# Quantification of methane emissions in Hamburg using a network of FTIR spectrometers and an inverse modeling approach

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**Abstract.** Methane ($CH_4$) is a potent greenhouse gas and anthropogenic $CH_4$ emissions contribute significantly to global warming. In this study the $CH_4$ emissions of the city of Hamburg, Germany were quantified with measurements from four solar-viewing Fourier Transform Infrared Spectrometers (FTIR), mobile in-situ measurements and an inversion framework. For source type attribution an Isotope Ratio Mass Spectrometer was deployed in the city. The urban district hosts an extensive

5  industrial and port area in the south, as well as a large conglomerate of residential areas north of the Elbe river. For emission modeling the TNO GHGco inventory was used as a basis. In order to improve the inventory, two approaches were followed: Firstly the addition of a large natural $CH_4$ source, the Elbe river, which was previously not in the inventory. Secondly mobile measurements were carried out to update the spatial distribution of emissions in the TNO GHGco gridded inventory and derive two updated versions of the inventory. The addition of the river emissions improved model performance, while the correction

10  of the spatial distribution with mobile measurements did not have a significant effect on the total emission estimates for the campaign period. A comparison of the updated inventories with emission estimates from a Gaussian Plume Model (GPM) showed that the updated versions of the inventory in several cases match the GPM emissions estimates well, highlighting the potential of mobile measurements to derive up-to-date emission inventories. The mobile measurement survey also revealed a large, so far unknown point source of fossil origin with a magnitude of 0.069 ±0.047 Gg/yr. The isotopic measurements

15  show strong indications that there is a large biogenic $CH_4$ source in Hamburg which produced repeated enhancements of over 1ppm. The $CH_4$ emissions (anthropogenic and natural) of the city of Hamburg were quantified as 14 ±8.0 Gg/yr of which 7.9 ±4.4 Gg/yr are of anthropogenic origin. This study reveals that mobile measurements at street-level may miss the majority of total methane emissions, potentially due to sources within buildings including stoves and boilers operating on fossil gas (also referred to as "natural gas"), as well as due to large area sources like for instance the Alster lake.

## 1 Introduction

Climate change has a profound impact on living conditions and human societies globally. To a large extent, it is driven by strong anthropogenic greenhouse gas (GHG) emissions. Methane ($CH_4$) is the second-most prevalent GHG emitted by human activities (Allen et al. (2013)). Over a 20-year horizon, the Intergovernmental Panel on Climate Change (IPCC) estimated the global warming potential (GWP) of $CH_4$ to be 81 times larger than that of Carbon Dioxide ($CO_2$) (Stocker and Qin (2013)).

25 Methane has a relatively short atmospheric lifetime of about $9.1 \pm 0.9$ years (Prather et al. (2012)), which makes it an attractive target to diminish the warming rates in the short- and medium-term.

In urban areas, there are various types of anthropogenic and natural $CH_4$ sources. Fossil fuel $CH_4$ emissions are for instance a typical anthropogenic source, such as fugitive emissions from gas pipelines contribute significantly to anthropogenic $CH_4$ emissions (Schwietzke et al. (2014); McKain et al. (2015)), or road transport and combustion of $CH_4$ (Defratyka et al. (2021)).

30 Biogenic sources include, among others, emissions from sewage systems (Fernandez et al. (2022)) and waste water treatment (Maazallahi et al. (2020)). Furthermore, wetlands and bodies of water are common natural $CH_4$ emitters. For instance, in Hamburg, Matousu et al. (2017) showed that the river Elbe releases Methane, and wetlands surrounding the Elbe produce Methane, too (Ragnhild Hummel (2021)).

Given the range of possible sources, there are various methodologies used to quantify $CH_4$ emissions from gas pipelines, 35 power plants, refineries and natural sources. To detect leak indications (LIs) for pipelines, frequently mobile measurements are applied, as shown by Maazallahi et al. (2020), who identified 145 LIs (i.e., $CH_4$ enhancements of more than 10 % above background levels) in Hamburg and 81 LIs in Utrecht while measuring $CH_4$ mole fractions at the street level (2018 and 2019). Data from such mobile surveys can then be further analyzed to quantify emissions from concentration measurements (Weller et al. (2019)). Similiarly, Phillips et al. (2013) identified 3356 LIs with concentrations exceeding up to 15 times the global 40 background level through mapping $CH_4$ LIs across all urban roads in the city of Boston. Moreover, they associated the LIs with fossil gas (also commonly referred to as "natural gas") after analyzing the isotopic signatures. Weller et al. (2018) evaluated the ability of a mobile survey methodology (von Fischer et al. (2017)) to detect fossil gas leaks and quantify their emissions. In a mobile laboratory downwind of fossil gas facilities in the Barnett Shale region, Yacovitch et al. (2015) measured $CH_4$ and ethane ($C_2H_6$) concentrations. To quantify emissions from a natural-gas-based power plant in Munich, Toja-Silva et al. 45 (2017) employed differential column measurements (Chen et al. (2016)), together with a computational fluid dynamics (CFD) model. Chen et al. (2020) presented the first investigation of $CH_4$ at a large folk festival, investigating the $CH_4$ emissions from Oktoberfest 2018.

Isolated $CH_4$ sources can be quantified best individually and gradually lead to a better understanding of mix of sources in a certain area. At a city scale, the mix of sources can however be quite complex and also above ground-level sources, which 50 cannot be picked up very well using ground-based mobile surveys, can play a role in the total emissions. Quantifying emissions of larger areas, thus entails the use of modeling frameworks, which incorporate wind information and mixing between a multitude of individual sources.

To determine fossil gas emission rates for the Boston urban area, McKain et al. (2015) and Sargent et al. (2021) incorporated a high-resolution modeling framework with a network of in situ measurements of $CH_4$ and $C_2H_6$. Luther et al. (2022) used a network of portable solar-tracking Fourier transform spectrometers (EM27/SUN) along with a Lagrangian particle dispersion model to calculate emissions from coal mining activity in Poland. The EM27/SUN is an instrument commonly used to measure column-averaged dry air mole fractions of $CH_4$ with high precision. Klappenbach et al. (2015) and Knapp et al. (2021) have deployed the portable instrument on ships to measure transects of $CH_4$ concentrations across the Atlantic and the Pacific Ocean and Hase et al. (2015) have set up EM27/SUN spectrometers in Berlin to determine emissions of $CH_4$ and $CO_2$.

In 2019, Dietrich et al. (2021) installed the Munich Urban Carbon Column network (MUCCnet), an urban sensor network, that constantly measures greenhouse gases with EM27/SUN instruments in a fully automated and long-term manner. The network consists of four spectrometers around the city and one at the center such that at least one station will always be upwind and another one downwind. The network of solar-tracking spectrometers measures the total column concentration of $CH_4$ and thus is sensitive to both near ground and above ground sources.

For this study we temporarily moved part of the MUCCnet infrastructure to Hamburg, and operated four of the spectrometers in locations distributed around the city.

With the third biggest port in Europe (one of the 20 largest in the world (Hamburg (2021)), Hamburg contains a large industrial area south of the Elbe river, with oil and gas refineries and it is one of the largest cities in Europe. Previous studies in Hamburg targeted only specific parts of the city or specific sources alone. Matousu et al. (2017) estimated the emissions from one part of the river Elbe. Furthermore, Maazallahi et al. (2020) explored gas leakages through mobile measurements in the mostly residential area north of the Elbe.

In this study we complement the column measurements, with mobile $CH_4$ surveys, to get a better understanding of the spatial distribution of sources. Additionally source type attribution was carried out to discriminate between biogenic and fossil origin of plumes.

A popular method to explore the types of sources is measuring the isotopic composition of plumes. Menoud et al. (2020), Lu et al. (2021) and Dietrich et al. (2022) demonstrate how the isotopic signature may reveal the source type. For $CH_4$, the isotope ratios between $^{13}C$ and $^{12}C$, and between $^1H$ and $^2H$ are particularly meaningful ($^2H$ is also denoted with D for Deuterium). Comparing the observed isotope compositions to references from the literature or previous measurements may then indicate the type of sources.

When quantifying $CH_4$ emissions, usually only one of the concepts of mobile measurements or inversion of column/in-situ measurements is applied. In this study we combined both of them to identify and quantify the sources in a top-down approach. We used a sensor network similar to MUCCnet together with an emission map with updated distributions based on mobile in situ measurements at the street level. The emission estimate is computed based on the updated map and is compared to the estimate based on the standard inventory. For instance, Lauvaux et al. (2016) and Jones et al. (2021) already compared different prior emission maps (priors) to improve modelling. Lauvaux et al. (2016) compared two emission maps for $CO_2$ but both were taken from literature, while our emission maps are updated using mobile measurements, conducted during the campaign. Additionally, we measured the isotopic composition of $CH_4$ in the city centre of Hamburg continuously for
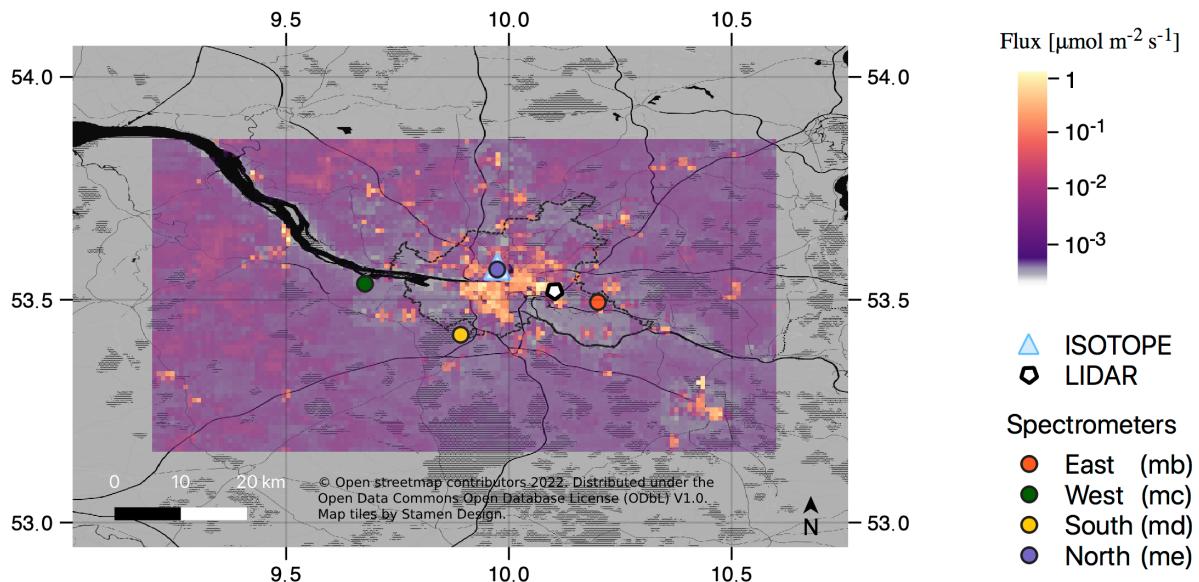
**Figure 1.** Locations of the FTIR Spectrometers and the wind lidar during the campaign. The original TNO GHGco emission inventory, which was used as a prior estimate for emissions, is shown for the modeling domain. Also the border of the administrative region of Hamburg is shown as a black dashed line. The spectrometer me was co-located with an in-situ $CH_4$ isotope instrument.

