume plotted versus time with both the model output for the platform (red) and for the vent stack (green).

The model plumes plotted in Figure 5 (red and green) show that the measured plume from the 40 m stack (left part blue) is narrower compared to the model plume, the plume width observed for the platform (right side blue) is more similar in width.

The red plume is a bit displaced versus the blue peak on the right, suggesting the wind direction should in fact not be 112 but 115 degrees. However for the emission calculation shown in the Figure 6 the difference is neglectable. Figure 6 shows how the integral of the measured peak and the integral of the modelled peak are compared to calculate the emission level.

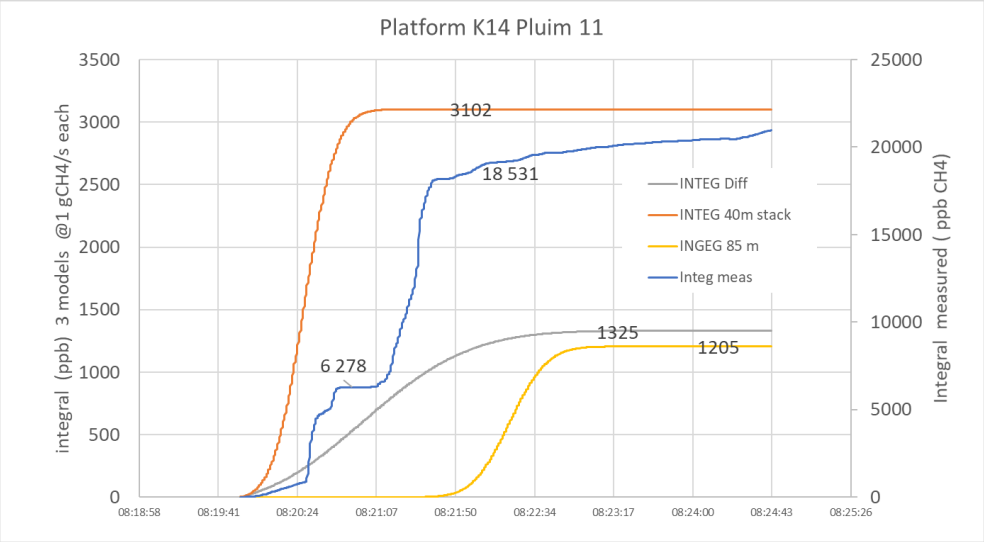

Figure 6 Example of measured and modelled plumes.

Figure 6 shows how the modelled and measured plumes are integrated versus time. The integral of the first plume in time gives 6278 ppb for the measurements, and 3102 ppb (orange) for the model run using 1 g/s CH_4 as input. This means that the emission estimated for the low stack for this plume is around 2 g/s (6278/3102)
The remaining part of the measurement integral (18531-6278) can either be explained by the grey curve, assuming all emissions originate at 40 m altitude on the platform or, using the yellow line, assuming that this CH_4 originated from the 80 m high stack. The difference between these two integrals (1325 and 1205) is relatively small, suggesting that the height difference in the model run is not that important here. This makes sense for a plume measured relatively far (1600m) away from the source. The ratio of about 12000/1200 suggests a source of around 10 gCH_4/s originating from the platform.

Plumes are not always be easy to evaluate, as shown in Figure 7.

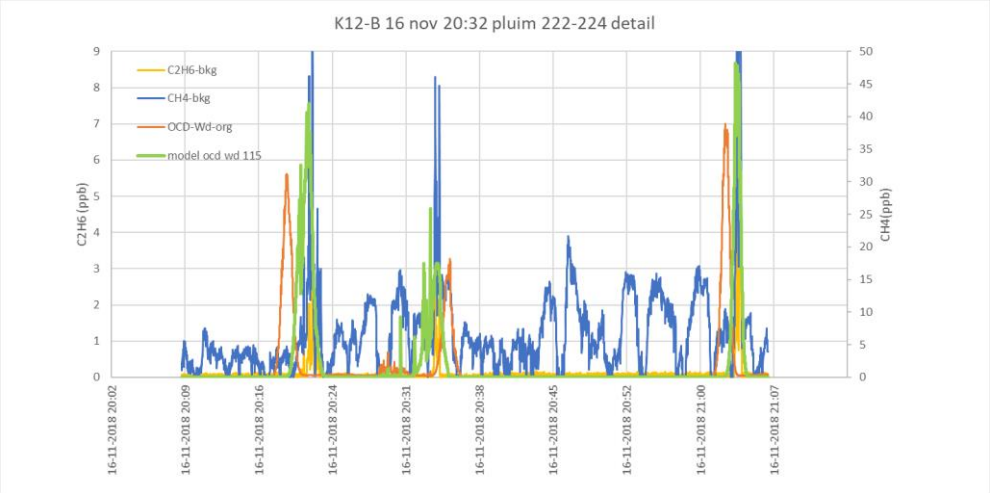

Figure 7 Three plumes observed downwind of the K12-B platform. The plumes are not big and the CH_4 variation is quite large compared to the plume peak concentration levels, (after subtracting the background concentration level of around 2000 ppb).

With C_2H_6 however the CH_4 plume from the platform can be separated from the variable background data, see Figure 8 below (yellow line). The red lines indicate the initial model run, using the measured windspeeds and wind direction onboard. The plumes end up in the vicinity of the measured plumes but not exactly on the same spot (and worse compared to Figure 5). If the background was as smooth as for C_2H_6 (orange) this would not be a problem, but now, for CH_4 it is important to get the modelled and measured plumes at the same position in order to do the plume integration well. The green line shows how the modelled plumes can match the measured plumes using a wind direction of 110, 120 and 115 degrees for the three subsequent plumes.

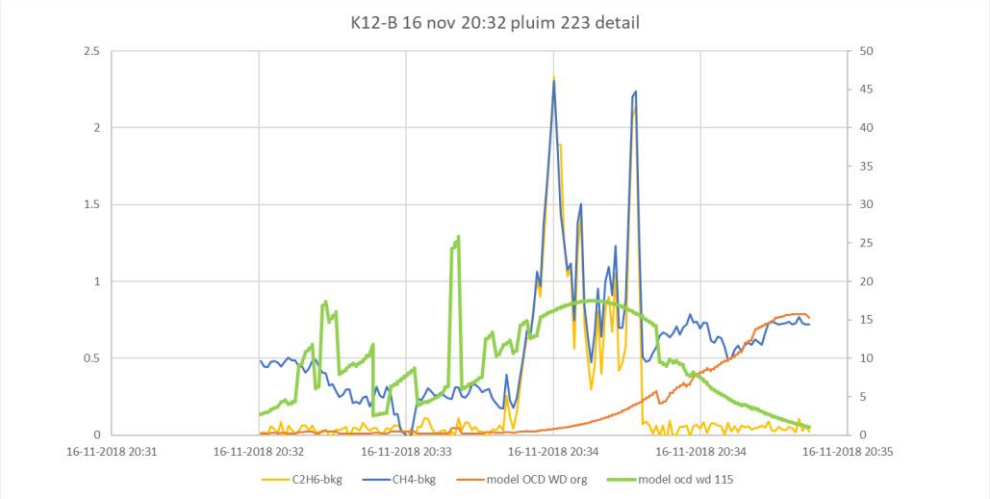

Figure 8 Example of measured and modelled plumes of platform K12-B.

The table below (Table 5) shows the effect of the analyses of plume 223 of platform K12-B. Using the first measurement with the average background subtraction (AUTO) and model integration with the average wind direction (ORG) a source strength of 3.2 gCH_4/s was determined. Subtracting another 10 ppb (based visual

estimation) or subtracting a 10 percentile value (4.6 ppb), the last method seems most robust, ending up with an emission level of 0.8 gCH_4/s.

Table 5 Platform K12-B:Horizontal, the integral values (ppb) for plume 223 for 4 model runs with different wind directions. Vertical the integral values (ppb) for the measurement with 3 ways of background subtraction.

K12-B plume 223		ORG	10 deg	20 deg	final
	Model (1g/s)	2286	4086	5721	5860
MEAS	Measure				
Auto	7325	3.2	1.8	1.3	1.3
Better	1115	0.5	0.3	0.2	0.2
10 Percentile	4498	2.0	1.1	0.8	**0.8**

A similar analyses for the other 2 plumes at this platform showed emission levels of 0.6 and 1.1 gCH_4/s respectively. In this case the average emission level using the automated method would provide 3.2 ± 1 gCH_4/s and the detailed analysis 0.8 ± 1 gCH_4/s

Sub plumes

Sometimes in the turbulent flow pattern the plume splits up into several sub plumes. When fast changes in windspeed and wind direction are used in the model the sub plumes will also be observed but that pattern will be different from the measured pattern. The Gaussian plume model (and in fact no model without a lot more on site meteo info) however cannot simulate these patterns well. So the model pattern should not be compared in detail with the measured pattern.

2.2 Instrumentation

A mobile laboratory that houses all relevant instrumentation was placed on board of an offshore-support vessel (Figure 9).

Figure 9 Measurement trailer on flatbed (left), the inside is shown on the right.

2.3 The vessel

The campaigns have taken place on an offshore supply ship that is allowed to enter the 500 m zone.

2.3.1 Campaign 1 - July

The first campaign took take place on the Pool Express, an offshore supply ship with a length of 72 m and 16 m width (Figure 10; http://www.skipslistene.no/samples-filer/Pool%20Express%20-%20K138821.htm)

Figure 10 Supply vessel Pool Express (Vroon Offshore Services B.V.).

2.3.2 Campaign 2 - November

The second campaign took take place on the Vos Base (sister ship of Pool Express), an offshore supply ship with a length of 72 m and 16 m width (Figure 11; https://www.vroon.nl/Files/VesselParticulars/VOS%20BASE20170809011351.pdf)

Figure 11 supply vessel Vos Base (Vroon Offshore Services B.V.).

2.4 Measurement method

All measurements were done on the vessel. Instruments were present in the trailer that was placed on a flatbed on deck (Figure 9).
The primary measurements were:

- $CH_4/C_2H_6/N_2O$ measurements from air (Aerodyne QCL-ILC spectrometer; Figure 12 + 2 Picarro CRD)
- CH_4 measurements for emissions from the sea water (Pulsed QCL spectrometer; Figure 13)
- Windspeed/direction
- GPS/AIS data collection

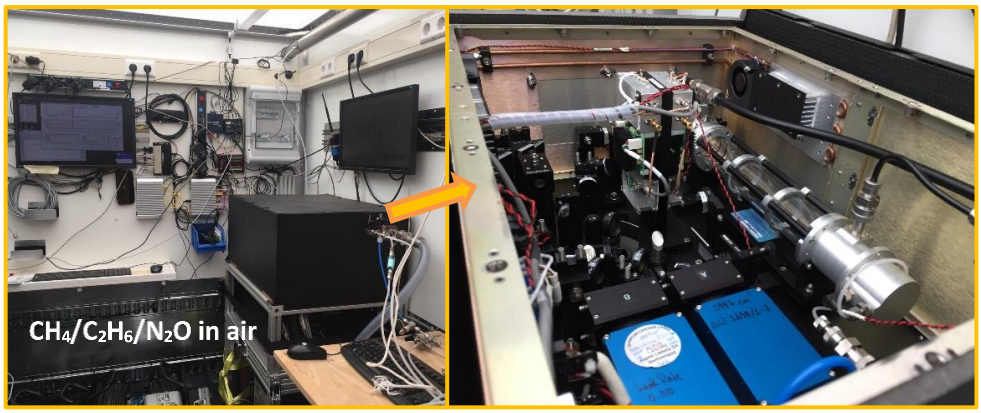

Figure 12 Aerodyne QCL-ILC spectrometer for $CH_4/C_2H_6/N_2O$ measurements from air.

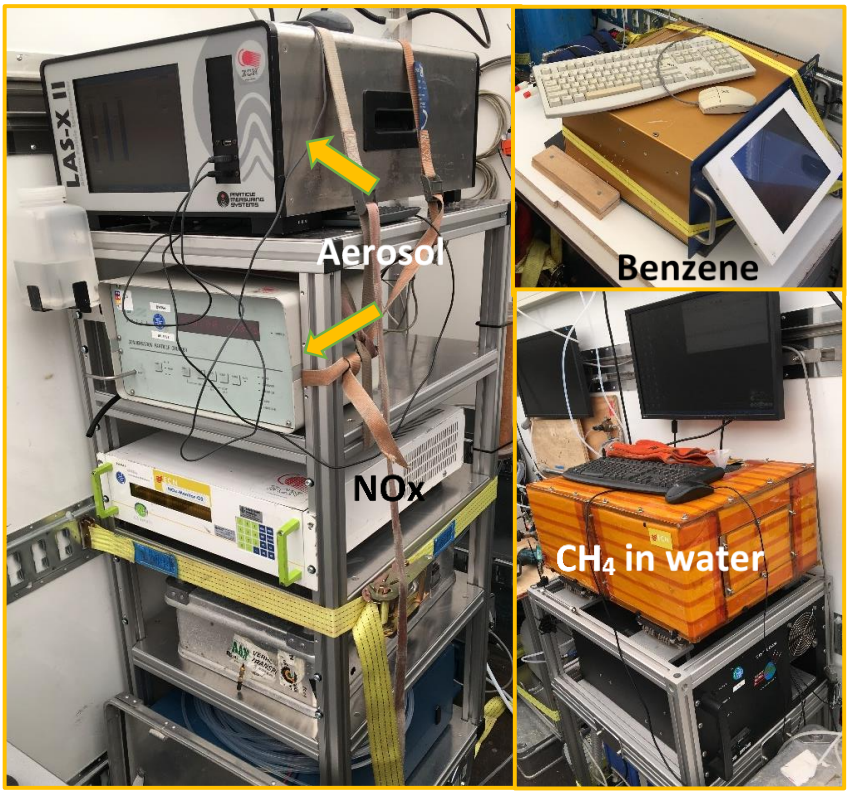

Figure 13 Measurements instrument for aerosol, NOx, benzene and CH_4 in water, present in the trailer on board.

Additional measurements on board covered (Figure 13):

- NOx (Eco Physics)
- Aerosol (particulate matter)
- Benzene

Gas inlets for the GHG and NOx measurements were fixed at the top of the ship, in front of the outlet to avoid contamination by the ship exhaust. For aerosol measurement a single inlet on top of the trailer is used because these components do not allow for long (untraced) inlet lines.

On approach of a target location (platform) the ship is moved to the leeside of the source and scanned the plume multiple times and multiple distances. Depending on the weather condition and the resulting plumes, the number of transects measured was determined.

The trailer instrumentation was linked to a computer that was placed on the bridge, facilitating communication between the measurement operators and the ship-crew.

To assess methane emission from sea, a large pump continuously filled a water container on deck, from where a smaller pump filled a container in the trailer. In the headspace of this container, the gas measurements were performed with a pulsed QCL spectrometer (Figure 14 and Figure 15).

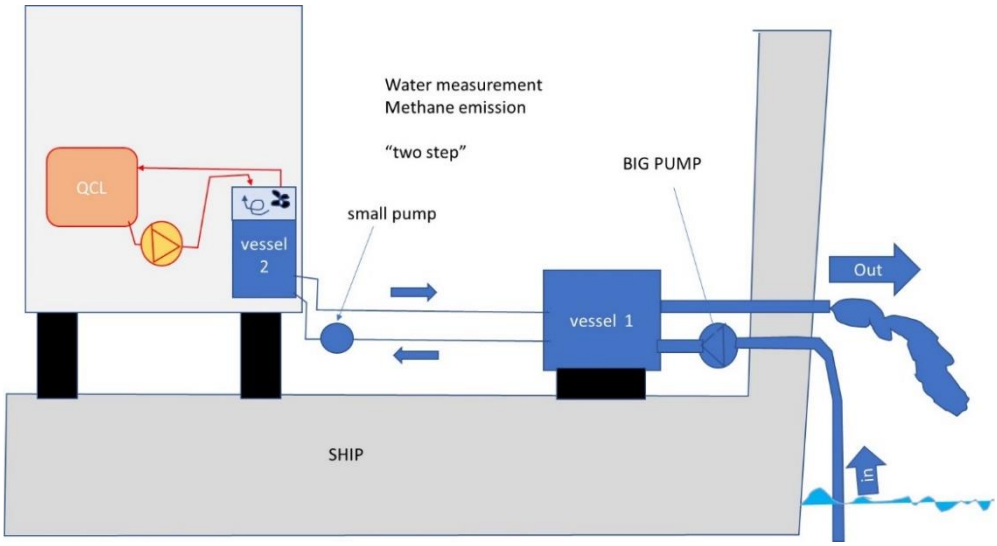

Figure 14 Schematic view of set-up to measure CH_4 from water.