the campaign period, to assign enhancements to biogenic or fossil sources. To quantify the uncertainty of the modeled wind field, we deployed a Leosphere Windcube 200S Doppler wind lidar that retrieves vertical profiles of wind direction and speed (Wildmann et al. (2020); Vasiljević et al. (2016)).

## 2 Method

In this study, the $CH_4$ emissions for the municipal area of Hamburg are quantified, including the port/industrial area south of the Elbe as well as the mostly residential area north of the river. To measure GHG emissions from a large spatial domain and source mix like Hamburg, remote sensing and in-situ measurements were combined. The in-situ measurements were used to correct the spatial distribution of an existing emission map. The remote sensing setup consists of four FTIR-Spectrometers, which were deployed around the city to scale the updated map and measure the total $CH_4$ emissions of the city. To get accurate wind information to aid with flux quantification and spatial attribution, a wind lidar was deployed to measure wind direction and speed. The locations of the total measurement setup can be seen in Figure 1.

## 2.1 FTIR Measurements

Our approach to determine urban emissions is based on the differential column methodology (Chen et al. (2016)). The column integrated dry air mole fractions of $CO_2$, $CH_4$ and carbon monoxide (CO) are measured with the help of at least two solar-tracking spectrometers that are placed upwind and downwind of an emission source. The concentration gradients between these stations represent the emissions that are generated in between. As the wind direction is not constant throughout the measurement period, we placed four spectrometers in different locations around the harbour area where the highest emissions are expected accoding to the TNO GHGco Inventory (Super et al. (2020)). The TNO GHGco Inventory is an European database that includes spatially resolved emission data for $CO_2$, $CH_4$, CO, $NO_x$ and NMVOCs. The spatial resolution is $(1/60)°$ for longitude and $(1/120)°$ for latitude, which represents an area of approximately $1\,\mathrm{km} \times 1\,\mathrm{km}$. The emissions are divided into 15 gridded nomenclature for reporting (GNFR) sectors. TNO GHGco is currently the highest resolved GHG emission inventory that is available for Hamburg. For this study yearly average emission estimates as recorded in the inventory were considered.

Between the 27th of July 2021 and the 9th of Sept 2021 our four FTIR-Spectrometers were measuring in Hamburg. From 30 July to 5 Sept, the instruments were deployed at different locations. Before and after that, side-by-side measurements of the four spectrometers were carried out on a roof at the University of Hamburg to make sure all instruments are properly calibrated to each other.

The EM27/SUN instruments were deployed in custom enclosures that protect the spectrometer from rainfall and adverse weather conditions (Dietrich et al. (2021); Heinle and Chen (2018)). These enclosures automatically open when the sun is visible, so that sunlight enters the spectrometer. When rainfall is detected, the system shuts its cover so that the spectrometer is protected against precipitation. The instruments are connected to the internet, which enabled us to operate the four spectrometers remotely during a long campaign. In August 2021 the weather was unexpectedly cloudy and many days the systems were in idle. However, we still had nine good measurement days with sufficient sun-shine to carry out the measurements.

The enclosures were located in the west, the south, the east and in the center of the city of Hamburg as visible in Figure 1. The three sites outside of the city were selected to have little point source influence by local near-by sources and were placed about 20km apart from each other, so the expected $CH_4$ concentration gradients, predicted by the inventory, between the stations are well above instrument precision.

The measurements of the column-averaged dry air mole fractions must be properly filtered to exclude measurement errors. In particular, these arise from non-optimal solar tracking, which is mainly caused by clouds. We used two successive filtering steps: The first filtering step is based on physical properties such as solar elevation, absolute solar intensity, and solar intensity variation during a Michelson interferometer scan. The second filtering step uses data statistics to remove outliers and measurement periods with too few data points. In addition, the measurement data are averaged using a 10 minutes moving average filter.

In order to filter out days with fragmented and interrupted measurements due to repeated cloud cover, we only consider measurement days when at least two stations were measuring at the same time for more than 5 hours.

## 2.2 In-Situ Measurements

To support the modelling and the calculation of the final emission estimate, in situ measurements were performed with a Picarro GasScouter G4302 which measures $CH_4$ and $C_2H_6$ and a Picarro G2301 greenhouse gas analyzer which measures $CH_4$ and $CO_2$. Both sensors were mounted inside a car and a tube was used to pipe the air from the inlet located on the front bumper into the sensors. The height of the inlet was ca. 60 cm above ground level. The $CH_4$ concentration measurements with a sampling frequency of 1Hz and 0.3Hz, for the Picarro G4302 and G2301 respectively, were averaged temporally using a moving average with a 10 seconds time window. The averaging improves the precision of the $CH_4$ measurements from 3 ppb at 1s integration time to 1ppb at 10 seconds integration time (Chen et al. (2020)).

In order to verify and update the prior estimate of an emission map derived from the TNO GHGco Inventory (Super et al. (2020)), mobile surveys were conducted in the city and in the industrial area. The first part of the surveys focused on the residential areas of Hamburg mostly to the north of the Elbe and were conducted in the year 2018 by Maazallahi et al. (2020). These were now complemented in 2021 by a mobile survey with the same instruments in the industrial harbour area (All tracks can be seen in Figure 2. The new survey took place between 9th and 21st of August 2021. During the surveys, $CH_4$, $C_2H_6$ and $CO_2$ concentrations were recorded and mapped with a GPS logger. In order to cover the areas in the harbour that were not accessible by public road on the 20th of August, a boat was equipped with the Picarro GasScouter G4302 and additional surveys were carried out on the Elbe river and the waterways in the harbor area. Some private roads in the harbour areas were sampled after permission was granted from the facility owners, including the wastewater treatment plant and two refineries.

The recorded $CH_4$ concentration during the mobile surveys was separated into its two components, the background and the enhancement peaks occurring near localized sources. While the background is generally rather smooth and varies only slowly with location, short-time component (peaks in the signal) is caused by emissions of nearby sources. In order to compile an improved estimate of the spatial distribution of the emissions, both the complete signal (background and enhancement peaks, later referenced as "upd:all") as well as the peaks only (later referenced as "upd:elv") were averaged on the inventory grid, as can be seen in the right and central plot of Figure 3.

The spatial distribution of emissions recorded in the original TNO GHGco inventory was then updated using the measurements, weighted according to the number of measurements per pixel. In pixels with few measurement points, the new value of the pixel was chosen close to the original value of the inventory. In pixels with many measurement points, the value was chosen closer to the value suggested by the mobile measurements.

For a better comparability between the updated and the original inventory, the sum of emissions in the area covered by our mobile measurements is equal in the original and the updated versions.

The original TNO GHGco inventory has been created using proxy data. For example, all industry emissions reported by Germany were distributed on a map according to the distribution of industrial areas in Germany. In the three inventories used in our study, the industry area south of the Elbe river has lower emissions in the updated versions than in the original inventory, because these emissions were distributed according to the mobile measurements over a wider area.
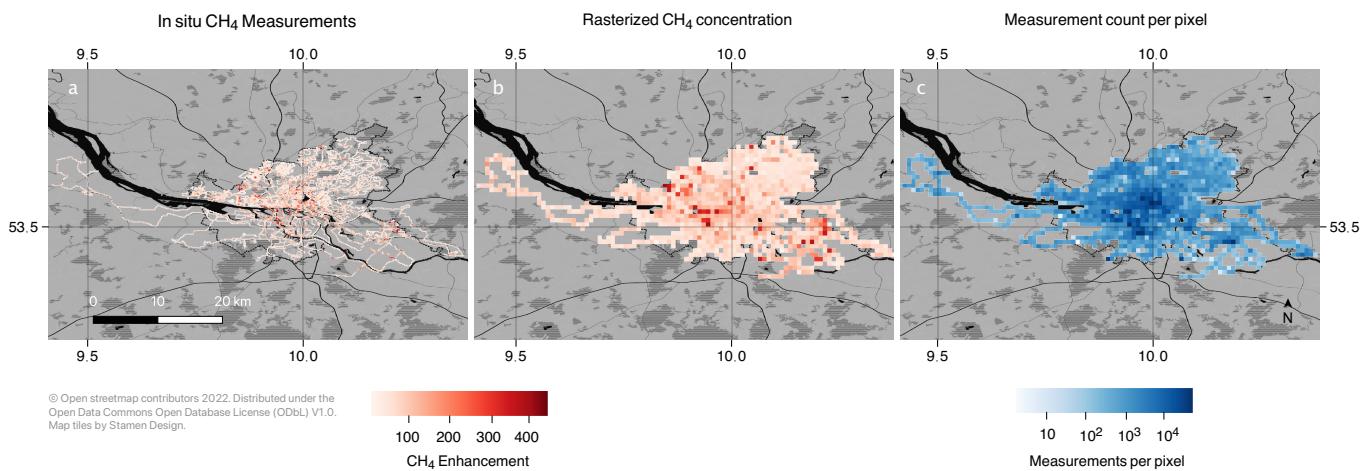
**Figure 2.** The measured $CH_4$ concentration along the driven tracks recorded during the mobile surveys in 2018 (Maazallahi et al. (2020)) and this campaign in 2021 is shown in the left map. The central map shows the concentrations rasterized onto the modeling grid. On the right, the density of measurement points per modeling pixel is plotted.

Furthermore, an inventory layer containing the Elbe and its estimated emissions was added. Matousu et al. (2017) estimated the $CH_4$ flux from the Elbe into the air for different sections of the river. The emission values for the Elbe in each grid cell is the average flux of the corresponding section multiplied with the proportion of the Elbe inside the grid cell. For parts of the Elbe that were not covered in the study by Matousu et al. (2017), the average emissions of the study were used as a prior estimate.

During the mobile survey carried out to map concentrations of $CH_4$, multiple transects were driven through observed plumes. For each plume and location between 3 and 15 transects were driven. Sections, when the car was standing were removed before further analysis. Emission estimates were derived based on a Gaussian plume dispersion model (GPM) as described in Maazallahi et al. (2020). As for several sources the exact emission location was unknown, we calculated an estimate of the emission location for each transect. For this purpose the width of the plume, the estimated Pasquill stability class, as well as the average wind direction during the transect was considered to derive the location estimates. For each location all relevant Pasquill stability classes were estimated based on the average wind speed and the time of the measurements (night time or day time). The presented emission estimates are the average of estimates obtained for each relevant stability class.

## 2.3 Wind Measurements

During the transect drives, carried out for emissions quantification, wind information close to the ground is important. When possible a local portable wind sensor (Lufft WS200-UMB Smart Weather Sensor), measuring wind direction and wind speed at an altitude of 2m was deployed. When no setup of the wind sensor was possible, wind data from the weather station Weathermast, Hamburg were used at an altitude of 10m.
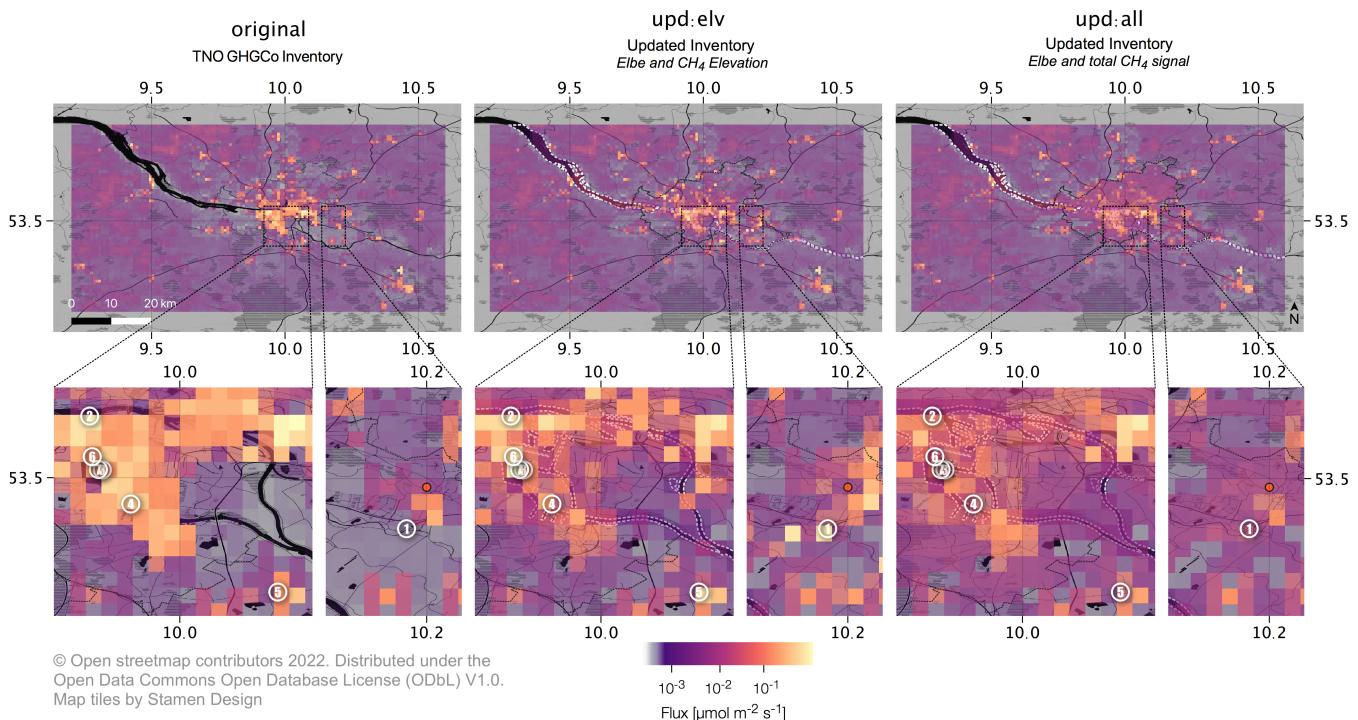
**Figure 3.** For this study, three different inventories were used. First the original TNO GHGco inventory, secondly the updated inventory using the measured $CH_4$ enhancement of the mobile survey ("upd:elv"). The third inventory ("upd:all") was updated using the complete $CH_4$ signal (background+enhancement). All versions of the inventory include an a priori estimate of the river Elbe derived from the findings of Matousu et al. (2017). In this plot, the TNO GHGco Inventory is shown without the Elbe for a better comparison. The close up sections show the locations where point sources were quantified using mobile measurements. Source 3 and 7 are co-located.

To evaluate the uncertainty of the atmospheric transport of the ERA5 model inside the modeling domain, a Leosphere Windcube 200S Doppler wind lidar was deployed at the Weathermast in Billwerder, Hamburg. The lidar provides a windprofile from 100m to the top of the atmospheric boundary layer. Measured wind direction and wind speed was compared to the ERA5 model data for all altitudes where model and lidar data was available (See Figure A5). For each measurement day a standard deviation of the wind direction and speed was derived.

## 2.4 Isotope Measurements

On the roof of the Geomatikum building of the University of Hamburg we took continuous measurements of $CH_4$ at an inlet-height of 80m. Measurements started on the 2nd of August and the setup was operational for most of the campaign period. It was shut down once for maintenance on the 25th of August and resumed operation on the 27th of August. We deployed an Isotope Ratio Mass Spectrometer (IRMS) which continuously measures $\delta^{13}C$ and $\delta D$ with a Delta V Plus/Deltaplus XL from Thermo Fisher Scientific Inc (Brass and Röckmann (2010), Röckmann et al. (2016)).

In addition to the continuous measurements air samples were taken at several locations while carrying out the mobile measurements to characterize the source types of observed plumes similar to Menoud et al. (2021).

195    To analyse the source mix of the measured $CH_4$ and to decide whether it is mainly of anthropogenic or biogenic origin, continuous analysis of the carbon isotope was performed. We used the $\delta^{13}C$ method and the Vienna Pee Dee Belemnite (VPDB) standard. Therefore, we analyse the ratio between $^{13}C$ and $^{12}C$ of the sample gas and compare it to the ratio of standard gases. In Eq. 1 the mathematical definition of the $\delta^{13}C$ method is illustrated:

$$\delta^{13}C_{sample} = \left( \frac{\left( \frac{^{13}C}{^{12}C} \right)_{sample}}{\left( \frac{^{13}C}{^{12}C} \right)_{standard}} - 1 \right) \cdot 1000‰ \tag{1}$$

200    We also analysed the ratio of deuterium to standard hydrogen using the $\delta D$ method, according to the following equation:

$$\delta D_{sample} = \left( \frac{\left( \frac{CH_3D}{CH_4} \right)_{sample}}{\left( \frac{CH_3D}{CH_4} \right)_{standard}} - 1 \right) \cdot 1000‰ \tag{2}$$

The standard gas used for the $\delta D$ method, was the Vienna Standard Mean Ocean Water (VSMOW).

The dominant source type that is responsible for the observed $CH_4$ elevations above background in Hamburg was obtained from a Keeling plot analysis (Keeling (1958)).

205    Sources were classified as biogenic when $\delta^{13}C$ values were between -45 ‰ and -90 ‰ while $\delta D$ values ranged from -245 ‰ to -360 ‰. Signatures with $\delta^{13}C$ values between -32 ‰ and -67 ‰ and a $\delta D$ value between -118 ‰ and -200 ‰ were attributed to fossil emissions Röckmann et al. (2016).

## 2.5    Inverse modelling approach

In order to quantify the urban emissions based on the concentration measurements, a Bayesian inversion framework was used.
210    We utilized and adapted the model as presented in Jones et al. (2021) according to the specific requirements of the Hamburg urban area.

This model was designed to quantify diffuse emission sources with the help of several ground-based spectrometers such as the EM27/SUN. The model accounts for temporal variations of the background concentrations using the so called background influence matrix (BIM). For each station, virtual particles are released (at the receptor time) and travel backwards in time until
215    they reach the simulation border (background time). A weighting factor is assigned to the times when the particles cross the border (background time), based on the number of particles passing the border at that time. It results in a nearly Gaussian shaped distribution of background time for each receptor time. Every 15 min, such a release of particles from each receptor station is initiated. Releasing particles backwards in time is also the basis to generate footprint matrices, which represent the influence of all locations in the domain on the measurement site at a certain receptor time.

220    In order to generate those backward trajectories and the footprints, the STILT (Stochastic Time-Inverted Lagrangian Transport) model is used. The meteorological input data for this model is provided by the ERA5 data-set (Muñoz Sabater (2019)).

As prior information, the TNO GHGco inventory is used (Super et al. (2020)). In addition, we also used the updated inventories that are depicted in Figure 3 and described in section 2.2.

Further assumptions for the model are a spatially homogeneous concentration at the boundary and a known spatial distribu-

225    tion of the diffuse emission sources provided by the inventory. The model minimizes a cost function to find for each emission sector the scaling factor that best fits the model to the measurements.