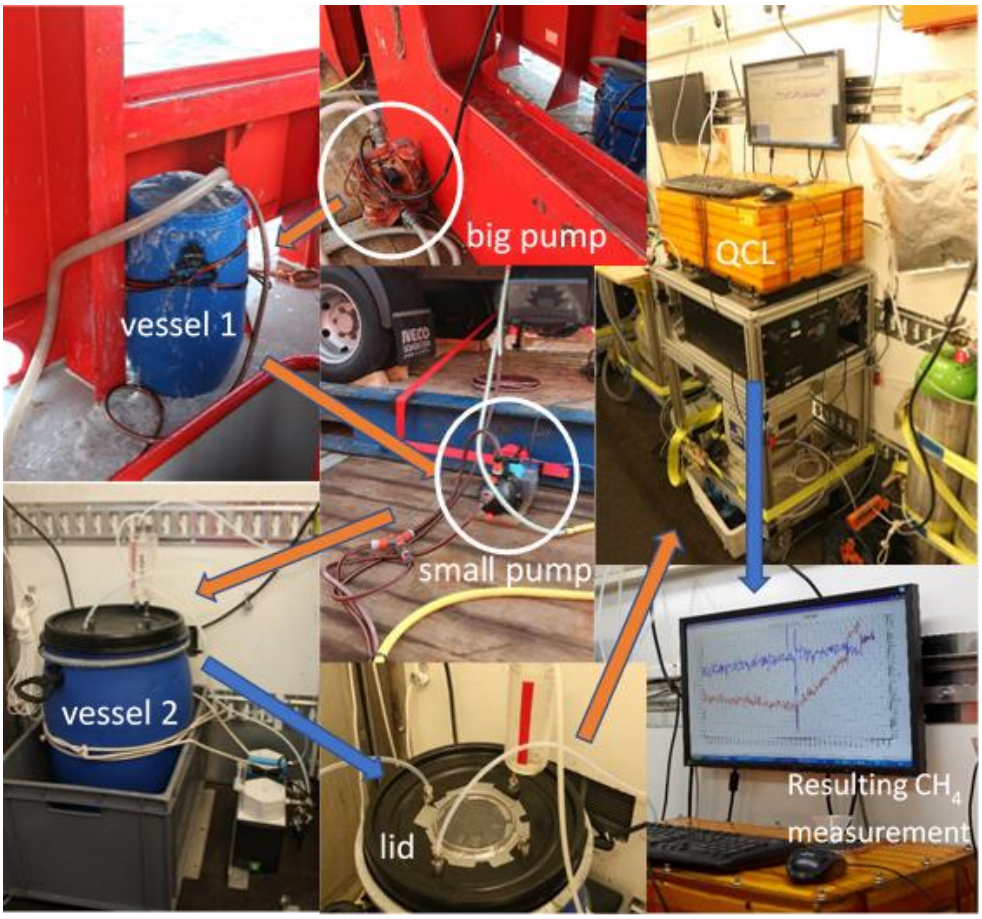

Figure 15 Pictures of the water sampling and measurement route.

Calibrations:

Instrument calibrations for CH_4 and N_2O were performed with a known amount of calibration gas. The gas cylinders used were intercalibrated versus international standards at the Cabauw atmospheric GHG station. This took take place inside the trailer (Figure 16).

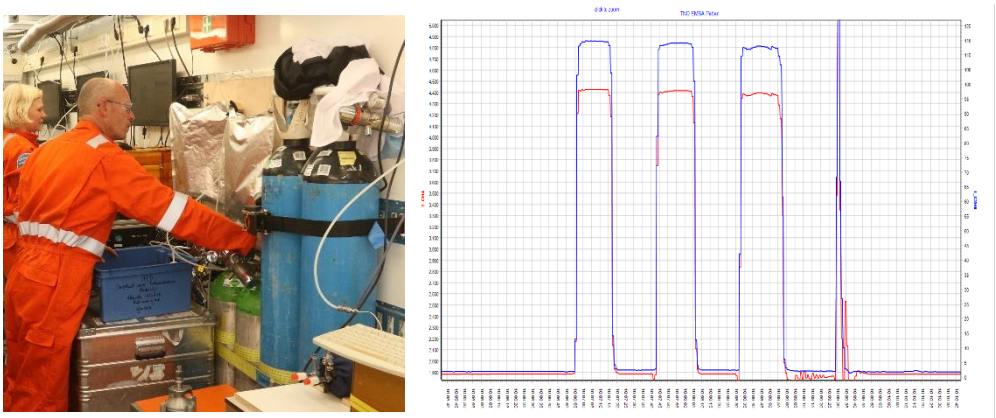

Figure 16 Calibration activity during the measurement onboard (left) and a resulting measurements for CH_4 and C_2H_6 (right).

2.4.1 *Campaign 1 - July*

During the first campaign, the top inlet, used for GHG and NOx was first fixed at 26 m and later at 35 m above sea level. Apart from the top inlet, there were two inlets on deck at starboard and portside at 10 m above sea level for GHG and NOx, together with a windsonic for meteo data. The aerosol inlet was fixed on top of the trailer on deck because aerosol measurements do not allow for long inlet lines. Apart from that with the GPS/AIS measurements were done. Another windsonic was placed on top of the bridge at the front side of the vessel.

2.4.2 *Campaign 2 – November*

During the second campaign, only a top inlet was used and fixed at 35 m above sea level for GHG and NOx. The aerosol inlet was fixed on top of the trailer on deck, together with the GPS/AIS measurements. The windsonic was placed on top of the bridge at the front side of the vessel. Here, also NO_2 instruments from KNMI were installed (max-DOAS for total column NO measurements and NO_2 sensor that is also used as balloon sonde for profile measurements).

2.5 N_2O tracer release

To enable evaluation of the performance of the dispersion modelling an N_2O tracer release was used in both campaigns. Based on the measured N_2O concentration and the known discharge rate of the tracer gas, the dilution factor between source and measurement location is simulated by the atmospheric dispersion model. Assumption is that the tracer gas follows the same route and is exposed to the same dilution (from discharge up to the analyzer) as methane.

2.5.1 *Campaign 1 – July*

During the first campaign, two N_2O release sets were used at the platforms K5 and K14. These sets were sent to the platform on an earlier shipment (Figure 17).
Each set consisted of:

- 5 B10 cylinders with 7.5 kg N_2O each and weight of approximately 20 kg/cylinder.

- Two zagres boxes of about 60*40*45 with a pressure regulator, critical capillary attached to two flowmeters and an outlet hose.
- Spare parts: extra critical capillaries, extra connection materials
- A fill in table is provided with the release set
- Each 10 minutes pictures are taken.

Two subsequent tracer experiments were done.

Figure 17 Example of the N_2O release; left insert shows the flowmeters; right insert shows the pressure regulator and critical capillary.

N_2O Experiment 1

Two sets of cylinders and release control boxes injected their combined output into the vent of the platform. The cylinders were fixed and placed in a tank with water (because they cool and tend to freeze when releasing the gas). After the pressure regulator, 2 mm capillaries were used to control the flow and this was measured with flowmeters. Both sets were set to (about) 2 g/s N_2O emission.

With 7500 gram of N_2O available in the cylinder this emission can last for about 1 hour (7200 g used). The flow meters were checked every 10 minutes to make sure the outflow of gas was constant.

- A fill in table was provided with the each release set
- Every 10 minutes pictures were taken

The fill-in form was delivered together with the release system and send back to Petten after the experiment.

N_2O Experiment 2

One set (cylinder + regulator box) was used. The same procedure as experiment 1, was applied. It was originally thought to exchange the critical capillary with a 1.1 mm capillary but in the end this was not done. A release of about 1 g/s was foreseen at the lee side of the platform.

2.5.2 Campaign 2 – November

During the second campaign N_2O releases were done at 5 platforms (K5CC, K2b, L08-P4, K14-FA-1, K15-FB-1). These were brought to the platform with the supply vessel along with the measurement trailer.

The N_2O release set was allocated in a container and at each platform the set was hoisted to the platform from the vessel with a crane (Figure 18).
The 5 ft container contains 6 B10 cylinders pure N_2O, each of these cylinders will have a pressure reducer to provide 3 bar output to a critical capillary which is designed to produce 0.6 g N_2O/second. The cylinder were mounted in the water vessel to provide heat to the adiabatic expanding N_2O gas.

Figure 18 N_2O release set in 5ft container (left), hoisting of container (right), insert shows the 1" hose.

Each cylinder was then able to produce a continuous N_2O flow during 1.5-2 hours. Gas flowmeters were located after the critical capillary to register the flow every 10 minutes. After the flowmeter a 50 m long 1" hose was used to bring the gas to the release point. This hose was either lifted by the crane as high as possible (experiment 1), to simulate high located emission or led lowered to a nearby location where the gas was released from the leeside of the platform at the process area (experiment 2). The hose was provided in a separate hoisting basked.
Handling of the cylinders and release of the gas was done by operators of the platforms, based on specific instructions from TNO. Communication with the vessel went via VHF.

N_2O Experiment 1 "high altitude release"

The 4 cylinders (1-4) were already connected to the flowmeters via the reduces with 0.9 mm capillaries and already placed in the (warm) water container.

- The hose was hoisted up with the crane as close as possible to the main vent stack and visual check was done to ensure there were no blocks/ twists in the hose.
- The hose was connected to connector 1 in the container (with a quick-connector).
- All sets were set to release 0.6 g/s N_2O emission (3 bar).
- After checking the N_2O cylinders were opened and the start time per cylinder was written down in the logbook.

With 7500 gram in the cylinder this emission could in theory last for about 2 hours. The flow meter was checked every 10 minutes to check the constant output level.

- A fill in table was provided with the set.
- Each 10 minutes pictures were taken.
- 4 cylinders (1-4) were used per platform for this experiment

N_2O Experiment 2 "low altitude release"

The procedure was very similar to experiment 1.
The 2 cylinders (labelled 5 and 6) were already connected to the flowmeters via the reduces with 0.9 mm capillaries and already placed in the water container.

- The hose lead the gas to a nearby location where the gas can be released from the leeside of the platform at platform height (process area).
- The hose was connected to quick-connector 2 in the container.
- All sets were set to 0.6 g/s N_2O emission (3 bar)
- After this check the N_2O cylinders are opened and the start time per cylinder is written down in the logbook.

With 7500 gram in the cylinder this emission can last for about 2 hours. The flow meter will be checked every 10 minutes to check the constant output level.

- A fill in table was provided with the set.
- Each 10 minutes pictures were taken

2.6 Other component measurements

Both greenhouse gas and additional measurements were performed during the two campaigns:

Methane / Ethane

Ethane is a good indicator of the origin of the methane. Whenever methane originates from oil/gas production, the ethane concentration will show a very similar spatial profile as the methane concentration. Methane from biogenic origin has no ethane component and can be identified as not natural gas production related.

Emissions from water surface

Based on previous measurements (Hensen et al., 2018) it is known that methane form the sea bottom (either from biogenic or thermogenic source) can contribute to the observed concentration levels. It is possible to measure the methane emission from the sea water during the vessel trip by pumping sea water into a container and measure the methane equilibrium concentration in the head space of this container.

The expectation was that the biogenic methane emission are mainly observed close to the coast in shallow water. However, this has never been checked and as the vessel was available for the cruise, it was decided to run these experiments in addition to the plume measurements.

Benzene

The two main sources of benzene emissions at the platforms are
1) High pressure and low pressure vents and
2) Glycol regeneration units (that most of the time is let through a low pressure vent).

Benzene is one of the substance of natural gas. The concentration varies per source. With the production of natural gas, a large part of the benzene will be separated and follows the route of the natural gas condensate. With the combustion of natural gas for generation of energy, uncombusted benzene is released, but the major part is converted to CO_2 and H_2O.

NOx, aerosol (PM), CO and CO_2
These components are mainly emitted from the exhaust of gas turbines, gas motors, diesel engines and the OVC (Overhead Vapor Combustor) unit.

Mercury
Mercury is often present natural gas. Therefore, in the first campaign, water samples were taken when sailing through the wastewater stream of several platforms (L10-A, K14, P11, P15 and P9). All samples were below the detection limit of 6.5 ng/kg.

The data for benzene, NOx and aerosol are not evaluated in this report, but are available for further research.

2.6.1 Campaign 1 – July

Aerosol measurements were done with a CPC (condensation particle counter) and LASX (particle size distribution). Benzene was measured with a BTX GC-monitor from TNO Utrecht. This system needs 15 to 30 minutes per measurement. Gas bottle samples were taken from the plumes, as the direct air measurements could not directly relate emissions from the platform. Another photo ionization detector (PID; PI-101, HNU Systems) from TNO Utrecht was used as well for benzene measurements.

2.6.2 Campaign 2 – November

Aerosol measurements were done with a EPC (environmental particle counter). Benzene was measured with an open path benzene DOAS system developed by RIVM-ECN and with TENAX tubes.

2.7 Sailing plan

2.7.1 Campaign 1 – July

Table 6 shows the platforms that were planned to be measured. At K14 and K5 also N_2O release experiment were performed. If possible, platforms in between the scheduled platforms were also measured.

Table 6 Platform list and anticipated arrival times of the July campaign.

Date	Time	Facility name	Facility code	action	Operat
17-8-2018	18:00	Den Helder port		Leave	
	23:00	UN-L/11B-PA	L11b-PA	Arrive	ONE
18-7-2018	24:00:00	UN-L/11B-PA	L11b-PA	leave	
	01:00	L10-AP	L10-AP	Arrive	Neptune
	02:00	L10-AP	L10-AP	leave	
	03:00	K15-FB-1	K15-FB-1	Arrive	NAM
	04:00	K15-FB-1	K15-FB-1	leave	
	05:00	K15-FC-1	K15-FC-1	Arrive	NAM
	06:00	K15-FC-1	K15-FC-1	leave	
	07:00	K14-FA-1C	K14-FA-1C	Arrive	NAM
	11:00	K14-FA-1C	K14-FA-1C	leave	
	15:00	PE-K5-PK	K5-PK	Arrive	Total
	19:00	PE-K5-PK	K5-PK	leave	
	22:00	J6-A-Markham	J6-A-Markham	Arrive	Spirit
	23:00	J6-A-Markham	J6-A-Markham	leave	
19-7-2018	07:00	P11b-De Ruyter	P11b-De Ruyter	Arrive	DANA
	08:00	P11b-De Ruyter	P11b-De Ruyter	leave	
	09:00	P11-E	P11-E	Arrive	ONE
	10:00	P11-E	P11-E	leave	
	11:00	P15-C-PP	P15-Rijn-C	Arrive	TAQA
	12:00	P15-C-PP	P15-Rijn-C	leave	
	15:00	P06-A	P6-A	Arrive	Wintershall
	16:00	P06-A	P6-A	leave	
	19:00	Q1-Helder-AW	Q1-Helder-AW	Arrive	Petrogas
	20:00	Q1-Helder-AW	Q1-Helder-AW	leave	
	24:00:00	Den Helder haven		Arrive	

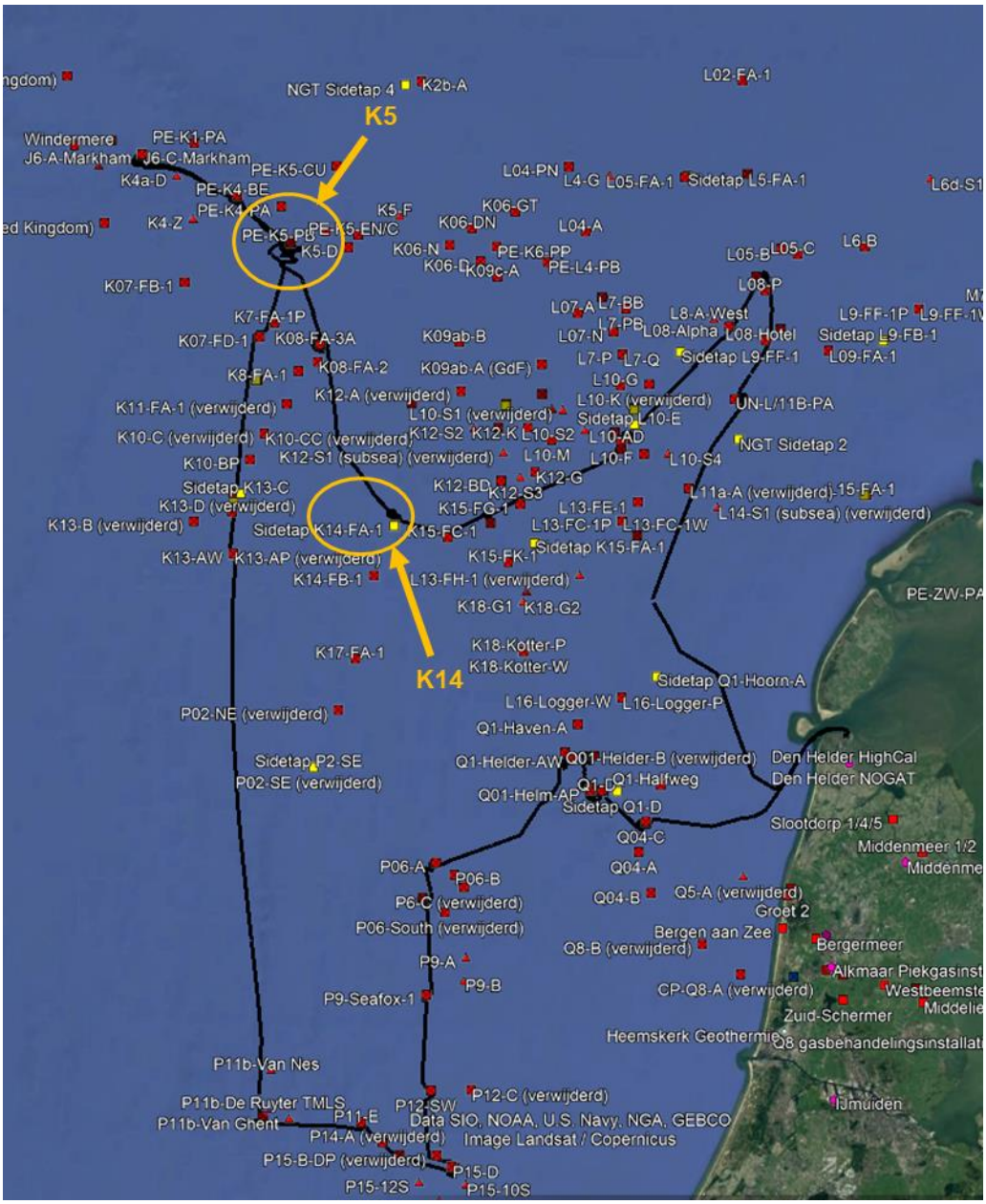

Figure 19 Sailing route of second campaign. The 2 platforms with N_2O release are indicated.

2.7.2 Campaign 2 – November

Table 7 shows the platforms that were planned to be measured. At all five platforms N_2O release experiment were performed. If possible, platforms in between the scheduled platforms were also measured.

Table 7 Platform list and anticipated arrival times of the November campaign.

Date	Time	Facility name	Facility cod	action	Operat
14-11-2018	19:00	Den Helder port		Leave	
15-11-2018	07:00	PE-K5-PK	K5-PK	Arrive	Total
	12:00	PE-K5-PK	K5-PK	leave	
15-11-2018	14:00	K2	K2	Arrive	Neptune
	19:00	K2	K2	leave	
16-11-2018	10:00	L08P4	L08P4	Arrive	Wintershall
	15:00	L08P4	L08P4	leave	
17-11-2018	07:00	K14-FA-1C	K14-FA-1C	Arrive	NAM
	12:00	K14-FA-1C	K14-FA-1C	leave	
17-11-2018	13:00	K15-FB-1	K15-FB-1	Arrive	NAM
	18:00	K15-FB-1	K15-FB-1	leave	
17-11-2018	22:00:00	Den Helder port		Arrive	

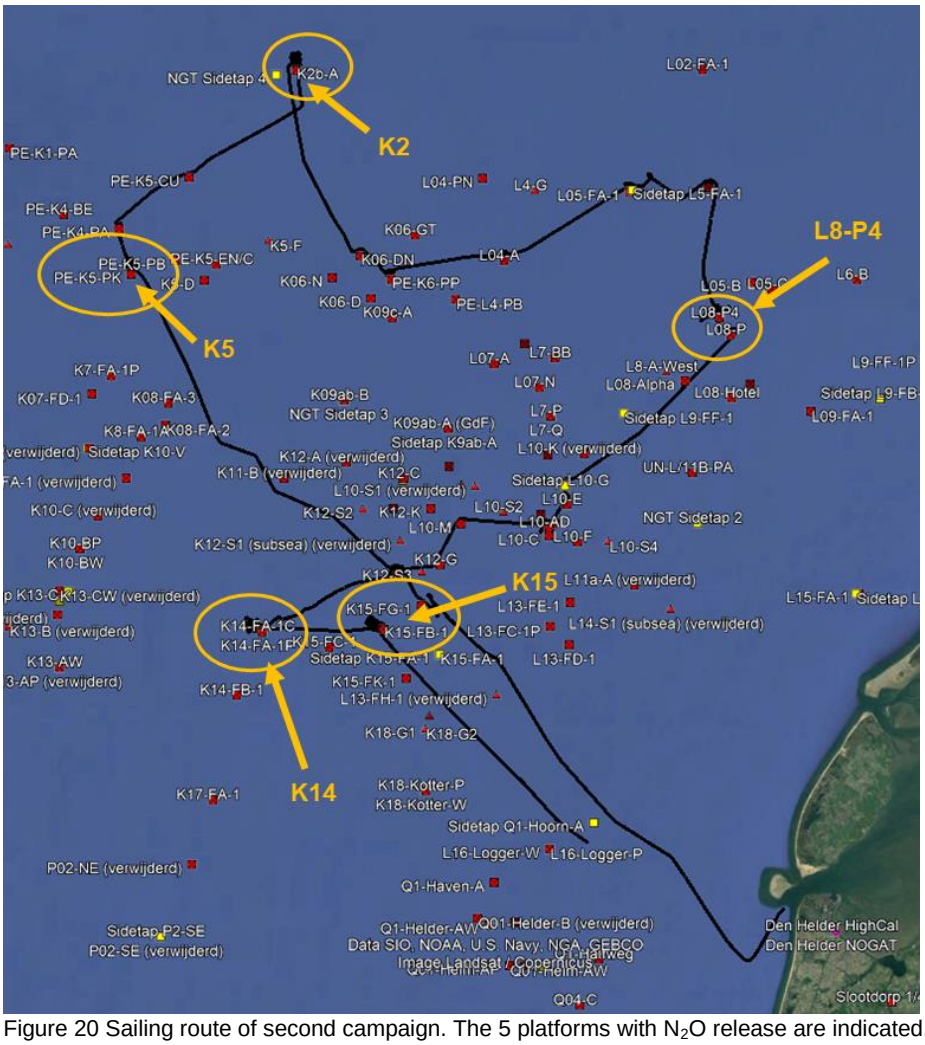

Figure 20 Sailing route of second campaign. The 5 platforms with N_2O release are indicated.

3 Results

3.1 Campaign 1 – July

Table 8 shows the list of platforms passed during the first campaign. At 2 platforms (K5CC and K14) N_2O was released as described in Paragraph 2.5.1. Figure 21 show the meteo-conditions during the campaign, provided by KNMI from a high resolution weather forecast model (2.5x2.5 km) with 3-hourly model simulations and an hourly model output.

Table 8 List of passed platforms during the first campaign; bold: platforms with release experiment; red: inversion layer below 100 m.

Operator	Platform	date	start	end	LAT	LONG
ONE	L11-B	17-jul	22:24:00	23:29:00	53.47333	4.49083
Wintershall	L08-Hotel	17-jul	23:57:00	00:00:00	53.56467	4.56804
Wintershall	L08-P4	18-jul	00:26:00	01:37:00	53.66139	4.54083
Wintershall	L08-Alpha	18-jul	02:10:00	02:14:00	53.58439	4.47227
Neptune	L10-B	18-jul	02:58:00	03:03:00	53.45763	4.23323
Neptune	L10-E	18-jul	03:13:00	03:17:00	53.43250	4.23703
Neptune	L10-D	18-jul	03:19:00	03:19:00	53.40918	4.21498
Neptune	L10-A complex	18-jul	03:24:00	04:49:00	53.40433	4.20252
NAM	K15-FG-1	18-jul	05:38:00	05:51:00	53.30611	3.94818
NAM	K15-FB-1	18-jul	05:51:00	06:37:00	53.27652	3.87305
NAM	K15-FC-1	18-jul	06:52:00	07:10:00	53.25270	3.76402
NAM	**K14-FA-1**	18-jul	07:14:00	10:59:00	53.26950	3.62776
NAM	K08-FA-3	18-jul	12:15:00	13:25:00	53.54218	3.42356
Total	**K5CC**	18-jul	14:58:00	19:42:00	53.69639	3.33876
Total	K4-BE	18-jul	20:06:00	20:29:00	53.76589	3.19657
Spirite Energy	J6-A-Markham	18-jul	21:10:00	00:10:00	53.82414	2.94528
Total	K4-BE	19-jul	01:01:00	01:45:00	53.76589	3.19657
Total	K4-A	19-jul	01:55:00	02:04:00	53.75101	3.31101
Total	K5CC	19-jul	02:16:00	04:20:00	53.69639	3.33876
NAM	K7-FA-1	19-jul	04:42:00	04:54:00	53.57281	3.30490
NAM	K7-FD-1	19-jul	04:57:00	05:07:00	53.55028	3.26725
Wintershall	K13-A	19-jul	06:38:00	06:43:00	53.21799	3.22037
Dana	P11b-De Ruijter	19-jul	11:34:00	13:37:00	52.35995	3.34199
One	P11-E	19-jul	14:25:00	15:00:00	52.35528	3.58779
Taqa	P15-F	19-jul	15:21:00	15:26:00	52.30677	3.68623
Taqa	P15-D	19-jul	15:42:00	17:10:00	52.29107	3.81776
Wintershall	P12-SW	19-jul	17:51:00	18:10:00	52.40723	3.75991
Petrogas	P09c-A	19-jul	18:48:00	19:30:00	52.55334	3.74236
Wintershall	P06-D	19-jul	20:13:00	20:28:00	52.70131	3.72671
Wintershall	P06-A	19-jul	20:42:00	21:30:00	52.75604	3.75751
Petrogas	Q01-Helder (+ Q01-Hoorn)	19-jul	22:11:00	23:55:00	52.92145	4.09841
Petrogas	Q01-Helm	20-jul	01:00:00	02:20:00	52.87248	4.14210
Petrogas	Q1-D	20-jul	02:21:00	02:53:00	52.87175	4.21009
Wintershall	Q04-C	20-jul	03:07:00	04:00:00	52.82633	4.28466

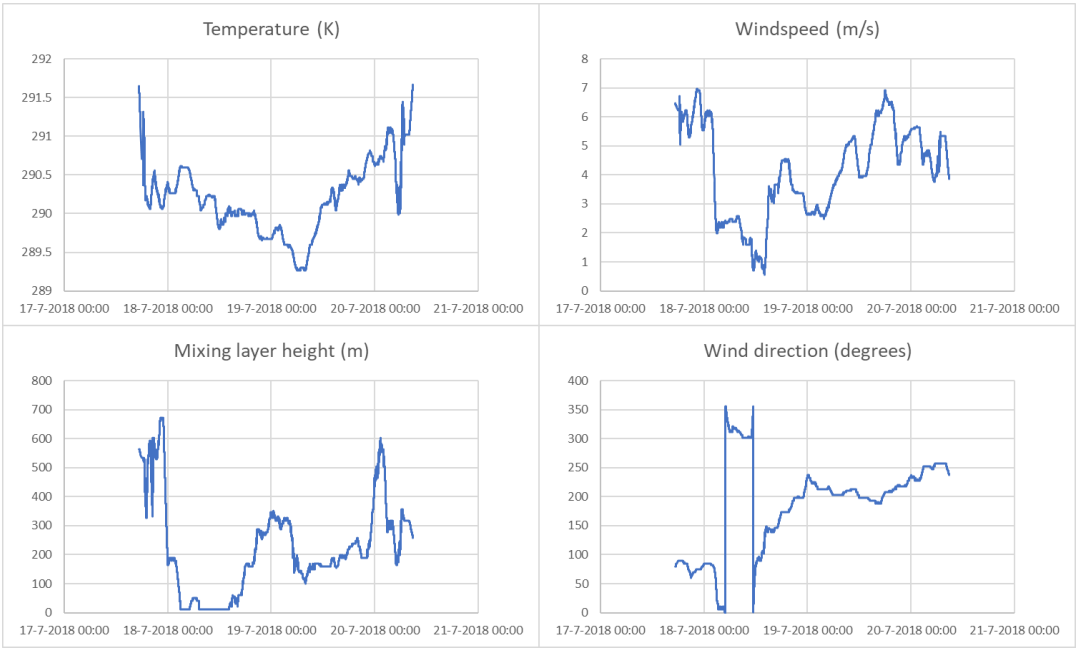

Figure 21 Meteo condition during the first campaign, clockwise temperature, windspeed, wind direction and inversion layer height.

The supply vessel sailed out in the afternoon of July 17. Measurements went well during the night. Emission estimates were obtained for L11 (Figure 22), and three L8 platforms.

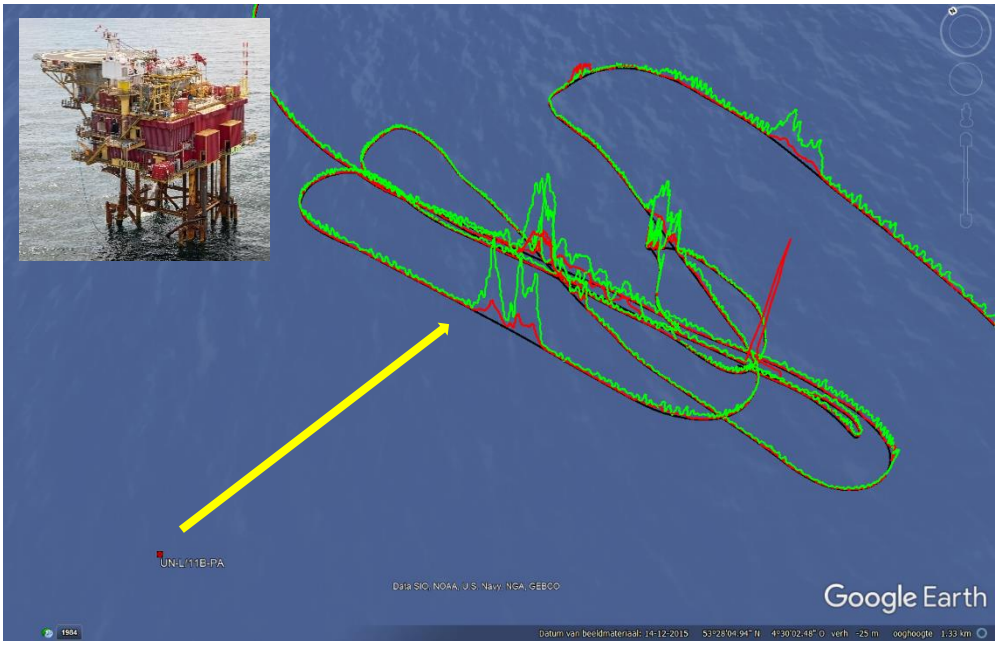

Figure 22 L11 measurements plotted in Google Earth, red=CH_4, green=C_2H_6.

A problem occurred on July 18 with the two N_2O release experiments. When doing the measurements almost no CH_4 or N_2O was observed. An example is shown in Figure 23 for the K5 platform. Fortunately three different CH_4 measurement systems were available (the two QCL systems and Picarro instruments) and

these instruments agreed, moreover using different inlet lines (leeside, portside or top) had no effect.

The interpretation on that day was that the amount of N_2O needed to get the whole release system in equilibrium (the big pipe going up to the stack exhaust) was misjudged. Before the experiment the release setup was discussed not realising well that the vents system volume in combination with the low and irregular vent gas flow would cause both a delay time for the N_2O release as well as an irregular emission pattern from the vent stack.