The cost function is described as follows:

$$\mathcal{J}(\mathbf{x}) = \frac{1}{2}(\mathbf{Kx} - \mathbf{y})^{\mathbf{T}}\mathbf{S}_{\varepsilon}^{-1}(\mathbf{Kx} - \mathbf{y}) + \frac{1}{2}(\mathbf{x_a} - \mathbf{x})^{\mathbf{T}}\mathbf{S_a}^{-1}(\mathbf{x_a} - \mathbf{x}) \tag{3}$$

where $\mathbf{x}$ is the unknown that needs to be fitted, which contains the information of the scaling factors for different emission

230    sectors and the background concentration. $\mathbf{K}$ is the sensing matrix that contains the footprints information and BIM. $y$ is the column concentration measurements obtained from the 4 EM27/SUNs. $x_a$ is the prior emission information. $S_a$ and $S_\varepsilon$ are the prior error covariance matrices for the prior emission and data-model mismatch.

In this study we use the existing framework developed by Jones et al. (2021) to estimate the emissions for individual days. The total emission estimate for the campaign period was calculated as the weighted average of the individual day results. The

235    average was weighted by the number of measurement points per day. Negative days were considered when forming the average.

Emission estimates for smaller areas such as the city of Hamburg or the northern part of Hamburg were calculated by summing up the prior emissions from inventory pixels in that region. This sum was then multiplied with the inversion result for all days of the respective inventory.

## 2.6    Uncertainty assessment for inverse model

240    The error assessment follows the approach described in Jones et al. (2021). The uncertainties are extracted from the posterior covariance matrix $\mathbf{S_p}$, which is mathematically computed based on the sensing matrix $\mathbf{K}$ and the prior error covariance matrices $\mathbf{S}_\varepsilon$ and $\mathbf{S_a}$:

$$\mathbf{S_p} = (\mathbf{K^T S}_\varepsilon{}^{-1}\mathbf{K} + \mathbf{S_a}^{-1})^{-1} \tag{4}$$

The uncertainty of the observations ($\sigma^{prior}_{observation}$) was chosen as the sum of instrument precision, which is 0.2 ppb when the

245    measurements are integrated over 10 min (Chen et al. (2016)), and the transport error calculated for each day. The transport error was obtained by simulating a set of footprints for different wind directions. The wind directions were drawn from a normal distribution, with a standard deviation derived for each day by comparing the wind direction of lidar and ERA5 model. This set of footprints was then multiplied with the three inventories used in this study to obtain a distribution of prior expected enhancements for all possible wind directions. The standard deviation of this distribution was used as the transport error.

250    The uncertainty of the prior emission map ($\sigma^{prior}_{sector}$) was chosen separately for the river layer and the layer with all anthropogenic sources. The river was given an uncertainty of $\pm200\%$ and the anthropogenic sector was given an uncertainty of

±100%. The uncertainty was chosen higher for the river because a priori information was only available for a section of the river in Matousu et al. (2017) and other areas were estimated. The uncertainty of the background ($\sigma_{background}^{prior}$) was set to 8ppb.

## 3 Results

### 3.1 Column Measurements

In Figure 4 the measured concentrations as well as the modeled signal and background is shown for each day. The corresponding emission estimates are shown in Figure 5 for the original inventory and the two updated inventory versions.

On two days, the 23rd of August and the 3rd of September, little enhancement <2ppb between the stations was observed for most of the time, while the stations were measuring simultaneously. This is visible in Figure 4 by looking at the measurements of the different spectrometers plotted as coloured dots. Small enhancements result in low emission estimates for these days as can be seen by comparing with Figure 5.

On other days, in general, larger enhancements between the stations were observed resulting in larger emission estimates. The 6th, the 11th, the 12th and the 24th of August all show emission estimates higher or equal to the prior. The 1st and the 5th of September have been estimated at values between the prior and zero emissions.

Looking at the result of the 12th of August in Figure 4, it becomes evident that the spectrometer **North(mc)** measured a peak at around 12:00 to 13:00 UTC, this peak was not measured by the other stations. During the time of the peak the wind did not change direction and was constantly blowing from the south. Thus the prominent elevation indicates the presence of an unknown temporary source. The inversion framework assigns this elevation to an enhancement of the background concentration (dashed black line at around 10:15 UTC) to balance out observations and prior expected contributions.

On the 31st of August the Spectrometer **West(mc)** which was located about 1.5km south from the Elbe river measured an enhancement of about 5ppb compared to the other stations throughout the whole day, as can be seen in Figure 6 a). During the course of this day the wind came from the north as can be seen by looking at the footprints visualized in white and blue on top of the TNO GHGco Inventory in Figure 6 b).

With the original inventory, the inversion cannot model the enhancement seen by station **West(mc)** because there is no large source in the inventory north of the Spectrometer. In such a case the modeled signal, visualized by solid lines in subplot a) in Figure 6 do not match the actual measurements (dots) very well. The difference is visible for instance by looking at the distance the blue line (station **West(mc)**) has from the purple dots in Figure 6.

In such a case the modeled background at the domain boundary (black dashed line) gets fitted higher than the signal (solid lines). This can result in negative emission numbers (Figure 6 c)), because the enhancement (measurements - background) becomes negative for most time steps.

When the Elbe river is included in the emission inventory as quantified by Matousu et al. (2017), the modeled signal fits the measurements better and the inversion result returns positive emissions. On this particular day the emissions of the Elbe were quantified much higher than the apriori annual emissions of the Elbe in our domain (3.1 Gg/yr). For consistency we thus
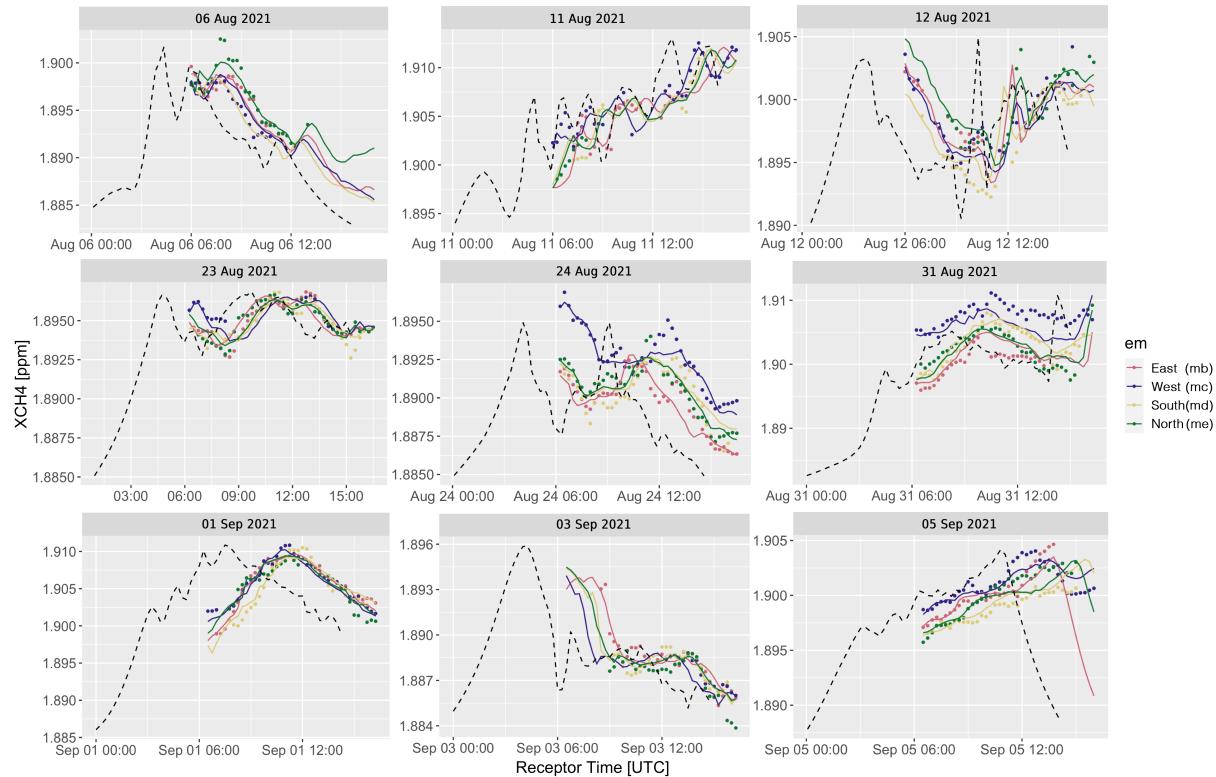
**Figure 4.** Plot of all selected measurement days as used in the inversion framework. The measurements are plotted as differently colored dots for each station. The colored lines represent the posterior observations generated by the inversion framework and the dashed line shows the fitted background at the domain boundary.

decided to include the Elbe river in all other model runs and days presented in this paper. On other days the emissions from the
285  Elbe were close to the prior estimate or around zero as can be seen in Figure A4.

The expected contributions from different sectors for the day 31st of August are shown in Figure 7. These expected contributions were calculated using the footprint and the inventory. As can be seen, on the 31st of August the station **West**(**mc**) was sensitive to river emissions. Also on the 23rd and 24th of August, as well as on the 5th of September station **West**(**mc**) was sensitive to river emissions. On all of these days the concentrations measured by station **West**(**mc**) were in general higher
290  than measured by other stations (Compare 4).