After the campaign the Dutch meteorological office, KNMI did a reanalysis of the wind field for the measurement campaign. It turned out that the inversion layer height, the first part of the atmosphere that is relatively well mixed but separated from the air layers above, was as shallow as 30-100 m all through the release day (Figure 24). This means there was a two-layer build-up in the lower atmosphere, the methane and N_2O (high altitude) plume were released above this inversion layer and these plumes did not reach altitudes where the measurements were done. The methane plume (and the N_2O released) from the lower situated process area of the platform could sometimes be measured because these plumes were trapped below the inversion layer, reaching the altitude of the measurements. This explained why both N_2O and CH_4 plumes were not detected, the gasses are released at 40-60 m altitude and above the inversion layer, the gas inlet on the ship were below that level.

The same problem persisted throughout the day and became even worse at the other platform K5CC where the tracer experiments took place in the afternoon of the same day. Being unaware of the low inversion layer at the time of measurements it was thought that the problems at K14 in the morning were because of the platform layout there. At K5 however it turned out that not any methane or N_2O plume was seen at all. An extensive discussion took place on board, several inlet and instrument tests were run, but 3 different instruments (2 QCL and 2 Picarro) all provided the same info: no trace of methane plumes.
The instruments were fine, the meteorological condition was the problem during this campaign.

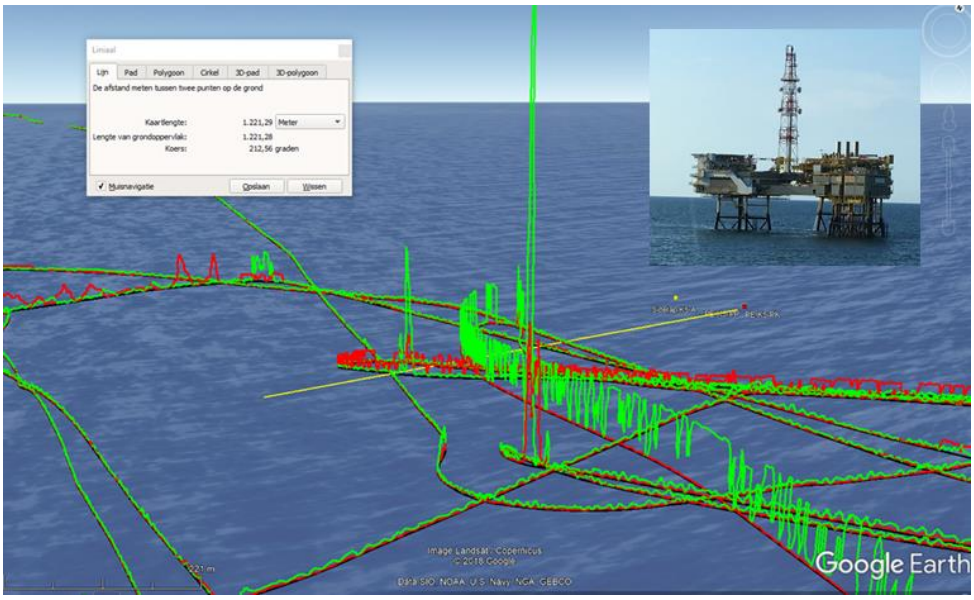

Figure 23 K5 measurements plotted in Google Earth, red=CH_4, green=C_2H_6.

In the evaluation of the failed N_2O release experiments at K5 and K14 it was also concluded that, especially for the release at high altitude, a substantial amount of N_2O is needed to fill up the whole vent system and come to an equilibrium concentration that will make the emission at the top equal to the emission from the release set. This is why the N_2O release system was modified for the November campaign. Since N_2O release measurements foreseen at the K5 and K14 could not be used, a proper evaluation and improvement of the dispersion model was impossible.

During the 3 day campaign 35 platforms were visited, for 10 platforms measured on July 18 the inversion layer height problem made it impossible to make emission estimates (L10-B, L10-E, L10D, L10-A complex, K15-FG-1, K15-FB-1, K15-FC-1, K14-FA-1, K08-FA-3 and K5CC, red in Table 8).

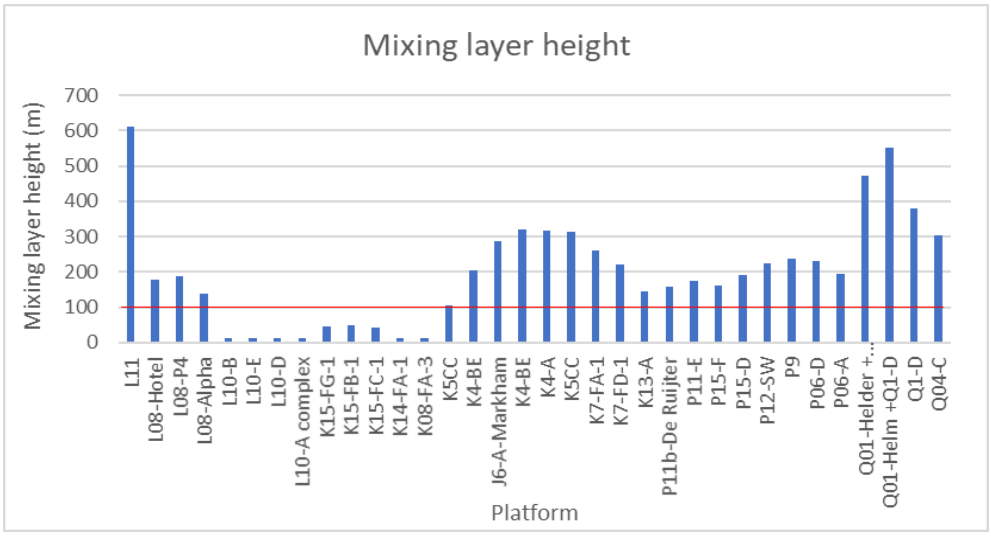

Figure 24 Average inversion layer height (m) per platform (first campaign).

First model calculations were performed after the July campaign using the Gaussian model to get a first idea about the emission level but it was decided to postpone that work and redo the tracer release measurements in order not to do all modelling and interpretation effort for the July campaign twice. After the November campaign (see below) several modifications and choices were made on how to run the model both for the other November platforms and for the platforms measured in July.

In these calculations for the July campaign, 80 plumes were used. This set covers multiple transects at 12 platforms, and single pass transects for the other 11 platforms (mainly the small one's). The results of the model calculations are shown in Table 9.

In the November campaign 33 platforms were visited (2 platforms, K5CC, K4-BE were visited twice). For 10 platforms no emission estimate can be made due to the inversion layer problem. For the 23 remaining platforms, meteo-conditions were good. In total 111 different transects downwind of platforms were sailed but for some of these scattered and noisy data was observed, the plumes are broken up into multiple small plumes and interpretation was not possible.

The table shows time, platform name, the range of distances covered with transects downwind, the average emission level during these experiments, the standard deviation and the number of plumes used to calculate the average emission. The standard error reported is the standard deviation divided by the square root of the number of measurements. Finally the median of the set and the estimate provided by the operator is listed. The last column indicates the factor between the operator estimate and the estimate based on the measurements, the colour of the cell indicates the level of difference:

- Blue: the measured emission seems below the operator's estimate
- Green: indicates both estimates agree well within the error margin
- Orange: the measurements show an emission level above the operator's estimate
- Red: the measurements are clearly above the operator's estimate

The table shows that all different options occur. As for the blue data, it is possible that the ship missed the plume. On the other hand, higher emission estimates can also occur when the plume happens to move along with the ship in the wind direction, making the measured plume wide in the dataset and leading to a (too) high emission level.

For this campaign the sum of all emission estimates provided by the operators adds up to 51 gCH_4/s using 18 platforms. The measurements for this same set adds up to 39 gCH_4/s.

Table 9 Emission calculation results for the platforms during the first campaign, platforms in red had the inversion layer problem.

JULY	Platform	Distance	Avg gCH4/s	Stdev gCH4/s	N	std err	Operator estimate	Class
17-7-18 22:26	L11-B	637 - 1560	2.7	2.1	9	27%	14	
17-7-18 23:36	L08-Hotel	750	0				0	
18-7-18 00:47	L08-P4	901 - 1603	0.9	0.5	2	39%	2.3	
18-7-18 02:14	L08-Alpha	906	11	11	1		0	
18-7-18 03:12	L10-B	2028					0	
18-7-18 03:18	L10-E	684					0	
18-7-18 03:19	L10-D	2032					0	
18-7-18 03:38	L10-A complex	1429 - 1940					29	
18-7-18 05:40	K15-FG-1	663 - 1404					0.008	
18-7-18 05:51	K15-FB-1	750 - 1500					6.9	
18-7-18 06:54	K15-FC-1	560 - 663					0.005	
18-7-18 07:14	**K14-FA-1**	750 - 2000					16	
18-7-18 12:15	K08-FA-3	1200					0.7	
18-7-18 14:58	**K5CC**	550 - 3500					14	
18-7-18 20:18	K4-BE	783			1		0.023	
18-7-18 21:37	J6-A-Markham	929 - 2137	0.9	1.4	9	51%	9.9	
18-7-18 23:58	K4-BE	802 - 1303	0.1	0.0	2	19%	0.023	
19-7-18 02:02	K4-A	4503	2.6	2.6	1		0.04	
19-7-18 06:42	K13-A	825	0.5	0.5	1		12	
19-7-18 12:37	P11b-De Ruijter	1000 - 1600	0.15	0.055	4		1.8	
19-7-18 14:35	P11-E	652 - 817	1.1	1.1	1		6	
19-7-18 15:57	P15-D	1123 - 1776	2.1	1.3	7	23%	4	
19-7-18 18:52	P09c-A	565 - 1333	0.6	0.3	4	22%	0	
19-7-18 20:23	P06-D	736	0.3	0.3	1		0	
19-7-18 20:44	P06-A	669 - 2391	3.9	4.0	6	42%	0.02	
19-7-18 22:43	Q01-Helder	909 - 3113	9.6	8.2	8	30%	0.4	
20-7-18 00:05	Q1-D	1942 - 7188	0.8	0.8	1		0	
20-7-18 03:20	Q04-C	679 - 1942	1.4	1.2	4	41%	0.2	

3.2 Campaign 2 – November

Table 10 shows the list of platforms passed during the second campaign. At 5 platforms N_2O was released as described in Paragraph 2.5.2. Figure 25 shows the meteo-conditions during the campaign, provided by KNMI from a high resolution weather forecast model (2.5x2.5 km) with 3-hourly model simulations and an hourly model output.

Table 10 List of passed platforms during the second campaign, platform in bold had N_2O release.

Operator	Platform	Date	start	end	LAT	LONG
NAM	K15-FG-1	15-nov	2:13:50	2:30:22	53.30611	3.94818
Neptune	K12-B	15-nov	2:30:24	3:03:25	53.34126	3.89723
Total	**K5CC**	15-nov	5:42:40	10:50:51	53.69639	3.33876
Total	K4A	15-nov	10:51:07	10:56:42	53.75101	3.31101
Total	K5-CU	15-nov	12:42:00	12:44:59	53.81563	3.52778
Neptune	**K2b-A**	15-nov	12:51:48	17:05:59	53.94945	3.66361
Total	K6-D	15-nov	19:34:27	19:35:28	53.72644	3.80578
Total	K6CC	15-nov	20:00:44	20:35:55	53.69918	3.87046
Neptune	K09c-A	15-nov	20:37:47	20:39:26	53.65328	3.87419
Total	L4-A	15-nov	21:40:07	22:18:01	53.72540	4.09899
Neptune	L05-FA-1	15-nov	23:52:25	0:41:20	53.81156	4.35275
Neptune	L5a-D	16-nov	1:15:42	1:43:52	53.81864	4.51426
Wintershall	**L08-P4**	16-nov	6:20:20	13:50:09	53.66139	4.54083
Neptune	L10-B	16-nov	15:23:30	15:45:39	53.45763	4.23323
Neptune	L10-E	16-nov	16:04:52	16:20:14	53.43250	4.23703
Neptune	L10-D	16-nov	16:20:18	16:35:30	53.40918	4.21490
Neptune	L10-A	16-nov	16:36:52	17:45:39	53.40433	4.20252
Neptune	L10-M	16-nov	19:15:06	19:23:33	53.40594	4.02400
Neptune	K12-G	16-nov	19:47:27	19:56:29	53.35600	3.98366
Neptune	K12-B	16-nov	20:17:09	21:06:35	53.34126	3.89723
NAM	**K14**	17-nov	6:11:32	10:09:00	53.26950	3.62776
NAM	**K15-FB-1**	17-nov	12:40:53	16:39:28	53.27652	3.87305

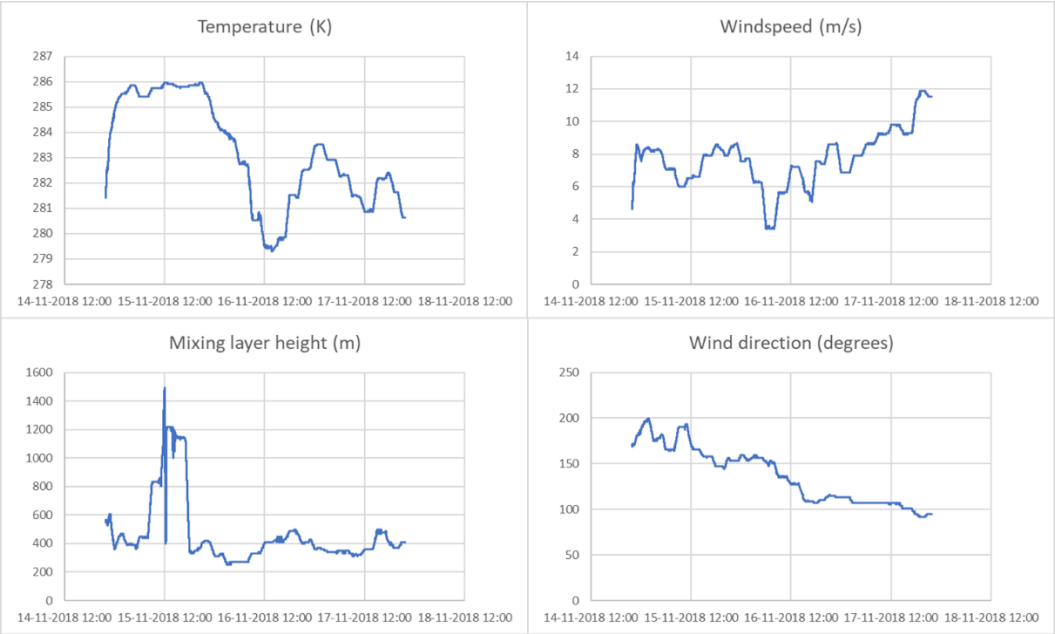

Figure 25 Meteo condition during the second campaign, clockwise temperature, windspeed, wind direction and inversion layer height.

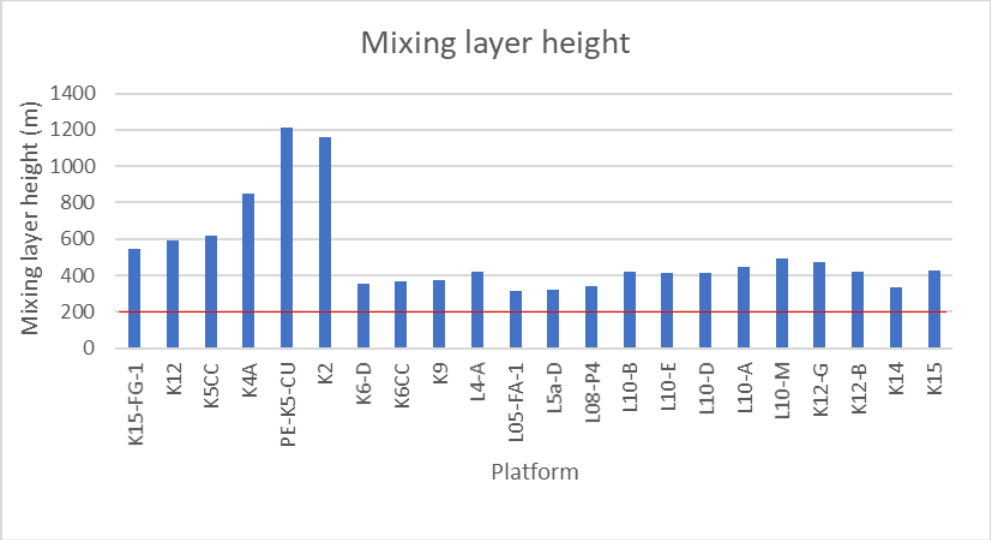

Figure 26 Average inversion layer height (m) per platform (second campaign).