### 3.2  Correlation assessment

For the selected days the correlation between modeled and measured $CH_4$ concentrations was very high for the total signal (modelled background + enhancement) as can be seen in Figure 8 a). Figure 8 b) shows the correlation for the enhancement only, which was weaker but comparable to other studies using the same modeling framework (Jones et al. (2021)).
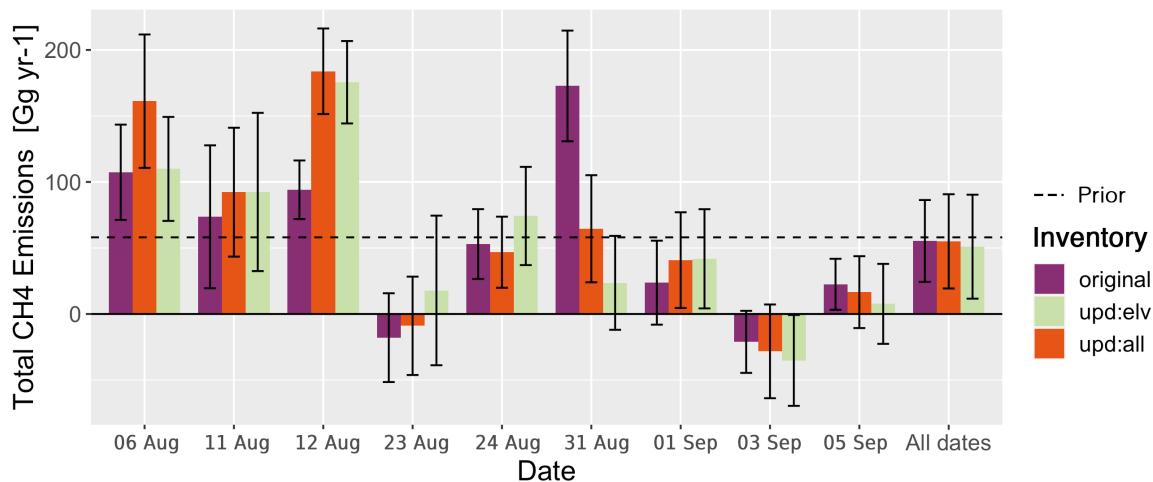
**Figure 5.** Inversion result for all selected days and the three different prior emission inventories ("original": unaltered TNO GHGco inventory, "upd:elv" and "upd:all" are the inventories updated using mobile measurements, filtered for only the peaks as well as the complete measurement signal respectively). The dashed line represents the prior yearly emission estimate of TNO GHGco inventory for the modeling domain. All daily emissions are multiplied up to yearly estimates for better comparison. The emission of the river Elbe was added to all versions of the emission inventory. See Figure A4 in Appendix for the split of total emissions into natural and anthropogenic emissions.

295   The correlation increased significantly when including the natural source into the modeling as visible in Figure A2 in Appendix.

### 3.3   Comparison of different inventories

In this study three different versions of the emission inventory have been used as a prior estimate for the spatial distribution of $CH_4$ emissions in Hamburg.

300   While all three versions lead to comparable results for all measurement days combined, the results differ significantly on single days as can be seen in Figure 5. Over the course of all 9 days the footprint has covered almost all the areas of the modeling domain (because of different wind directions throughout the campaign), while on single days only small parts of the domain are covered. The difference in inventory emissions in certain sections of the prior, can result in different scaling factors for the different inventories, depending on what section of the prior is covered by the footprints on that particular day.

305   For instance, the inversion result can differ with original and the modified inventories, when there is footprint covering the industrial zone of the inventory. With the same observations, the scaling factor calculated by the inversion framework will be slightly lower with the original inventory (as the inventory has already higher emissions recorded here), and higher with the updated inventory, as the updated inventories have lower emissions recorded here and need to be scaled up higher.
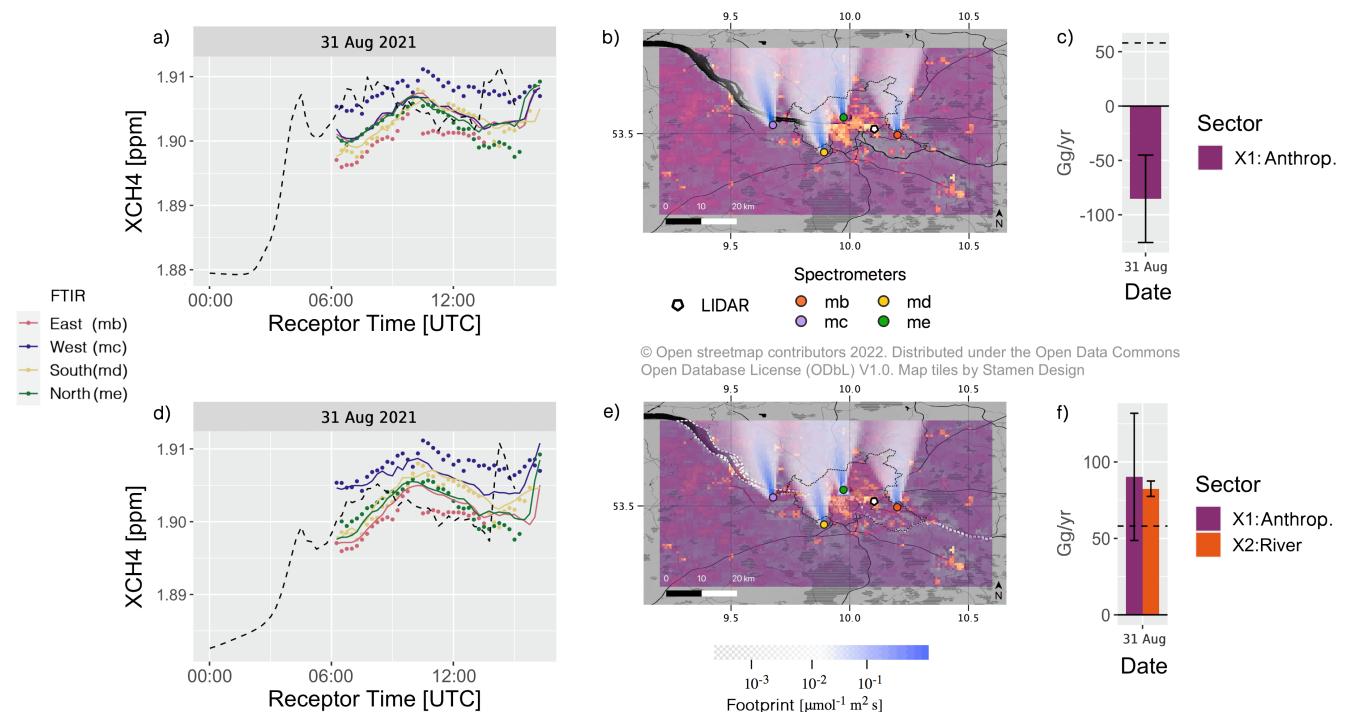
**Figure 6.** Comparison of the inversion result for different priors on the 31st of August. In the top row the inversion result for the original inventory is shown. The second row shows that the inversion result changes from negative emissions (subplot c) to positive emissions (subplot f) when the Elbe river is added into the emission inventory (compare the river region, outlined with a dashed white line, in subplot b and e). When the river is included in the inventory, the modeled signal (solid line) in subplot d) is closer to the measurements (dots) for station **West(mc)** than in subplot a. The dashed black line shows the fitted background at the domain boundary.
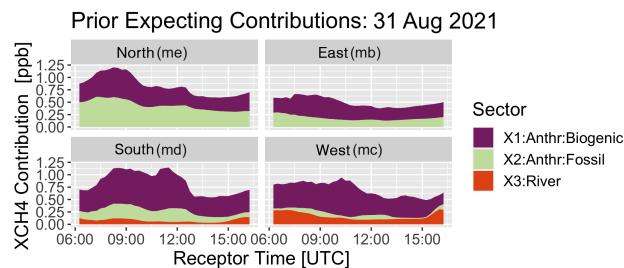
**Figure 7.** Expected prior contributions from different sectors on the 31st of August for the different stations. **Me** is the northern station, **mb** the eastern station, **md** the southern station and **mc** the western station. Emission estimates are multiplied up to yearly estimates for better comparison.
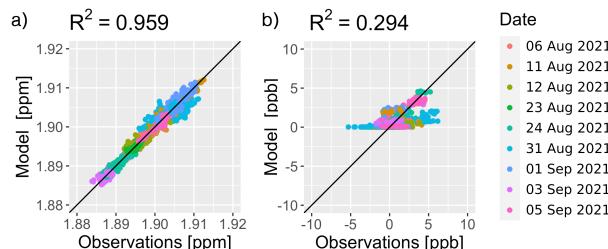
**Figure 8.** Regression plot of the measured and modelled $CH_4$ signal for all nine selected measurement days. The left plot refers to the whole signal (background and enhancement) while the right plot shows the correlation for the enhancement only.

For all days the area covered by footprints is covering the domain more uniformly and thus a result in a similar magnitude
310 can be expected for all versions.

### 3.4 Emission rate estimates from column measurements

We ran the inversion for all inventories (the "original", the "upd:all" and "upd:elv") with the Elbe river as a separate sector. Therefore the emissions are split between river emissions (natural) and anthropogenic sources. We determined the emissions for the entire modeling domain as well as for the area inside the municipality border of Hamburg. The extent of the modeling
315 domain and the area considered as the city (see Figure 1).

The emission rate estimates for natural and anthropogenic sources combined in our modeling domain sum up to 55 ±31 Gg/yr for the original inventory, 55 ±36 Gg/yr for the updated inventory using peaks and background ("upd:all") and 51 ±39 Gg/yr for the updated inventory using peaks only ("upd:elv") (see Table 1). 16 ±6.1 Gg/yr of these emissions were attributed to a natural source spanning the whole modeling domain (potentially the Elbe river and associated wetlands).

320 For the municipal area of Hamburg (including the river, the port, industry and residential zones) natural and anthropogenic $CH_4$ emissions estimated by this study are ranging from 13 ±10 Gg/yr to 14 ±8.9 Gg/yr. The $CH_4$ emissions from natural processes for the Hamburg area were estimated as 6.4 ±2.4 Gg/yr and thus the emissions from anthropogenic sources around 7.9 ±4.4 Gg/yr (for the original prior).

When we split anthropogenic emissions into biogenic emissions and emissions of fossil origin according to the split in the
325 TNO GHGco inventory (see A1), in Hamburg 4.2 ±2.3 Gg/yr are attributed to fossil sources and 3.7 ±2.1 Gg/yr to man-made biogenic origin, for instance wastewater and landfills (See Figure 10).