During the second campaign, the inversion layer height was suitable for the experiments, as it was at least above 300 m (Figure 26). The results of the platforms where the N_2O release experiments took place, are described first, which are K5CC, K2b-A, L8P4, K14-FA-1 and K15-FB-1. After that, the emission estimates of the other platforms that were passed during the campaign are described.


K5CC

3.2.1 K5CC

Previous page: Figure 27 Picture of platform K5CC.

On the previous page a picture of K5CC is shown (Previous page: Figure 27). Below the schematic picture of platform K5CC is shown (Figure 28). Wind direction, position of the N_2O releases and the main CH_4 and CO_2 sources are indicated.
N_2O was released leeward of the platform at 30 and 60 m height. The vent stack of 80 m is located at the lower left platform (K5P) and in line with the N_2O release point, when looking at the wind direction. On this platform the power gas turbines are also located at helicopter deck height. On the upper platform (K5PK), there are compressors located which provide CO_2 emissions with an exhaust temperature of 350°C, furthermore that platform is full with cooler banks (the circles).
The results of the measured and modelled emissions are listed in Table 11.

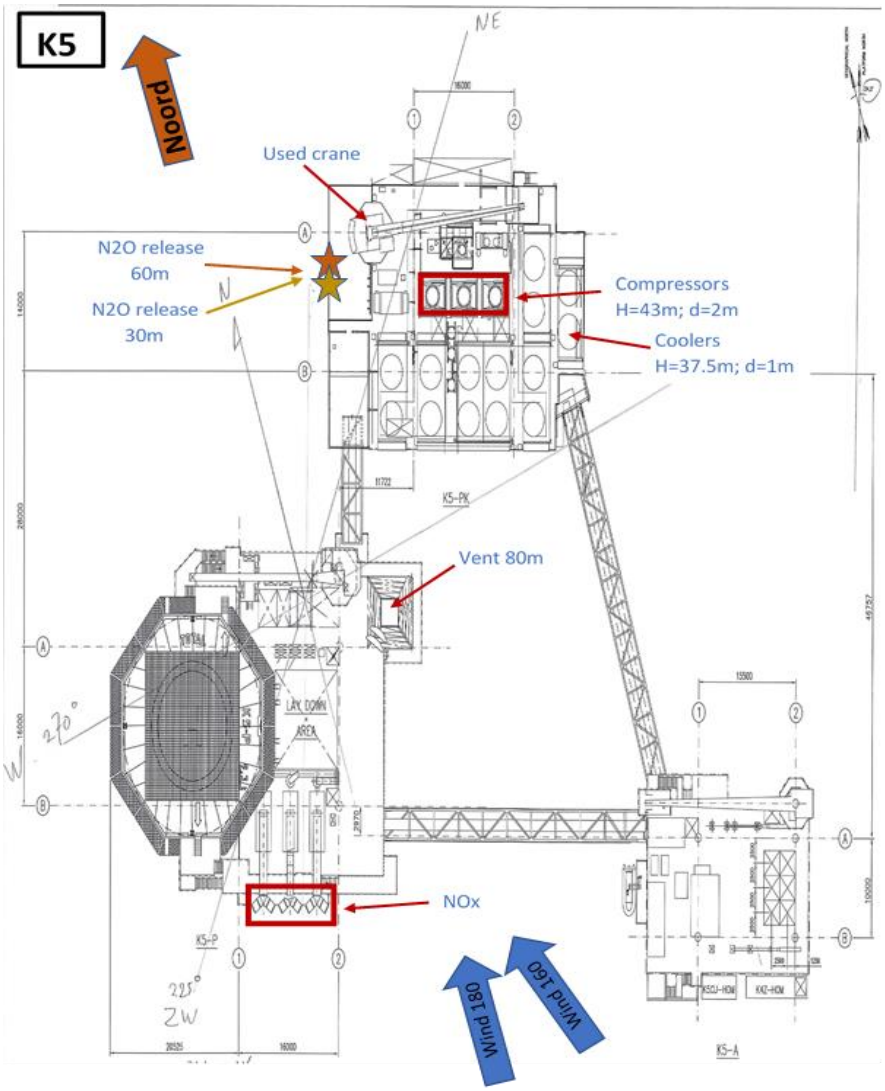

Figure 28 Schematic picture of K5CC with average wind direction and main CH_4 and CO_2 sources.

Table 11 Overview of results K5CC.

		Operator			Operator
Method	CH_4	13.64		CO_2	3288
Measurement only		gCH_4/s	n	rel err	gCO_2/s
via meas N_2O	high	70	1	n.d.	4422
	low	1.4	9	13%	539
via meas CO_2		32	21	16%	

Model for N_2O		gN_2O/s			factor vs release
model N_2O OCD	high 1.90	0.1	1	n.d.	17
	low 1.45	0.6	9	16%	2.3
model N_2O sigz	high 1.90	0.2	1	n.d.	12
	low 1.45	2.5	8	73%	0.6

Model for CO_2		gCO_2/s			factor vs operator
model CO_2 OCD		412	21	15%	8.0
model CO_2 sigz		345	20	16%	9.5

Model for CH_4		gCH_4/s			N_2O or CO_2 factor
model CH_4 stack OCD		10	12	27%	
with N_2O corr		174			17
with CO_2 corr		83			8.0
model CH_4 stack sigz		32	10	49%	
with N_2O corr		397			12
with CO_2 corr		304			10
model CH_4 diffuse OCD		1.7	11	32%	
with N_2O corr		3.9			2.3
with CO_2 corr		13			8.0
model CH_4 diffuse sigz		3.2	9	66%	
with N_2O corr		7.5			0.6
with CO_2 corr		31			9.5

Conclusion		gCH_4/s
Measured stack		70
Measured diffuse		1.4

		No corr	N_2O corr	CO_2 corr
Model stack average		**14**	286	193
Model diffuse average		**2.4**	5.7	22

*Red indicates that this value has a problem

Emission based on measurements of N_2O and measured CH_4 plumes
For the release at 60 m there was only 1 plume with a sufficient high measured N_2O plume left from the 10 transects, which ends up with an emission of 70 gCH_4/s. For the 30 m release 9 N_2O plumes could be used from the 9 transects and an emission of 1.4 gCH_4/s was determined. Unfortunately this last set only has plumes within 1000 m, not showing the plume released from the stack. Therefore, the emission from the stack cannot be quantified sufficient with the tracer method, based on 1 plume.

With the OCD and SigZ model runs, 10 and 32 gCH_4/s were obtained respectively for the stack emission. For the diffuse emissions from the platform height, emissions of 1.7 and 3.2 gCH4/s were obtained which is well in line with the tracer based estimate. The standard deviation of the emission estimates is relatively high with around 30% standard error for the OCD calculations and around 50% standard error for the SigZ calculations.

Correcting the model for N_2O and CO_2 measurement versus model
With the very small N_2O plumes observed during the 60 m release experiment, a correction for the modelled CH_4 plumes is not possible.
For the 30 m level N_2O release the agreement between modelled and measured N_2O plumes is best for the SigZ model with a correction factor of 0.6, for the OCD model this factor is 2.3. When applying the N_2O factors to the CH_4 model calculations emission levels of 3.9 and 7.5 gCH_4/s were obtained. When applying the CO_2 factors to the CH_4 model calculations emission levels of 83 and 304 gCH_4/s for the stack and 13 and 31 gCH_4/s for diffuse emissions respectively were obtained. Temperature is not incorporated in the model, and therefore the height of the plume rise is not taken into account. This can at least partly explain the differences between the modelled CO_2 release compared the amount provided by the operator. Besides that, the CO_2 emissions could also have influenced the N_2O release plumes, explaining the fact that the high release experiment was not successful.

In the end Table 11 shows how the emission from a platform can be obtained in different ways, using different combinations of data. When all these methods would have been in agreement the resulting emission estimate is robust. In this case the different paths lead to different answers. It was attempt to understand and explain the differences and choose the estimate that is most consistent. For the K5CC platform the best estimated emissions are 14 gCH_4/s for the stack and 2.4 gCH_4/s for diffuse emissions. Both emissions are the average outcomes of the OCD and sigZ model without a N_2O or CO_2 correction with a relative error ranging between 27% and 66%. These emissions are well in line with the provided emission from the operator.


K2
PL-K2b-PA

3.2.2 K2

Previous page : Figure 29 Picture of platform K2b-A.

On the previous page a picture of K2b-A is shown (Previous page : Figure 29). Below the schematic picture of platform K2b-A is shown (Figure 30).
Wind direction, position of the N_2O releases and the main CH_4 and CO_2 sources are indicated. N_2O was released leeward of the platform at 30 and 40 m height. The vent stack is not vertical but horizontal positioned at 40 m above sea level located at the upper part of platform next to the N_2O release point. There were 2 compressors (located in the middle of the platform) and 1 generator (exhaust pipe on the left of the platform) working during the measurements. The cooler banks were located below the helicopter deck.
The results of the measured and modelled emissions are listed in Table 12.

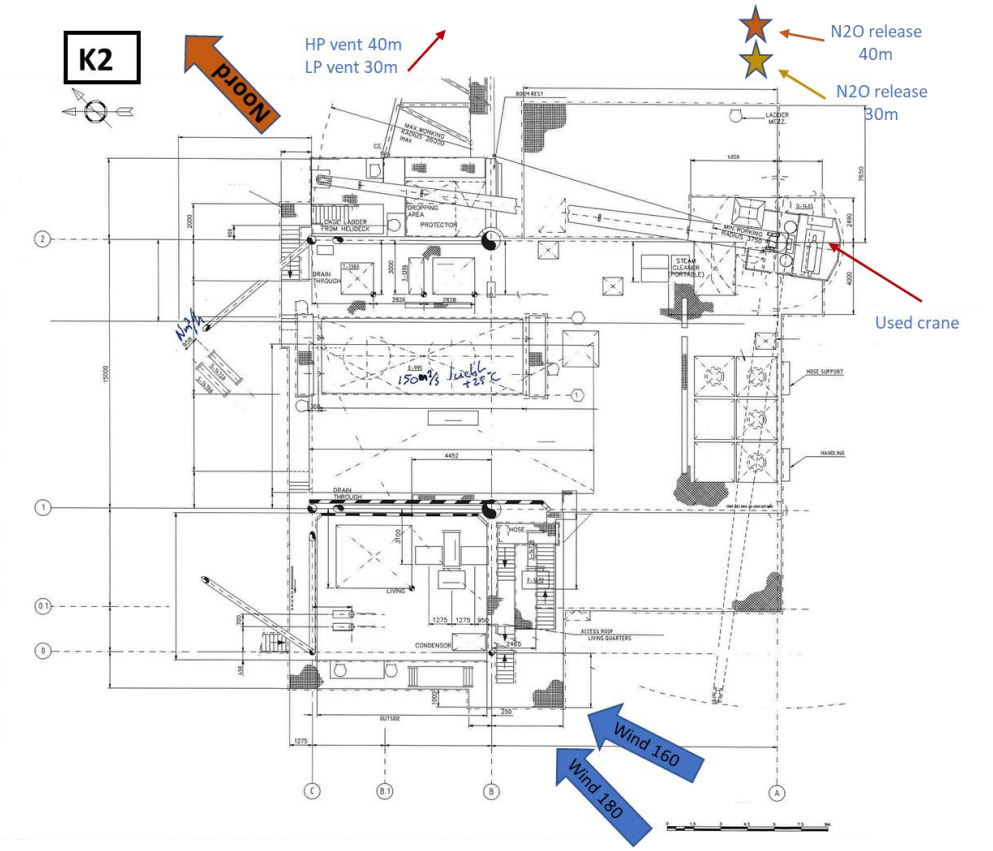

Figure 30 Schematic picture of K2b-A with average wind direction and main CH_4 and CO_2 sources.

Emission based on measurements of N_2O and measured CH_4 plumes
For K2b-A, the high and low N_2O release experiment were comparable as the releases were done at 30 and 40 m respectively. The stack and diffuse emissions cannot be separated as the plumes from both sources are mixed in a single plume.
For the 40 m release 11 N_2O plumes could be used from 11 transects and an emission of 5.1 gCH_4/s was determined. For the 30 m release, 10 N_2O plumes could be used from 10 transects resulting in an emission of 3.9 gCH_4/s.

Table 12 Overview of results K2b-A.

		Operator			Operator
Method	CH_4	1.63		CO_2	305.6
Measurement only		gCH_4/s	n	rel err	gCO_2/s
via meas N_2O	high	5.1	11	20%	659
	low	3.9	10	9%	233
via meas CO_2		4.8	22	8%	

Model for N_2O		gN_2O/s			factor vs release
model N_2O OCD	high 2.48	1.7	11	12%	1.4
	low 1.34	0.9	10	12%	1.6
model N_2O sigz	high 2.48	1.0	11	11%	2.0
	low 1.34	0.3	10	13%	5.2

Model for CO_2		gCO_2/s			factor vs operator
model CO_2 OCD		447	22	8%	0.7
model CO_2 sigz		157	22	8%	1.9

Model for CH_4		gCH_4/s			N_2O or CO_2 factor
model CH_4 stack OCD		6.5	22	8%	
with N_2O corr		9.4			1.4
with CO_2 corr		4.5			0.7
model CH_4 stack sigz		2.2	22	8%	
with N_2O corr		5.7			2.0
with CO_2 corr		4.4			1.9
model CH_4 diffuse OCD		6.2	22	8%	
with N_2O corr		9.6			1.6
with CO_2 corr		4.2			0.7
model CH_4 diffuse sigz		2.2	22	8%	
with N_2O corr		10.6			5.1
with CO_2 corr		4.3			1.9

Conclusion		gCH_4/s
Measured stack		**5.1**
Measured diffuse		**3.9**

		No corr	N_2O corr	CO_2 corr
Model stack average		**2.9**	**7.6**	**4.4**
Model diffuse average		**4.2**	**10.1**	**4.3**

With the OCD and SigZ model runs, 6.5 and 2.2 gCH_4/s were obtained respectively for the stack emission. For the diffuse emissions from the platform height emissions of 6.2 and 2.2 gCH_4/s were obtained which is well in line with the tracer based estimate. The standard deviation of the emission estimates are relatively low with 8% standard error for both the OCD and SigZ calculations.

Correcting the model for N_2O and CO_2 measurement versus model

Based on the correction factor for N_2O versus the release amount, the factors for the OCD routine are lower than for the SigZ routine.

When applying the N_2O factors to the CH_4 model calculations emission levels of 9.4 and 5.7 gCH_4/s were obtained from the OCD and SigZ routine for the stack and 9.6 and 10.6 gCH_4/s for the diffuse emissions. When applying the CO_2 factors to the CH_4 model calculations emission levels of 4.5 and 4.4 for the stack and 4.2 and 4.3 gCH_4/s for diffuse emissions respectively were obtained.

The model results for CH_4 without correction and with correction for N_2O and CO_2 are all in the same range and also with emissions derived via the measured N_2O release. For the best estimated total emission for K2b-A the average of the measured and modelled average without and with corrections for N_2O and CO_2 is taken resulting in 5.3 +/- 2.4 gCH_4/s. These emissions are higher than the provided emission from the operator, but are still in the same order of magnitude.


L8P4
KENZ
L8-P4

3.2.3 L8P4

Previous page: Figure 31 Picture of platform L8-P4.

On the previous page picture of platform L8-P4 is shown (Previous page: Figure 31). Below the schematic picture of platform L8P4 is shown (Figure 32).
Wind direction, position of the N_2O releases and the main CH_4 and CO_2 sources are indicated. N_2O was released leeward of the platform at 30 and 60 m height. The vent stack is positioned at the upper part of the platform and is 98 m high. On the left side of the vent stack the OVC is located, which is an CO_2 source. On the left side, the exhaust pipes of the turbines are positioned toward the upper side of the platform. The results of the measured and modelled emissions are listed in Table 13.