If we only look at the part of Hamburg which is located north of the Elbe, which was also studied by Maazallahi et al. (2020) our emission estimate is 3.7 ±2.0 Gg/yr for anthropogenic sources. This is higher than the 0.4 ±0.07 Gg/yr Maazallahi et al. (2020) report in their study based on up-scaling emissions from a mobile $CH_4$ survey with a car. The difference can be
330 at least partly explained by the different scientific objectives (and thus methodologies) used in both studies. While our study targeted total emission quantification (i.e. from all sources) using column instruments and thus can also capture sources, which are emitting above street level, the in-situ measurements, carried out by Maazallahi et al. (2020) were used to specifically

**Table 1.** Emission estimates for modeling domain

|  | Original | Upd:all | Upd:elv | Inventory |
|---|---|---|---|---|
| Domain | 55 ±31 | 55 ±36 | 51 ±39 | 58 |
| Natural (Dom) | 16 ±6.1 | 16 ±6.0 | 16 ±6.1 | 3.1 |
| City | 14 ±8.0 | 14 ±8.9 | 13 ±10 | 13 |
| Anthrop. (Ci) | 7.9 ±4.4 | 7.5 ±4.9 | 7.0 ±5.4 | 12 |
| Natural (Ci) | 6.4 ±2.4 | 6.2 ±2.3 | 6.2 ±2.4 | 1.2 |

The emission estimates are reported in Gg/yr for the different sections of the study area. "Domain" refers to the entire modeling domain including natural and anthropogenic sources. "City" refers to natural and anthropogenic emissions calculated for the area inside the municipal border of Hamburg. "Natural (Dom)" and "Natural (Ci)" refers to the emissions from a natural source in the whole modeling domain and the in the city respectively, of which emissions from the river likely represent a large share. Anthrop. (Ci) refers to emissions from anthropogenic activity in the city area.

target ground-level emissions near public roads including the identification and and quantification of fugitive emissions from gas pipeline leaks and the sewer system (not including the wastewater treatment plant). If we consider only fugitive emissions according to the TNO split (A1), our study estimates 1.8 ±1.0 Gg/yr for the northern part of Hamburg. This is between two to seven times higher than the estimate presented by Maazallahi et al. (2020). One potential source which is usually not measurable on the street-level, and could thus explain the lower emissions measured by Maazallahi et al. (2020), is end use inside homes (cook stoves, heating, etc.) (Lebel et al. (2022),Dietrich et al. (2022)). Accumulated emissions from end use, while not affecting street-level concentrations, could be observable in total-column measurements and thus contribute to the higher emission estimates of this study. Another source in Hamburg which could potentially contribute to higher column measurement based estimates is the Alster lake near the city centre. Around this lake Maazallahi et al. (2020) have detected $CH_4$ enhancements, which were low in magnitude but spread over a large area. These low enhancements could not be used for quantification and are thus not included in their estimate, but might be noticeable in the column measurements.

### 3.5 Emission estimates from mobile survey

For several locations inside the study area emission estimates were derived using a GPM from transects recorded during the mobile survey. These estimates are presented in Table 2 and are compared to the emissions recorded in the TNO GHGco inventory as well as the two updated versions. While the emissions of the two updated inventory versions were only spatially re-distributed according to the recorded spatial distribution of $CH_4$ concentrations, the GPM emission estimates take into account wind information to obtain emission estimates.

For Location 1, an oil refinery, sample bags were analysed and an isotopic signature of fossil fuel related $CH_4$ emissions was detected. These emissions were quantified as 69±47 t/yr by driving multiple transects around the source location as visualized

in Figure A3. This value is significantly larger than the value recorded in the TNO GHGco inventory for fossil $CH_4$ emissions in the corresponding pixel (approximately 1km by 1km). Also there is no source recorded in the European Pollutant Release and Transfer Register (E-PRTR) European Environment Agency (2022), which suggests that it is an unknown source. The updated

355    version of the inventory "upd:all" is closest to the Gaussian plume emission estimate for the corresponding inventory pixel. The updated inventory version "upd:elv" suggests even higher emissions for that pixel. The fact that the source at Location 1 was observed on several measurement days and was already observed during the measurements in 2018, suggests that this source could have been emitting continuously for a longer time.

At Location 2 north of the Elbe, the industrial area and north of the municipal waste water plant, transects were driven and an
360    emission estimate was derived from the measured plumes as shown in Figure 9. This estimate of 59±110 t/yr has a relatively high uncertainty because the estimated source location was far away from the transect lines. The GPM estimate includes the values of the original and the Upd:all inventory versions within the error bars. The value in the Upd:elv inventory over estimates the GPM emissions. Emissions for this location were estimated during a period of south wind and thus they could originate from various sources from within the industrial area as well as the wastewater treatment plant. At this location no samples were
365    taken because plumes were not always stable.

Location 3 is situated in the industrial complex south of the Elbe near harbour water ways and adjoining several ports used to load or tank boats with gas and oil derived products. The location is visualized in Figure 9. For this location several large plumes were observed on the site of a refinery. These were attributed to fossil and biogenic source signatures. Biogenic sources however turned out to be dominant in a Keeling analysis of the sample bags. Biogenic emissions could originate from the near
370    by waterbody or from fermentation of waste water from the facility. The estimated emissions from this location are 27±20 t/yr which confirms the value recorded in the corresponding TNO GHGco Inventory pixel. The updated inventory version "upd:all" is within the error bars of the GPM estimate, while the value in the "upd:elv" version lies considerably higher.

The transects at Location 4 were driven on the private roads of a refinery after permission was granted from the operator. First drives were carried out distributed around the accessible area of the refinery and were narrowed down to locations where
375    plumes were detected. The emissions of a prominent point source, present during the time of the survey, were quantified at 9.8±6.3 t/yr which confirms the values recorded in the TNO GHGco inventory and the updated versions as can be seen in Table 2.

At Location 5 plumes were detected downwind of two large sheds of a farm near Meckelfeld. Isotope measurements of air samples collected at this location indicated a biogenic origin of the source. For this source the "upd:elv" inventory provides
380    the closest estimate. The GPM estimate of 74±22 t/yr is considerably higher than the values recorded in the original and the "upd:all" version of the inventory.

Transects at Locations 6 and 7 were both driven by boat. Two point sources with a magnitude of 57±110 t/yr and 39±38 t/yr, respectively, were found in the industrial area. No sample bags were analysed for these locations. For both locations the original inventory is closest to the emission estimate, however the difference between updated and original inventories is small.
385    Both estimates have a high relative uncertainty, because only very few transects were available and the source location could

**Table 2.** Emission estimates from mobile measurements

| L | Lat | Lon | Type | GPM | Original | Upd:all | Upd:elv. | Sign. |
|---|-----|-----|------|-----|----------|---------|----------|-------|
| 1 | 53.468 | 10.187 | refin | 69±47 | 5.3 | 56 | 660 | f |
| 2 | 53.539 | 9.943 | wwp | 59±110 | 47 | 130 | 170 | - |
| 3 | 53.505 | 9.951 | refin | 27±20 | 35 | 41 | 350 | b |
| 4 | 53.483 | 9.969 | refin | 9.8±6.3 | 13 | 12 | 16 | f |
| 5 | 53.427 | 10.062 | farm | 74±22 | 7.6 | 4.8 | 33 | b |
| 6 | 53.513 | 9.944 | refin | 57±110 | 39 | 24 | 36 | - |
| 7 | 53.505 | 9.948 | refin | 39±38 | 43 | 26 | 38 | - |

The emission estimates (GPM) from the mobile survey are reported in t/yr for
selected point sources (L) in the study domain in column "Emission".
Estimates are compared to the emissions recorded in the TNO GHGco
inventory in column "Original" (without natural emissions). The columns
"upd:all" and "Elev." refer to the updated versions of the inventory (including
natural emissions). The column "Sign." records the isotopic source signature
type f:fossil and b:biogenic. Records marked with - were not analysed for
source types.

possibly be estimated too far from the transects. Both GPM estimates include all values recorded in the original and updated inventory versions within their error bars.

In general several significant $CH_4$ sources were quantified during the mobile survey. While several GPM estimates confirmed the values recorded in the emission inventory (both updated and original versions), some of the biogenic and fossil sources were significantly above the values recorded in the TNO GHGco inventory.

### 3.6 Comparison with other emission inventories

The emissions from anthropogenic activity in the administrative region of Hamburg was estimated at 7.9 ±4.4 Gg/yr which is lower than the 12 Gg/yr reported in the TNO GHGco inventory for the year 2015. This difference is however not significant and the inventory value falls within the uncertainty of this study.

During our study, influence from a biogenic source, potentially the river, was found. This natural source was previously not recorded in the TNO GHGco inventory.

The column-measurement-based $CH_4$ emission estimates for all sectors (natural and anthropogenic sources) in the whole domain, covering the city of Hamburg and parts of the surrounding land outside of the administrative region of Hamburg, are of the same magnitude as reported by inventories, as can be seen in Figure 10.