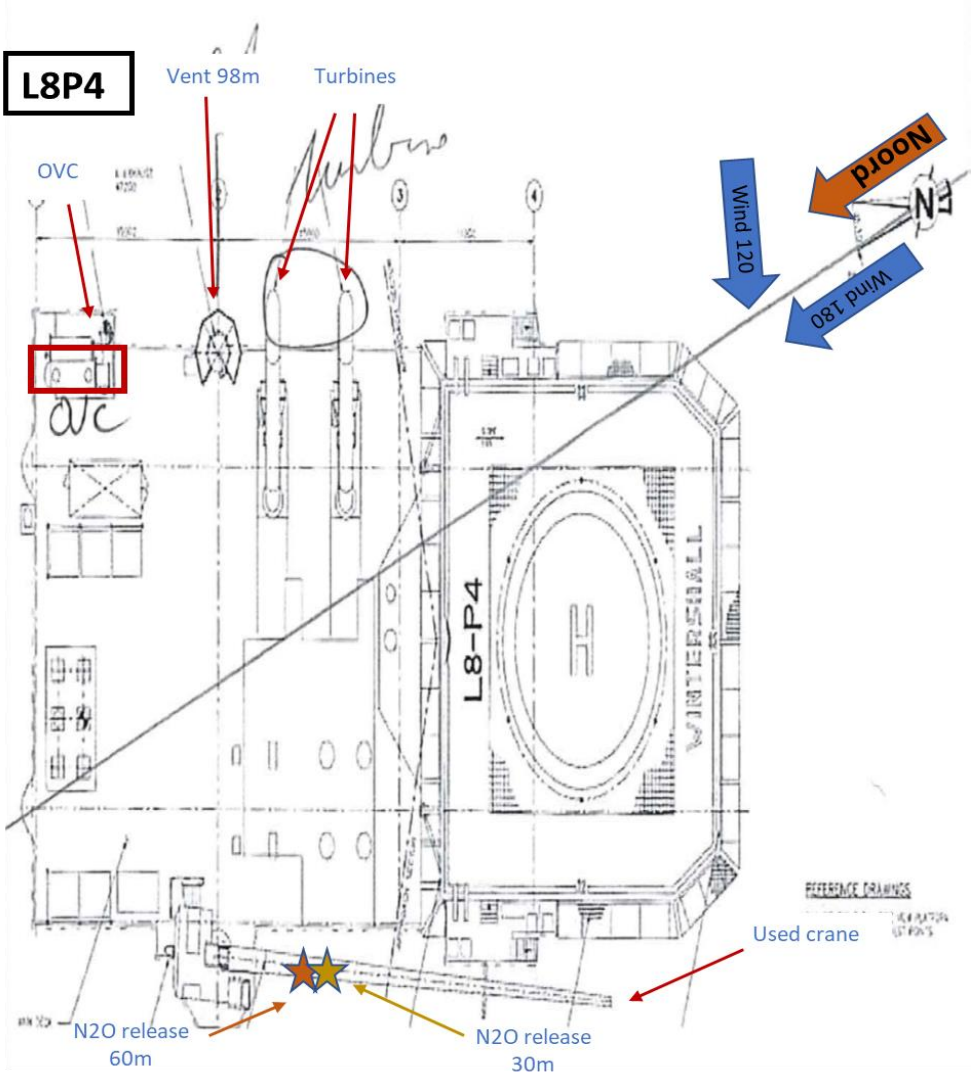

Figure 32 Schematic picture of L8P4 with average wind direction and main CH_4 and CO_2 sources.

Table 13 Overview of results L8P4.

		Operator			Operator
Method	CH_4	2.60		CO_2	1602
Measurement only		gCH_4/s	n	rel err	gCO_2/s
via meas N_2O	high	20	9	17%	4368
	low	10	11	24%	1834
via meas CO_2		10	29	12%	

Model for N_2O		gN_2O/s			factor vs release
model N_2O OCD	high 2.46	0.3	9	18%	10
	low 1.38	0.2	11	16%	7.5
model N_2O sigz	high 2.46	0.4	8	52%	6.6
	low 1.38	0.1	11	23%	22

Model for CO_2		gCO_2/s			factor vs operator
model CO_2 OCD		424	29	14%	3.8
model CO_2 sigz		371	29	25%	4

Model for CH_4		gCH_4/s			N_2O or CO_2 factor
model CH_4 stack OCD		25	3	43%	
with N_2O corr		339			10
with CO_2 corr		97			3.8
model CH_4 stack sigz		26	3	43%	
with N_2O corr		167			6.6
with CO_2 corr		110			4
model CH_4 diffuse OCD		1.8	13	17%	
with N_2O corr		10			7.5
with CO_2 corr		6.9			3.8
model CH_4 diffuse sigz		0.4	13	24%	
with N_2O corr		9.6			22
with CO_2 corr		1.9			4

Conclusion		gCH_4/s
Measured stack		20
Measured diffuse		10

		No corr	N_2O corr	CO_2 corr
Model stack average		26	253	103
Model diffuse average		1.1	9.7	4.4

*Red indicates that this value has a problem

Emission based on measurements of N_2O and measured CH_4 plumes

For the release at 60 m there were 9 N_2O plume with sufficient high measured N_2O plume from 12 transects resulting in an emission of 20 gCH_4/s. For the 30 m release 11 N_2O plumes could be used from 11 transects and an emission of 10 gCH_4/s was determined.

With both the OCD and SigZ model runs, 26 gCH_4/s was obtained for the stack emission. The stack was that high, that the building effect within the OCD model had no effect on the stack plumes. For the diffuse emissions from the platform height emissions of 1.8 and 0.4 gCH_4/s. The standard deviation of the emission estimates ranged between 17% and 43%. The model estimated with OCD and sigZ are related.

Correcting the model for N_2O and CO_2 measurement versus model

Based on the correction factor for N_2O versus the release amount, the factor for the OCD routine is 10 versus 6.6 for the SigZ routine for the stack, where the factor for the OCD routine is 7.5 versus 22 for the SigZ routine for the diffuse emissions. The correction factors for N_2O are high, suggesting that the emissions cannot be sufficiently quantified with the tracer method. An explanation for this could be the influence of the OVC, which might have disturbed the N_2O release plumes.

When applying the N_2O factors to the CH_4 model calculations emission levels of 339 and 167 gCH_4/s were obtained from the OCD and SigZ routine for the stack and 10 and 9.6 for the diffuse emissions. When applying the CO_2 factors to the CH_4 model calculations emission levels of 97 and 110 for the stack and 6.9 and 1.9 gCH_4/s for diffuse emissions respectively were obtained. The high correction factors for both N_2O and CO_2 show that the model estimates cannot explain the measured emissions, resulting in an overestimation of the emissions when applying the correction factors.

Best estimated emissions for L8P4 is 26 gCH_4/s for the stack and 1.1 gCH_4/s for diffuse emissions, which deviate from the 2.6 gCH_4/s that the operator provided. Both emissions are the average outcomes of the OCD and sigZ model without a N_2O or CO_2 correction with a relative error ranging between 17% and 43%.

K14

3.2.4 K14

Previous page: Figure 33 Picture of platform K14-FA-1.

Previous page: Figure 33 shows the picture of platform K14-FA-1 is shown. The picture clearly shows the outrigger extending into the sea with the 48 m vent. The same is shown as “tripod Jacket” in the schematic picture below (Figure 34). Wind direction, position of the N_2O releases and the main CH_4 and CO_2 sources are indicated.
N_2O was released leeward of the platform at 30 and 60 m height. The vent stack of 85 m is located at the lower right platform, next to the N_2O release point, when looking at the wind direction. On the left platform the biggest gas turbines are located, which are the largest CO_2 sources. Furthermore, K14 has another vent stack on an outrigger with a height of 48 m on the upper side of Figure 34.

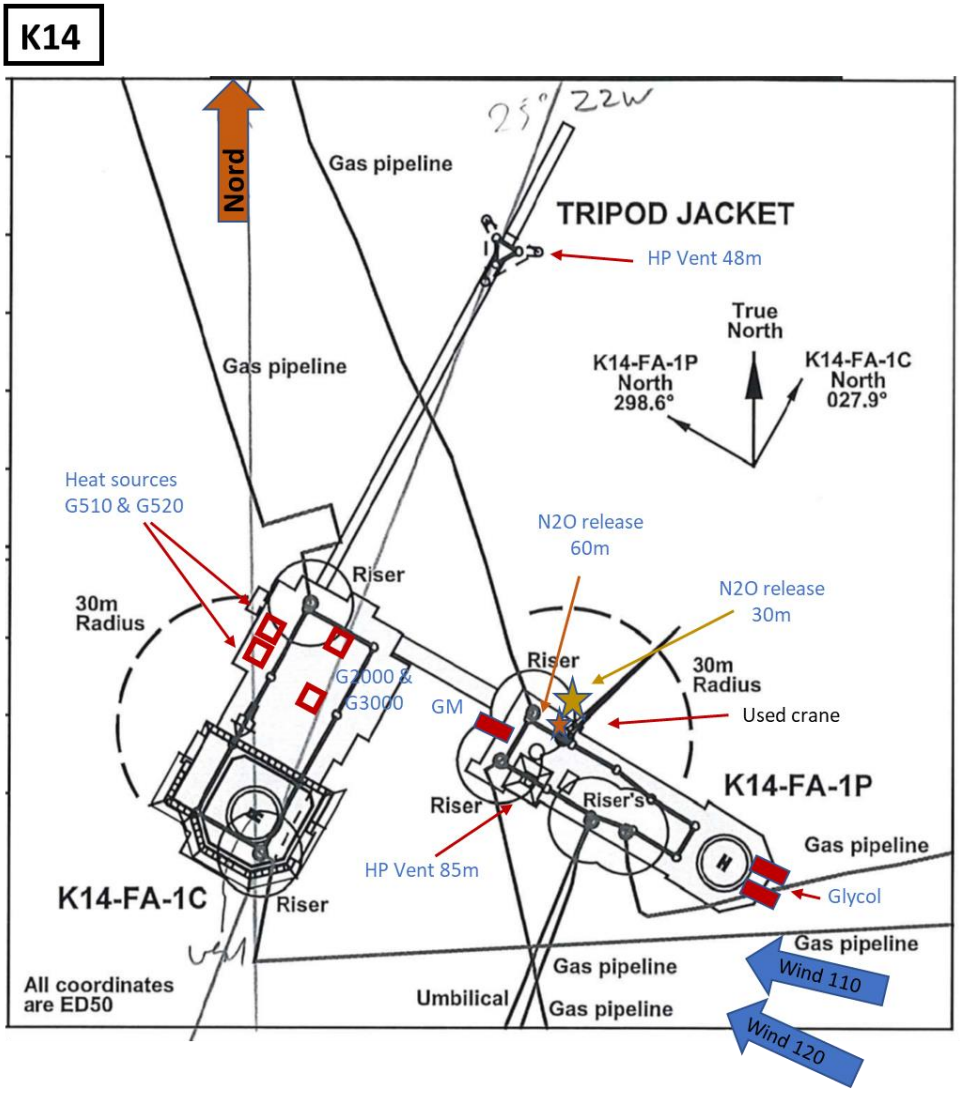

Figure 34 Schematic picture of K14 with average wind direction and main CH_4 and CO_2 sources.

K14 is more complex compared to the other release platforms, as this platform has the outrigger with ventstack next to the platform which also has a ventstack.

Depending on the distance of from the platform, the plumes originating from the three different source areas can sometimes be separated or are all together in one plume. Therefore, the plumes are first sorted into:

- Plumes measured very close to the platform, where only the diffuse emission and not the high vent stack from the platform can be seen and the separated vent stack on the outrigger
- Plumes measured at >750 m, where there are separated plumes for the outrigger and the platform (diffuse and high stack) and single plumes with al emissions in one plume.

Then determination of the emission was done in the three following ways:

- Use the measured N_2O and CH_4 to derive an emission. For the high release, the emissions are expected to overestimated as the hot CO_2 plumes mix with the cold N_2O plumes and it was not known what effect that has on the measurements.
- Use the measured CO_2 and CH_4 to derive an emission, by using CO_2 as a tracer. Because the CO_2 plumes are hot, this is only suitable for the plumes at larger distances, when the plumes comes down and is sufficiently mixed.
- Use the model separate for the 3 sources, the vent stack on the outrigger (48m), the diffuse emission from the platform (40 m) and the high vent stack on the platform (80m), to explain the plumes with the different sources.

The results of the measured and modelled emissions are listed in Table 14 and Table 15.

Table 14 Overview of the plume emissions for the different approaches for K14.

Time	Plume	Distance (m)	Wind m/s	N2O release based on diff	plat	all	CO2 (operator 4300g/s)	Model low stack low	all	Model high stack	Model diff platform	Ratio diff/low stack	Total A (fix ratio diff)	Total B (sum)
17-11-18 06:38	1	983	10		55			34		10	4	13%	34	41
17-11-18 06:44	2	1421	7.5			20	29			2	0		2	3
17-11-18 06:52	3	2007	9		31		59		6	6	7		9	13
17-11-18 06:59	4	2358	10			60	37		6	9	16		6	18
17-11-18 07:11	5	2744	8.4			81	77	14		16	39		14	41
17-11-18 07:19	6	2260	8.3		16		46		10	8	13		15	21
17-11-18 07:44	7	1706	11		26		54	8		7	9	117%	12	16
17-11-18 07:54	8	1524	9.8		51		33		1	4	6		3	7
17-11-18 08:03	9	1103	10.3		39			10		6	3	29%	11	15
17-11-18 08:19	10	1261						21		3	3	16%	21	24
17-11-18 08:40	11	1761	8.7		64			3		12	15		8	16
17-11-18 08:49	12	552	11	2				53			2	3%		
17-11-18 08:55	13	405	7.3	2				7			2	31%		
17-11-18 09:02	14	310	7.8	2					13		4			
17-11-18 09:09	15	282	9	1							4			
17-11-18 09:15	16	395	10	2				38			3	9%		
17-11-18 09:21	17	339	8.1	1				8			4	47%		
17-11-18 09:30	18	480	9.6	2				31			2	8%		
17-11-18 09:36	19	596	8	3				4			5	133%		
17-11-18 09:44	20	708	11		36			94			31	33%	85	126
17-11-18 09:50	21	938	10		21			42		31	13	32%	45	64
17-11-18 09:59	22	1192	8.4			81			17	48	35		16	34
17-11-18 10:05	23	908	10	4				5		15	6		7	15
17-11-18 10:07	24	433	10		12			22			3	14%	21	25

Table 15 Conclusions per set of plumes per source.

	N2O based three classes	CO2 based (dist >1500m)	Model Low stack only	Model High stack model >500 ppb	Model Platform Diffuse source	Ratio	Total A using ratio	Total B low + avg (high&diff)	Concusions
Platform and high stack oly meas > 750m distance plume 1,3,6-9 11&21									Platform (stack+diff)
Average	**38**			**12**	**8**				
stdev	17			12	4				**11 (8-16) gCH4/s**
rel std err	11%			27%	13%				38 probably too high
Median	34			9	7				
Diffuse (only using measurements within 600m, plume 20 & 24 not clear) plumes 12-19 & 23									of which diffuse
Average	**2**				**3**	37%			
stdev	0.9				1.1	41%			**2.5 (1-4) gCH4/s**
rel std err	15%				18%				
Median	2				4	29%			
Only 40 m stack									40m stack
Average			**24**						**24 (18-32) gCH4/s**
stdev			25						
rel std err			28%						
Median			19						
All emission	n=3	n=8							TOTAL
Average	**54**	**48**					**19**	**30**	**35 (24-46 gCH4/s)**
stdev	31	17					21	30	or
rel std err	41%	13%					27%	25%	19-54 gCH4/s
Median	60	46					13	20	

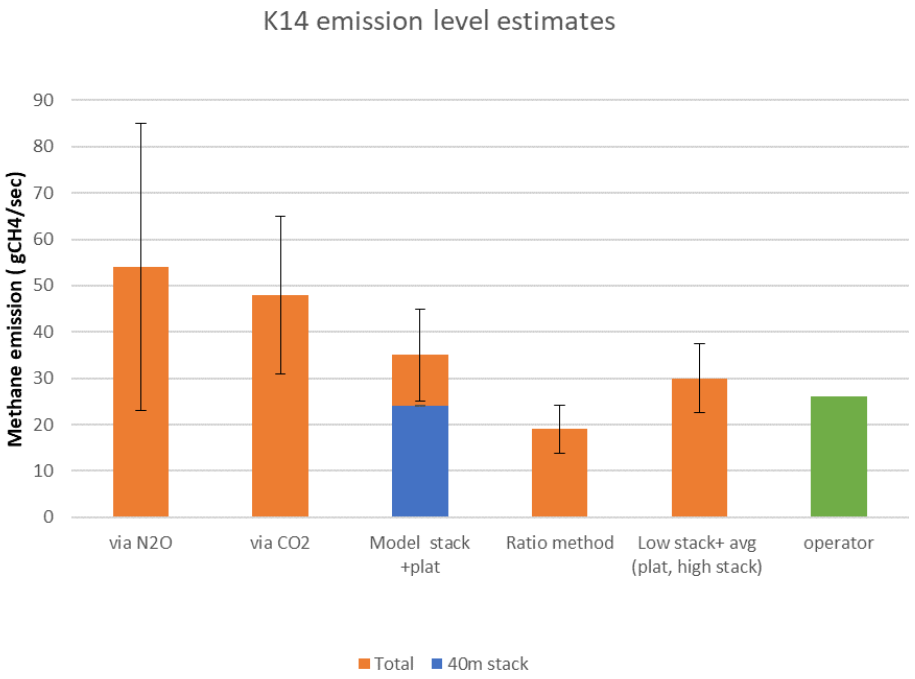

Figure 35 CH_4 emission estimates for the different approaches for K14.