### 3.7 Isotope measurements

The stationary in-situ measurements on the roof of the Geomatikum building (University of Hamburg) show numerous concentration peaks of around 1 to 2 ppm enhancement, as visible in Figure 11 and A1. During the campaign these peaks were only measured during the night or when the column instrument was not measuring due to cloud cover. Both $\delta^{13}C$ and $\delta D$ Keeling
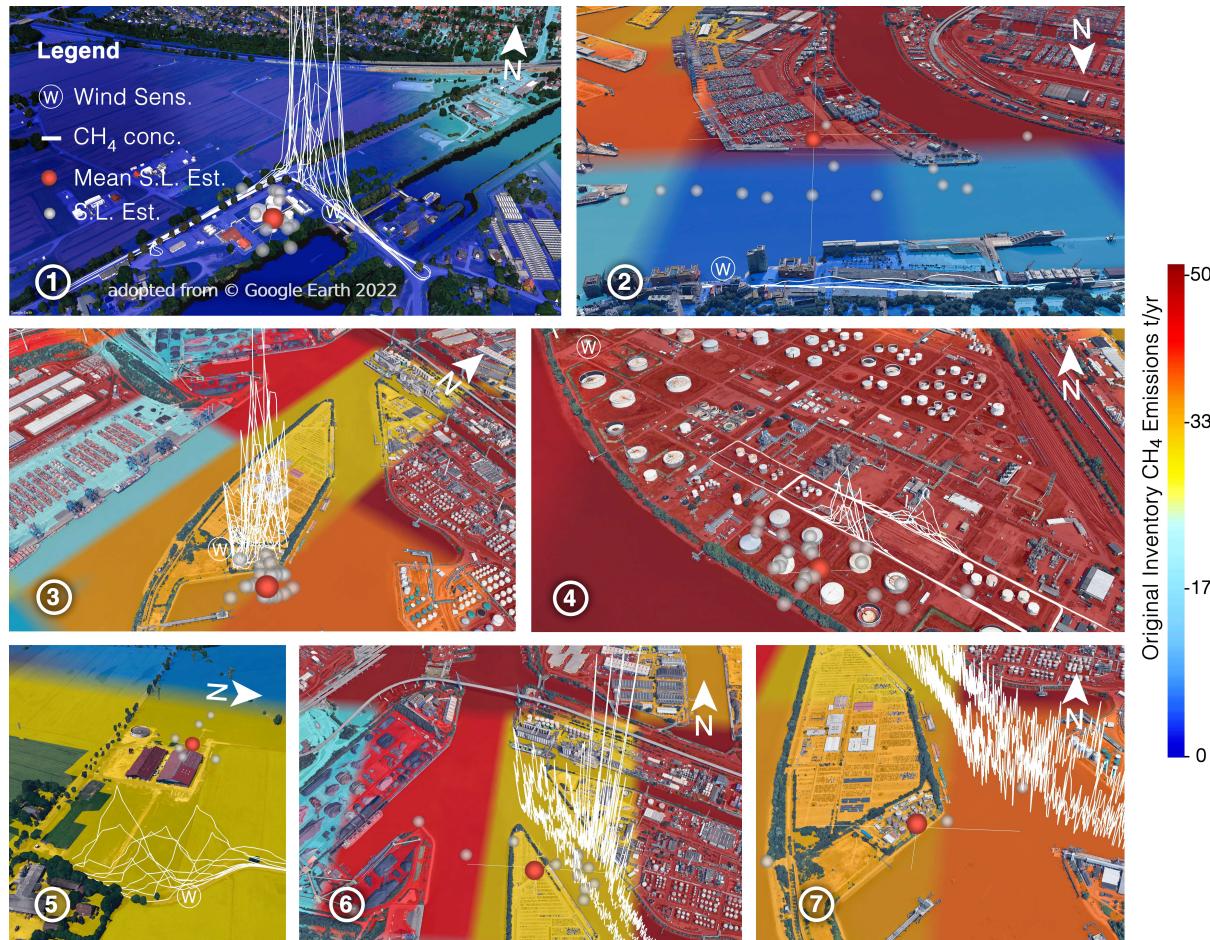
**Figure 9.** Transects of CH$_4$ concentration measurements are visualized as white lines. These were used to determine the emission strength of point sources with a Gaussian Plume model. Estimated Source Locations (S.L. Est.) are shown as grey bubbles. The mean source location estimate (Mean S.L. Est.) is shown as a red bubble, with white perpendicular lines indicating the error of the Mean S.L. Est. The background colors indicate the emissions recorded in the original TNO GHGco inventory (biogenic and fossil). Blue areas indicate zones where the original inventory has low emissions recorded, red and yellow areas indicate high emission zones. The locations where a local wind sensor has been mounted, are marked with a "W". Images taken from Google Earth.

plots indicate a biogenic origin ($\delta^{13}$C = -58.9 $\pm$0.18 ‰, $\delta$D = 306 $\pm$1.5 ‰) of these peaks, as can be seen in Figure12. Potential
405 sources that have a similar signature are in general microbial sources (Menoud et al. (2021)). Both agricultural sources (for instance cattle Lu et al. (2021)) and waste have overlapping signatures with the unknown source in Hamburg. A study on a river estuary at the border between Belgium and the Netherlands by Jacques et al. (2021) found a comparable signature for $\delta^{13}$C (between -25.2 ‰ and -65.6 ‰), however a more enriched signature for $\delta$D (between +101 ‰ and -212 ‰). $\delta$D signatures of down to -260 ‰have been measured by Martens et al. (1999) for gassy sediments in an estuary in Germany. The slightly less
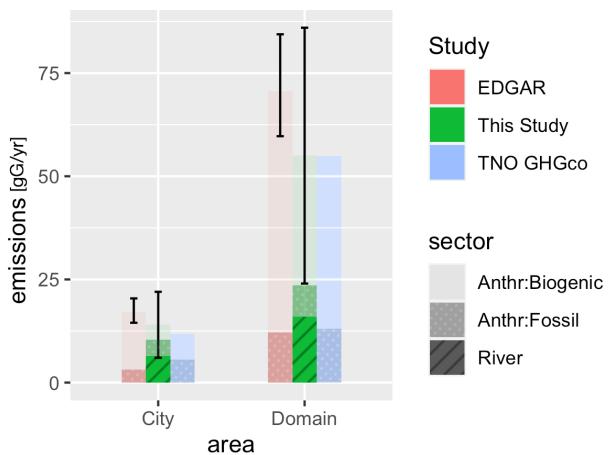
**Figure 10.** Comparison of Inventories and yearly emission estimates of this study for the city of Hamburg and the whole modeling domain. Emission estimates are split by emission sectors according to the split in the TNO GHGco inventory. Error bars for EDGAR are the overall uncertainties for EDGAR GHG from Solazzo et al. (2021). For the TNO GHGco inventory no uncertainty for CH$_4$ is available. The TNO GHGco and the EDGAR inventory both do not include river emissions.
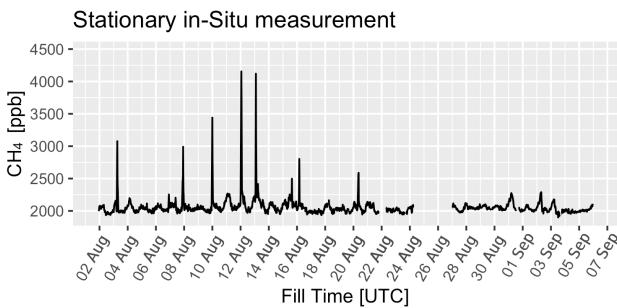
**Figure 11.** CH$_4$ concentration measured on the rooftop close to Spectrometer me. Sharp, short-term peaks were observed repeatedly

410  enriched $\delta$D signature measured in this study suggests that the unknown source in Hamburg could be a mix of several different biogenic (microbial) sources. One of these could be a large natural CH$_4$ source, like for instance the river or wetlands that emit in Hamburg (See also section 3.1). The river flow in the city area is however also influenced by anthropogenic activity (harbor traffic, wastewater, etc.) which could contribute to lower $\delta$D values.

### 3.8 Wind lidar measurements

415  Wind direction and wind speed model mismatch was calculated for the selected measurement days by comparing lidar data and ERA5 model data. Table A3 shows that in general the windspeed is matched well by the model. A mean difference between model and lidar of 0.5 m/s was recorded (Or in other words, the lidar on average recorded a slightly faster windspeed). The
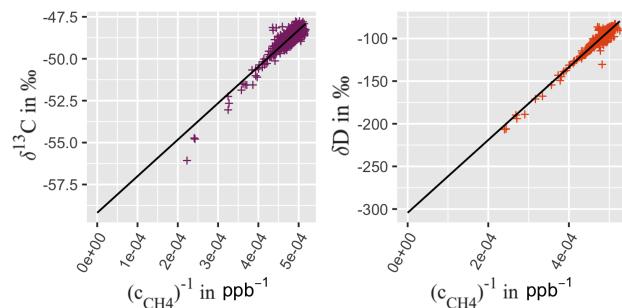
**Figure 12.** Keeling plot for C and H isotopes suggest a biogenic signature of the peaks.

**Table 3.** Comparison ERA5 vs. lidar wind data

| Date | W. Spd. Model Mism. (m/s) | | W. Dir. Model Mism. (ºCW) | |
|------|------|------|------|------|
| | Mean | Std. Dev. | Mean | Std. Dev. |
| 06 Aug 2021 | 1,1 | 1,1 | -2,5 | 23,7 |
| 11 Aug 2021 | -0,1 | 0,9 | 11,6 | 19,8 |
| 12 Aug 2021 | -0,1 | 0,6 | -4,8 | 19,7 |
| 23 Aug 2021 | 0,7 | 0,7 | 6,0 | 6,5 |
| 24 Aug 2021 | 0,1 | 0,5 | 12,8 | 11,3 |
| 31 Aug 2021 | 0,1 | 0,7 | 14,6 | 10,0 |
| 01 Sep 2021 | 1,1 | 0,5 | -2,5 | 12,6 |
| 03 Sep 2021 | 1,2 | 0,5 | 6,3 | 8,1 |
| 05 Sep 2021 | 0,3 | 0,6 | 12,9 | 12,9 |
| mean | 0,5 | 0,7 | 6,0 | 15,6 |

Standard deviation and mean of the mismatch of wind direction (W. Dir. Model Mism.) and
wind speed (W. Spd. Model Mism.) between the ERA5 model and lidar data on the selected
measurement days. To compute these values the model values have been subtracted from the
lidar values.

wind direction is off by an average of 6.0 degree. As lidar measurements are only available from an altitude of 100m on, model
data could only be validated until this altitude.

420     The calculated mismatch was considered when calculating the transport error for each day as recorded in Table A2. These
daily transport error values were then considered in the inversion framework.

## 4   Discussion

In our study two ways of correcting the spatial distribution of the prior emission map were attempted. Firstly, the addition
of sources quantified by other studies, that are not yet part of standard inventories (river emissions were previously reported
425  by Matousu et al. (2017)) and secondly the correction of the spatial distribution of existing gridded inventories (via mobile
measurements).

The example of the 31st of August illustrates how the first approach can have a significant impact on the modeling. When a localized source is not in the inventory, but observable in the measurements, the framework cannot model the prior expected concentrations correctly and thus the modeled enhancement is inexplicably low. In this case the inversion framework will adjust the background to higher values than the measurements and thus leads to negative enhancements as well as negative emissions. Only when the spatial distribution of the emission sources in the model is representative of the real distribution, the inversion framework is able to constrain the total emissions based on the measurements. Once the river was added as a new source to the emission map, the results turned from negative emissions to positive emissions, which shows that adding unlisted sources to the inventory can improve the modeling significantly.