The column in Table 14 with N_2O show the data aligned right (diff): when sailing close to the platform. These measurements show the N_2O released and methane emitted from the low altitude sources at the platform. The methane measurements are expected to miss the plume released at 80 m from the high altitude stack. These plumes together show an average of 2 gCH_4/s (see: average -diffuse only in Table 15). That level agrees well with the estimates using the model in column Model-Platform diffuse source with 3 gCH_4/s.

At larger distances the high altitude plume will reach the inlet system (Table 14 in N_2O data column aligned in the center; plat) in that case the emissions from the high vent stack plus diffuse (low altitude) emissions is observed (since these plumes are overlapping.) For this set the N_2O direct tracer method gives a level of 38 gCH_4/s (Table 15) which is now significantly above the level for the model which is between 12 and 8 gCH_4/s depending on our assumption that all methane either originated form the high vent stack (12) or from the sources at lower altitude (8) on the platform. This estimate also includes the measurement with the N_2O released at 60m height and there are indications that that plume has interaction with the hot CO_2 plumes emitted from the platform. Since the model seems to reproduce the low release (that does not have this problem) it is now assumed that it can also give good estimate for the other measurements. Therefore it was concluded that the platform emits 11 gCH_4/s with a range between 8-16 gCH_4/s. Out of which 2 (1-4) gCH_4/s is probable from real diffuse sources.

What is left is the emission from the outrigger. Depending on the wind direction the plume for the outrigger and the combined high stack-platform plume can be separated. For the outrigger no tracer estimate was available so here only the model is used, but assuming that the effect of the platform building that was taken into account for the platform part can now be switched off. This provides an emission estimate of 24 (18-32) gCH_4/s (see Table 15).

Adding up these two numbers, it becomes 24+11= 35 (24-46) gCH_4/s as total estimate. That level can be compared using the three N_2O tracer experiments where the plumes of all three sources merged into one plume (54 gCH_4/s estimate) and the estimate using the CO_2 emission provided by the operator as an internal tracer (48 gCH_4/s). Finally, there are also two estimates that add up the emission from the rigger and the platform/vent stack plume by plume on method uses derives the ratio between outrigger and other emissions and uses the modelled plumes in that ratio to compare with the actual measured data (Total-A) ending up with 19 gCH_4/s. The other method (Total B) used the outrigger emission and ads the average of the model runs estimates using either the vent stack or the diffuse platform emission as source: 30 gCH_4/s. In the end the conclusion is that these estimates are in reasonable agreement with the level of 25 gCH_4/s reported by the operator.

K15

3.2.5 K15

Previous page: Figure 36 Picture of platform K15-FB-1.

On the previous page a picture of platform K15-FB-1 is shown. Below the schematic picture of platform K15 is shown (Figure 37). Wind direction, position of the N_2O releases and the main CH_4 and CO_2 sources are indicated. N_2O was released leeward of the platform at 25 and 60 m height. The vent stack of 80 m is located at the lower left of the platform, next to the N_2O release point, when looking at the wind direction. The exhaust pipes of the gas and diesel engines are located at the left side. The results of the measured and modelled emissions are listed in Table 16.

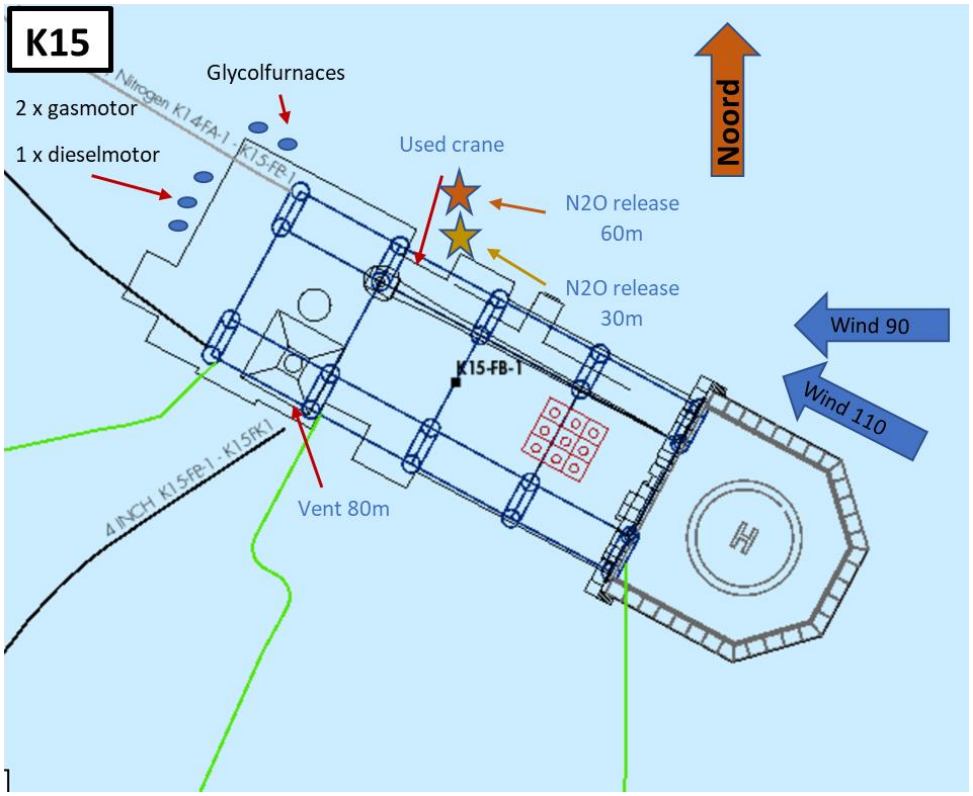

Figure 37 Schematic picture of K15 with average wind direction and main CH_4 and CO_2 sources.

Table 16 Overview of results K15.

		Operator			Operator
Method		18.89			443
Measurement only		gCH_4/s	n	rel err	gCO_2/s
via meas N_2O	high	20	11	18%	1264
	low	5.0	11	17%	253
via meas CO_2		8.3	22	6%	

Model for N_2O		gN_2O/s			factor vs release
model N_2O OCD	high 2.62	1.6	11	4%	1.6
	low 1.39	0.7	11	12%	1.9
model N_2O sigz	high 2.62	1.1	11	5%	1.7
	low 1.39	0.5	11	7%	3.1

Model for CO_2		gCO_2/s			factor vs operator
model CO_2 OCD		639	22	14%	0.7
model CO_2 sigz		275	22	13%	1.6

Model for CH_4		gCH_4/s			N_2O or CO_2 factor
model CH_4 stack OCD		21	10	16%	
with N_2O corr		35			1.6
with CO_2 corr		15			0.7
model CH_4 stack sigz		33	7	21%	
with N_2O corr		78			1.7
with CO_2 corr		53			1.6
model CH_4 diffuse OCD		5.6	9	14%	
with N_2O corr		11			1.9
with CO_2 corr		3.9			0.7
model CH_4 diffuse sigz		4.3	10	24%	
with N_2O corr		13			3.1
with CO_2 corr		6.9			1.6

Conclusion		gCH_4/s
Measured stack		20
Measured diffuse		5.0

		No corr	N_2O corr	CO_2 corr
Model stack average		18	57	34
Model diffuse average		4.9	12	5.4

Emission based on measurements of N_2O and measured CH_4 plumes
For the release at 60 m there were 11 N_2O plume with sufficient high measured N_2O plume resulting in an emission estimate of 20 gCH_4/s. For the 30 m release 11 N_2O plumes could be used and an emission of 5.0 gCH_4/s was determined.

With the OCD and SigZ model runs, 21 and 33 gCH_4/s were obtained respectively for the stack emission. For the diffuse emissions from the platform height emissions of 5.6 and 4.3 gCH_4/s were obtained which is well in line with the tracer based estimate. The standard deviation of the emission estimates are relatively low with 14 to 16% and 21 to 24% standard error for the OCD and SigZ calculations respectively.

Correcting the model for N_2O and CO_2 measurement versus model
Based on the correction factor for N_2O versus the release amount, the factor for the stack for the OCD routine are lower than for the SigZ routine, suggesting that the OCD routine performs better.

When applying the N_2O factors to the CH_4 model calculations emission levels of 35 and 78 gCH_4/s were obtained from the OCD and SigZ routine for the stack and 11 and 13 for the diffuse emissions.
When applying the CO_2 factors to the CH_4 model calculations emission levels of 15 and 53 for the stack and 3.9 and 6.9 gCH_4/s for diffuse emissions respectively were obtained.

The factors for both N_2O and CO_2 are close to 1. For the best estimate for the total emission for K15 is therefore based on the ensemble of the measured and modelled estimated with and without corrections for N_2O and CO_2. This results is 20 +/- 18 gCH_4/s. This emission level is in the same range as emission level provided by the operator.

3.2.6 Other platforms

For all other platforms the plumes were evaluated. As from the 5 release platforms seen, the OCD routine gave on average better factor for N_2O and CO_2 and lower relative errors. Therefore the OCD routing was processed for the other platforms. In Table 17 and Figure 38 the results of both the calculations using the OCD version model and the SigZ version of model are shown and compared. An automated routine was developed to process and integrate the data that summarises the results.

Table 17 Resulting emission estimates for 12 platform data sets using both the OCD and sigZ version of the model.

			OCD Routine				sigZ routine		
Time	Platform	Dist(m)	avg	std	rel std	n	avg	std	rel std
15-11-2018 02:30	K15-FG-1	600	1.9			1			
15-11-2018 02:36	K12-B	817 - 5881	1.1	0.3	17%	3	1.3	0.4	17%
15-11-2018 10:59	K4A	505 - 1330	2.0	0.9	27%	3	2.5	0.9	22%
15-11-2018 19:35	K6D	764	0.6			1	0.8		
15-11-2018 20:01	K6CC	576 - 1061	3.6	5.4	66%	5	4.2	4.4	47%
15-11-2018 21:44	K09c-A	2782	42			1	44		
15-11-2018 21:44	L4A	498 - 869	19.0	19.6	46%	5	33	20	26%
15-11-2018 23:56	L5FA1	844.4	1.7			1	2.0		
16-11-2018 01:41	L5a-D	491 - 908	9.8	4.5	32%	2	12.0	5.5	32%
16-11-2018 16:30	L10E	317.7	0.4			1			
16-11-2018 16:59	L10A	370 - 1205	21	19	40%	5	26	18	31%
16-11-2018 20:23	K12-B	621 - 1082	0.8	0.3	15%	3			

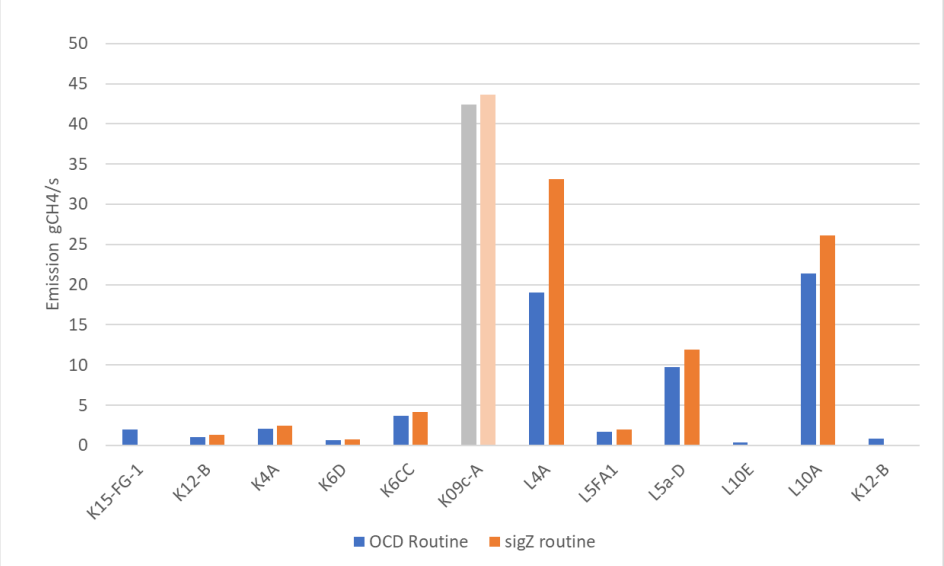

Figure 38 Overview of estimated emissions of the other platforms from the second campaign, using both the OCD and sigZ version of the model.

After having made the decision to use the OCD model implementation for the total dataset, both the July and November sets were evaluated in terms of the measurement based emission levels and the levels provided by the operators. The result of this comparison for the November data is shown in Table 18.
The columns in the table subsequently show time, platform name, the range of distances covered with transects downwind, the average emission level during these experiments, the standard deviation and the number of plumes used to calculate the average emission. The standard error reported is the standard deviation divided by the square root of the number of measurements. Finally the estimate provided by the operator is listed. The operator estimates are obtained using the same procedures that are used for the emission reporting to the authorities, but (possible for most platforms) zoomed in to the day and hour of the actual measurements.
The last column in Table 18 indicates the level of (dis)agreement between the operator estimate and the estimate based on the measurements, the colour of the cell indicates shows:

- Blue: the measured emission seems below the operator's estimate
- (>factor 3)
- Green: indicates both estimates agree well within the error margin
- Orange: the measurements show an emission level above the operator's estimate (between factor 3-10)
- Red: the measurements are clearly above the operator's estimate (> factor 10)

The table shows that all different options occur. When looking at the data, the conclusion might be that it is possible that the ship missed the plume. On the other hand, higher emission estimates can also occur when the plume happens to move along with the ship in the wind direction, making the measured plume wide in the dataset and leading to a (too) high emission level. This uncertainty is significantly higher for the one-off transect measurements and less of an issue for the datasets that rely on multiple plume measurements.

The highest emissions were observed at the K14, L10, K15 and L4-A. The agreement between operator and measured estimates is reasonable, except for platform L4A with an average of 19 gCH_4/s (Figure 39) and an operator estimate of 2.8 gCH_4/s. For the K09c-A platform a high estimate was determined, but there a wide plume at almost 3 km distance was measured. It was thought that the plume originated from K09c-A but at this distance (and sailing in the dark), it is hard to be sure.

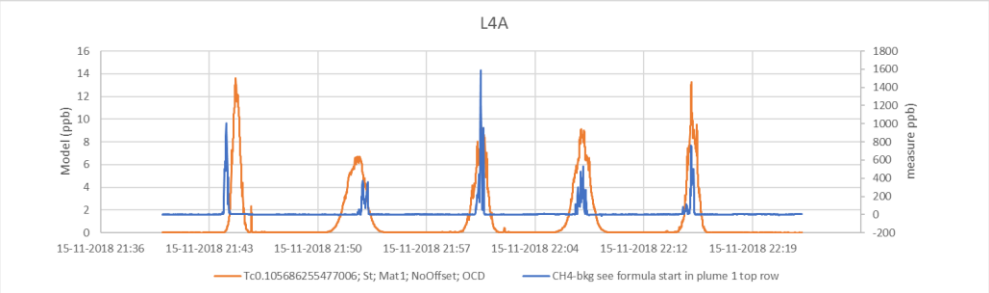

Figure 39 Plume example for L4A with modelled and measured plumes.

Table 18 Overview of the November results.

NOVEMBER	Platform	Distance	Avg gCH4/s	Stdev gCH4/s	N	std err	Operator estimate gCH4/s	Class
15-11-18 02:30	K15-FG-1	500-1000	1.9		1		0.005	
15-11-18 02:36	K12-B	500-1000	1.1	0.3	3	20%	6.16	
15-11-18 07:00	K5CC	100-2500	14	13	12	27%	14	
15-11-18 10:59	K4-A	500-1300	2.0		3		0.04	
15-11-18 13:00	K2b-A	100-2000	6	2	22	8%	1.6	
15-11-18 19:35	K6-D	750	0.6		1		0.08	
15-11-18 20:01	K6CC	500-1100	3.6	5	5	62%	26	
15-11-18 21:44	K09c-A	2782	42		1		1.45	
15-11-18 21:44	L4-A	500-1000	19	19	5	45%	2.8	
15-11-18 23:56	L05-FA-1	500-800	1.7		1		2.6	
16-11-18 01:41	L5a-D	500-1000	9.8		2		0.04	
16-11-18 13:50	L8P4	100-2000	17	5	3	16%	2.6	
16-11-18 15:43	L10-B	1000	0.6	13	1		0.03	
16-11-18 16:30	L10-E	500-1000	0.2		1		0.03	
16-11-18 16:59	L10-A	500-1000	21	19	5	40%	28	
16-11-18 19:20	L10-M	700	0.01		1		0.01	
16-11-18 19:47	K12-G	600	0.01		1		0.01	
16-11-18 20:23	K12-B	500-1000	0.8		3		4.57	
17-11-18 10:09	K14	100-2000	35	10	16	28%	26	
17-11-18 16:39	K15-FB-1	100-2000	18	9	10	16%	19	

3.3 Benzene

Results of the benzene measurements are presented in Table 19. From the July campaign, benzene concentrations taken with gas flasks and measured with a BTX monitor ranged from 0.03 µg/m^3 to 1.21 µg/m^3. The background concentrations ranged between 0.03 µg/m^3 and 0.06 µg/m^3. From the second campaign, mixed samples taken with TENAX tubes resulted in benzene concentration of 1.3 µg/m^3 to 5.1 µg/m^3 within the 500 m zone and 1.2 µg/m^3 to 2.6 µg/m^3 outside the 500 m zone. Next to these samples, data of the mini-DOAS providing open path benzene measurements were collected, but this method is still in a developing phase. Further study is needed to process these data.

Table 19 Preliminary results from the benzene measurements.

Platform	Sample	Concentration (µg/m^3)	Remarks
L11	Mixed sample	0.19	> 500 m
L11	Gas flask 320	0.13	3e plume
L11	Gas flask 548	0.06	
L11	Gas flask 569	0.06	
L8-Hotel	Gas flask 579	1.21	0.7 mile
L8-P4	Gas flask 711	0.26	0.7 mile
L10-A complex	Gas flask 6014	0.26	
L10-A complex	Gas flask 722	0.13	
L10-A complex	Gas flask 6017	0.48	
K14	Gas flask 725	0.22	
K14	Gas flask 565	0.06	In N_2O plume
P15-D	Gas flask 633	0.03	
P15-D	Gas flask 522	0.03	
P15-D	Gas flask 084	0.03	
P15-D	Gas flask 057	0.03	
K2b-A	TENAX	1.5	< 500 m
K2b-A	TENAX	2.2	> 500 m
L8-P4	TENAX	1.3	< 500m
K14	TENAX	1.9	< 500 m
K14	TENAX	1.2	> 500 m
K15-FB-1	TENAX	5.1	< 500 m
K15-FB-1	TENAX	2.6	> 500 m


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4 Conclusions

Over recent years several studies were conducted to evaluate the CH_4 emission for onshore oil and gas installations (ECN-E--18-032 and TNO 2019 R10332). Recent studies in the US had shown that emission factors used for oil and gas production were underestimated (Yacovitch et al, 2018). A study was carried out by EDF in the Groningen gas fields area in 2017 because the reported Dutch emission levels per unit of produced oil and gas are among the lowest in the world. Even though the emission levels were in the order if 20% above the reported level during the campaign, the study indeed confirmed that the Dutch emission factors are low compared to those reported by many other countries (Yacovitch et al, 2018).
In the discussion on this subject, the uncertainty for the emissions from offshore installations triggered NOGEPA to commission this project and do actual independent measurements to quantify the emission level for a significant set of North Sea oils and gas platforms.
From a logistic point of view, emission evaluation for offshore installations is more complex compared with onshore measurements. The positive aspect of measurements at sea is that, no matter what the wind direction is, a plume measurement downwind of the platform is almost always possible, but the availability of the vessel, the demands for the right meteo and sea conditions and the combination of measurements on the platform (using the helicopter and a crew that can measure on location) simultaneously with the vessel measurements takes a lot preparation time and flexibility from all partners involved.

Two campaigns were carried out and this report documents the results. The primary aim of the experiments was to assess the total methane emissions of offshore oil and gas platforms independently. The secondary aim was to compare the overall methane emissions from the measurements with the methane emissions provided by the operators.
During these campaigns, tracer release experiments with N_2O were performed from several platforms. This is the first time since the ’80s when atmospheric dispersion models were initially developed that this type of release experiments were done offshore.

4.1 Overall conclusions

The two measurement campaigns have resulted in methane emissions of 18 platforms from the July campaign (+ 10 without good data due to the meteo-conditions) and 20 platforms from the November campaign.

The comparison of the emission levels provided by the operators and the levels obtained from the measurements can be done in multiple ways. Figure 40 below shows the x-y plot comparing the data. The red line indicates the 1:1 line. For all points above the red line the operator estimate is lower compared to the measurement based estimate; for all points below the red line the operator estimate is above the measurement based estimate. The green lines show a plus or minus 50% difference between the two estimates. The orange lines show a difference of a factor of 3. A linear regression can be made to this dataset but the figure already

shows that the slope of that regression will be determined by the 4 platforms with higher emission levels.

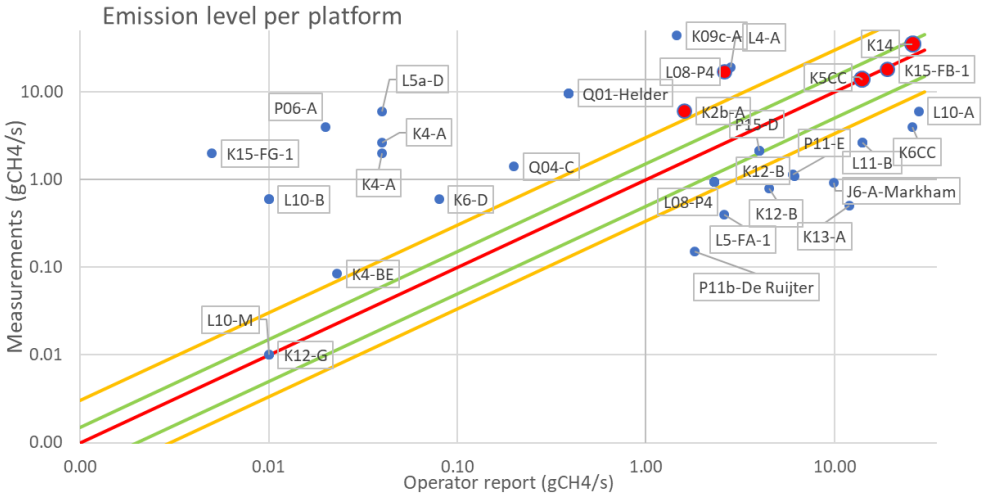

Figure 40 Platform measurement versus operator report. The red dots indicate the platforms with the tracer release experiments carried out in November.

The conclusion is that there are platforms with higher and platforms with lower emissions when operator and measured estimates are compared.

Another way to assess the same data is to add up all emissions estimated from the measurements and to compare that with the same date for the operator estimated values. This is shown in Figure 41. The total estimated emission for 37 platforms for both cruises ends up at 191 gCH_4/s based on the measurements and 184 gCH_4/s using the estimates provided by the operators. In this calculation it was decided to leave out the K9 estimate. With this estimate included the two estimates would end up at (233 and 185 gCH_4/second respectively). It was considered that the K9 estimate was very uncertain. Given the uncertainty in the measurement bases emissions (10-40% random error and a potential non-random error in the order of +/- 50%), the conclusion is that these two levels are similar.

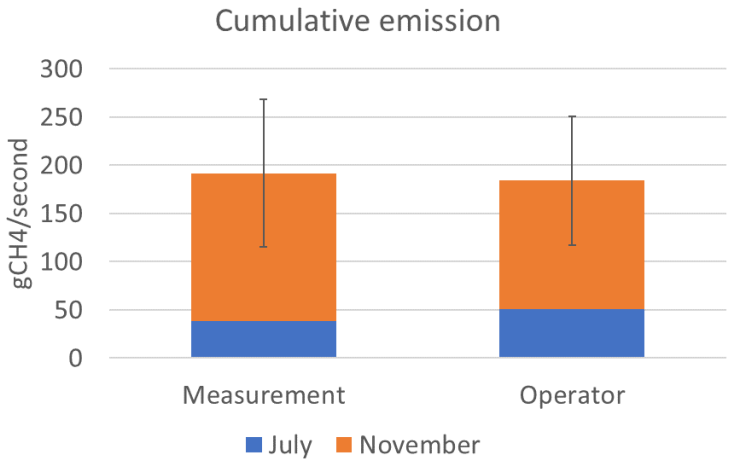

Figure 41 Emission for all platforms together for July (blue) and November (orange) campaign added up using the measurement based estimated (left) and the operator provided estimates (right). The error bar shows the 50% uncertainty level.

There are some considerations to take into account while making this statement:

- It has to be noted that with the measurements a plume can be missed (passing over the ship for example) and therefore will not be generated in the data when there is no plume. In other words, the measurement dataset shows a minimum level for the emission rather than a maximum level.
- The measurement based estimates require the atmospheric dispersion model to translate the measured concentration levels in the atmosphere (in ppb or ng/m^3 CH_4) into emissions (in gCH_4/s). Sets of plumes together using different conditions (mainly different distances) show that this method has a random uncertainty in the order of 30% (for >3 plumes). This however does not cover systematic (non-random) errors that can be made when setting the constants and factors used in the dispersion parametrisation calculation. The N_2O tracer experiments were designed to overcome that problem. Successful tests show that under or overestimate the emission somewhere in the order of 40% for a platform is possible. Where concentration at valves and the emission numbers can result in a factor 10 uncertainty, 40% uncertainty is reasonably good. When adding up results for multiple platforms that error can be different per platform and thus become a random issue again. With only 5 release tests there were not enough statistics to make that claim.
- The “unsuccessful” tracer experiments (the ones that seem to be messed up when hot CO_2 plumes mix with the cold N_2O tracer plumes) can show a mismatch between measured and modelled plumes that can easily be in the order of a factor 10. That implies that when the CH_4 plumes obtained from the measurements are evaluated as cold plumes but were in fact modified by the hot CO_2 plumes, the measurement based emission could be significantly higher. This problem might occur for a subset of all platforms measured (the ones with significant fuel use and CO_2 generation and a wind direction that makes the hot and warm plumes overlap.

Assessing differences in overall platform emissions and the effectiveness of already implemented methane reducing measures was not possible in this stage of the research, but the project meetings with NOGEPA and the operators of the

platforms where the release experiments were done resulted in extra observations. More awareness was created by the operators, especially as there are different types of platforms. From the measured methane emission results, the operators should be able to judge if the already implemented reducing measures meets the expectations. This has already resulted in specific actions and awareness where possibilities are for methane reduction. Together this can lead to an improved emission registration.

Preliminary conclusions from the measurements of the potential contribution of methane emissions from sea water, including screening of potentially leaks from the sea bed, are that no reproducible elevated methane concentrations were detected with the available instrument. Potentially leaks from the seabed were not detected visually. Clear elevations of methane coming from the water phase were seen in the port of Den Helder, presumably from sludge digestion processes on the harbour floor. Further study on the collected data is needed, together with the possibility to measure isotopes from some samples could provide more details on the origin of the available methane.

Data from measurement on other relevant emissions (NOx, benzene, PM) were collected. The NOx and PM data are not yet processed, but available for further evaluation. A part of the benzene measurements are available (Table 19). From the July campaign, benzene concentrations taken with gas flasks and measured with a BTX monitor ranged from 0.03 µg/m^3 to 1.21 µg/m^3. The background concentrations ranged between 0.03 µg/m^3 and 0.06 µg/m^3. From the second campaign, mixed samples taken with TENAX tubes resulted in benzene concentration of 1.3 µg/m^3 to 5.1 µg/m^3 within the 500 m zone and 1.2 µg/m^3 to 2.6 µg/m^3 outside the 500 m zone. Next to these samples, data of the mini-DOAS providing open path benzene measurements were collected, but this method is still in a developing phase. Further study is needed to process these data.

The cooperation between the research team and the operators was a crucial step in getting a scientific well documented dataset. With this cooperation is was possible to do the tracer release tests, enter the 500m safety zone and having the emission levels reported by the operators available for comparison. The discussion in joined project meetings between different operators about the high or low emission levels found by the TNO measurement analyses has already facilitated exchange of knowledge on various types of leaks and their relative importance.

5 Recommendations

A set of lessons learned during the first campaign in July 2018 were “taken on board” for the second campaign in November 2018. After the second campaign, another set of recommendations was generated.

- Gather additional knowledge on the vertical dispersion of the plume. The availability of vertical methane and ethane profiles would enable a relatively simple mass balance calculation (multiplying the plume concentration and wind speed throughout the plume shape). This would either avoid the plume dispersion modelling or facilitate improvement towards robust offshore turbulence parametrisations. These kind of vertical profiles could be done using a drone/ balloon/kite systems, an upward looking LIDAR system or simultaneous airplane measurements with a downward looking LIDAR.
- As for the tracer release tests, a big step would be to have a release output lines installed close to the vent exit at multiple platforms. Using the tracer gas release set with the crane in November had a great advantage compared to the July experiments because the tracer release test could be performed in a flexible way on multiple platforms. However, the crane cannot reach the altitude of the highest vent stacks. While this would be only a minor problem over land (because the difference between a 80 and 60 m high plume is relatively small in turbulent over-land conditions), this is a problem over sea.
- Furthermore, be aware of hot CO_2 containing flue gas plumes, that can interfere with the cold CH_4 and N_2O plumes, to disturb emission measurements.
- Having the model calculation available simultaneously during the measurements will help ship track planning. This can help doing extra measurements at larger distances at some platforms when doing the low altitude release test.
- When possible, perform two (or more) ship passes downwind of a platform because the single pass data is a lot more uncertain. It is probably better to do more platforms with 3 transects instead of some platforms with only 1 transect and some with 5-10 transects.

There are a number of possibilities of data interpretation with the dataset that was obtained thus far. Using the available data for further interpretation will facilitate further improvement of our knowledge on atmospheric dispersion of gas over the sea and of the level off emission for various gaseous and aerosol components form offshore installations.

- Calculate the width of the plume in the horizontal (sigma-Y) from the available plumes. Now the sigma-Y and sigma-Z (width and height) parametrisations based on the models were used to modify that. The sigma-Y value however could be obtained from the measurement data for about 60-70% of the plumes, in that case only a relation between sigma-Y and sigma-Z is required to get the full plume form match the measurements.
- Learn from the campaign in the Gulf of Mexico – Aerodyne presented during the last NCGG8 conference in Amsterdam (June 2019) (Herndon et al, 2019).
- Share our lessons learned and experiences for a follow-up tracer experiment in the Gulf of Mexico.
- Also evaluate the PM and NOx data obtained during the cruise. For the second cruise the results of the KNMI and TNO measurements can be compared.

- Further evaluate the Benzene concentration measurements. A first order evaluation of these data did not reveal significant results. The DOAS data processed on site did not seem good enough but can be re-evaluated together with the RIVM and Admatech teams (with whom the mini-DOAS system was developed).


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Notes:

Vlog 1 t/m 13: https://www.onsaardgas.nl/meetprogramma-methaanemissies/
- ➔ Made by Jarno Verhoef

Pictures used in this report are made by Arjan Hensen, Aart Tacoma and Jarno Verhoef.

Tara Yacovitch (Aerodyne) has reviewed the report as external reviewer
- ➔ EDF (Environmental Defense Fund) and Aerodyne Research, Inc. did a comparable study in the Gulf of Mexico in February 2018.

7 Signature

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