The results for the 31st of August suggest higher emissions from a source north of the western station **mc**. In this paper the source was modeled as river emissions, but it could also be caused by another source further north of the Elbe. For instance, if there were large cattle farms to the north of **mc**, these could possibly produce similar enhancements and would also match the isotopic signature measured in this study. During the campaign however no mobile survey was conducted in the north of **mc** and the river, which could have revealed emissions from the agricultural sector. Also exceptional emissions from ships circulating on the river could cause or contribute to similar enhancements. Other studies in urban environments, such as a study by Pickard et al. (2021) found that polluted urban lakes in India contribute significantly to $CH_4$ and $CO_2$ emissions. Also a study by Zazzeri et al. (2017), who measured isotopic $CH_4$ signatures in London, suggest that river emissions can contribute significantly to the $CH_4$ mix. The proximity to the shelf areas of the North sea and the Elbe estuary could additionally influence the measurements, as around 75% of ocean $CH_4$ emissions come from these areas (Bange et al. (1994)). For natural sources like a river, an oscillation of emissions with the tide cycle could be expected. Such oscillations could however not be resolved in our daily emission estimates. Further analysis of the ongoing isotope measurements could however give more insights if there is some correlation with the tide.

Other potential sources include $CH_4$ emissions from soft soil layers, as reported by the city administration for the Elbe glacial valley, which is located mainly to the south of the current river course (Ragnhild Hummel (2021)). While rather unlikely during a day with moderate wind speeds, these emissions from the ground could have accumulated near the instrument location and caused the observed rise in concentration.

Probably the isotopic signals observed in Hamburg are a mix of several microbial sources of natural and anthropogenic origin. Further investigations here are necessary and mobile measurements near the wetland, which was covered by footprints on the 31st could give a better insight.

Also the second approach, the correction of the spatial distribution of sources with mobile measurements, has an effect, especially on individual days. This may be due to temporal variability of the emissions (different sources emit only for a short period of time) and sometimes the updated inventory matches better, while on other days the original inventory can be used to model the observed enhancements better. In addition to that, on different days, due to specific wind directions, different sections of the inventory are covered with footprints. In some sections the differences between the original and the updated inventories are more pronounced than in other regions. Also it is possible that one of the principal assumptions of the framework, that the background concentration on the whole domain boundary is equal at each time stamp, does not always hold.

The average emission estimate "all Dates" however remains relatively constant for the three versions of the emission inventory. This indicates, that when averaging over multiple measurement days the result is representative for total city emissions and variations in the spatial distribution of prior emissions are of minor importance, whereas they can be important for single days due to the reasons mentioned above. The variability on single days is quite large, which could also show the limits of Bayesian inversion for short measurement periods.

The correction of the inventory using mobile measurements seems to be a promising approach to update the spatial distribution of emissions. However mobile measurements cannot be carried out everywhere at once and multiple drives over the course of weeks need to be combined to get corrections on a city scale. How representative this relatively short snapshot of measured concentration is of the yearly emissions, needs to be studied further. Nevertheless it should provide a better estimate than bottom up inventories in some cases and could be used to distribute emissions on higher resolution grids in areas where there are no high resolution inventories available.

The combination of the two correction methods, the inclusion of natural sources together with using mobile measurements, can improve the spatial distribution of the prior emission map. Scaling this updated map according to the findings of an inversion framework (using column concentration measurements), turns out to be a promising technique to update city scale emission inventories.

In this study, we have updated all sectors of the emission inventory at once. Since mobile measurements are however only sensitive to near ground sources such as fugitives from gas infrastructure and waste water, in future studies the information obtained from mobile surveys could be used to correct only the corresponding sectors in the inventory.

In order to improve the inversion framework further work is necessary especially regarding approaches on how to find a more reliable background prior. At the moment, a constant value has been used which is then fitted by the framework to the measurements. This can lead to errors especially when the spatial and temporal variations of the emissions in the inventory does not conform to the measured enhancements.

The emission estimate for the city of Hamburg was derived over the period of one and a half months, which is a relatively short time period to derive yearly emission estimates. The GPM estimates were derived during an even shorter time and according to Brantley et al. (2014) might not be representative of yearly emissions. Long term measurements especially in the different seasons of the year are necessary to quantify the quite variable ensemble of sources. Natural sources such as the river might be emitting more in the summer, while fossil gas fired heating is mainly used in the winter months. The gap between the emission estimate of the mobile survey by Maazallahi et al. (2020) and the column-based estimate derived in this study could, in the future, be investigated further. For instance, measuring indoor fugitive emissions in representative households and up-scaling these results to a city scale could give further insights where the difference is coming from.

During the mobile surveys we visited several refineries and fossil fuel powered facilities in the harbour area. One large refinery was in the process of disassembly, because the industrial site is moving to another location in Germany. This example shows that although the measured emissions being currently lower than the emission inventory suggests, sources such as industrial processing sites might have just moved their facilities and are now emitting somewhere else. Further studies and

updated emission inventories are necessary, which take into account the spatial changes of emission sources over time and across administrative borders and countries.

## 5 Conclusions

This study shows that the $CH_4$ emissions of a large source region like the municipal area of Hamburg can be quantified
500  with FTIR Spectromenters and inverse modeling. The Bayesian inversion framework turned out to be dependent on a correct modeling of the emission sources in the prior emission inventory and the addition of river emissions, which were quantified in a previous study by Matousu et al. (2017), was necessary to obtain positive emission results on the 31st of August. Small sources and sectors, could not be quantified separately using this methodology, because the expected concentrations were below the instrument precision. The total emissions from a city of the scale of Hamburg can however be measured and quantified.
505  Our study shows, that it is feasible to correct the spatial distribution and the magnitude of sources in emission inventories using a combination of mobile measurements and the inversion of column measurements. The addition of natural sources, that are not listed in the inventory, improved the modelling significantly on some days. While the corrections using mobile measurements, changed the emission estimates for particular days, this effect averaged out for the whole campaign period and the all days estimate was similar for updated and non updated inventories. On the one hand side our analysis of column
510  measurements suggests that there is a large natural $CH_4$ source, potentially the Elbe river, in Hamburg, which is not listed in common emission inventories. Some standard inventories such as the TNO GHGco inventory do not include natural sources, such as wetlands and rivers and adding these manually to the inventory can improve the modelling significantly. On the other hand side our isotope measurements revealed $CH_4$ signals which were attributed to a biogenic origin. Further investigations are necessary to show if this source is in fact the Elbe river and wetlands, or if the calculated natural emissions are a summation
515  of several biogenic sources (of natural and anthropogenic origin). Our ongoing isotope measurements in Hamburg will give us more insights about this in the near future.

Although the contributions from natural sources are significant in Hamburg (6.4 ±2.4 Gg/yr), the study also shows that the largest share in the total $CH_4$ emissions in Hamburg are of anthropogenic origin (7.9 ±4.4 Gg/yr). A comparison between an earlier study in Hamburg by Maazallahi et al. (2020) and this study showed that the $CH_4$ emissions derived via street-level
520  mobile measurements could potentially underestimate total emissions, not capturing fossil gas related $CH_4$ emissions from end use in homes (e.g. gas stoves, boilers for heating; Lebel et al. (2022), Dietrich et al. (2022)). Also large area sources like for instance the Alster lake or the Elbe, could contribute to the differences in emission estimates. In the course of this study a large and so far unknown emission source of fossil origin was located and quantified at 0.069 ±0.047 Gg/yr using mobile measurements. This finding highlights the need for further surveys of unknown sources in cities and that an increased effort in
525  the reduction of anthropogenic $CH_4$ emissions in cities is required.

*Data availability.* The retrieved CH4 concentration measurements can be accessed at: https://retrieval.esm.ei.tum.de/. The raw data will be provided by the authors upon request.

## Appendix A

## A1 Figures
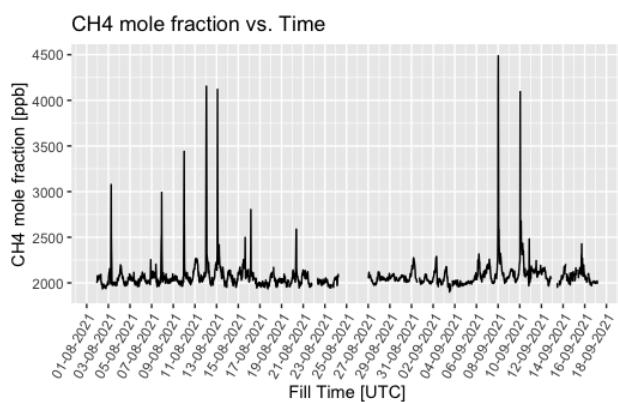
**Figure A1.** Stationary in-situ measurements of $CH_4$ for a longer timeframe. Even after the end of the campaign peaks are visible. These will be discussed in a future study.
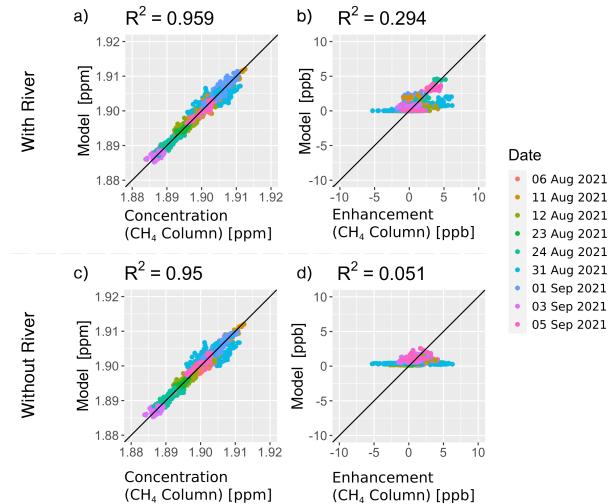
**Figure A2.** Regression plot of the measured and modelled $CH_4$ signal for all nine selected measurement days. The top row shows the result for a prior with the river added as a separate sector. The bottom row shows the result using the unchanged TNO GHGco inventory (no river emissions added). The left column refers to the whole signal (background and enhancement) while the right column shows the correlation for the enhancement only. The addition of the river emissions increased the correlation of the enhancement significantly.
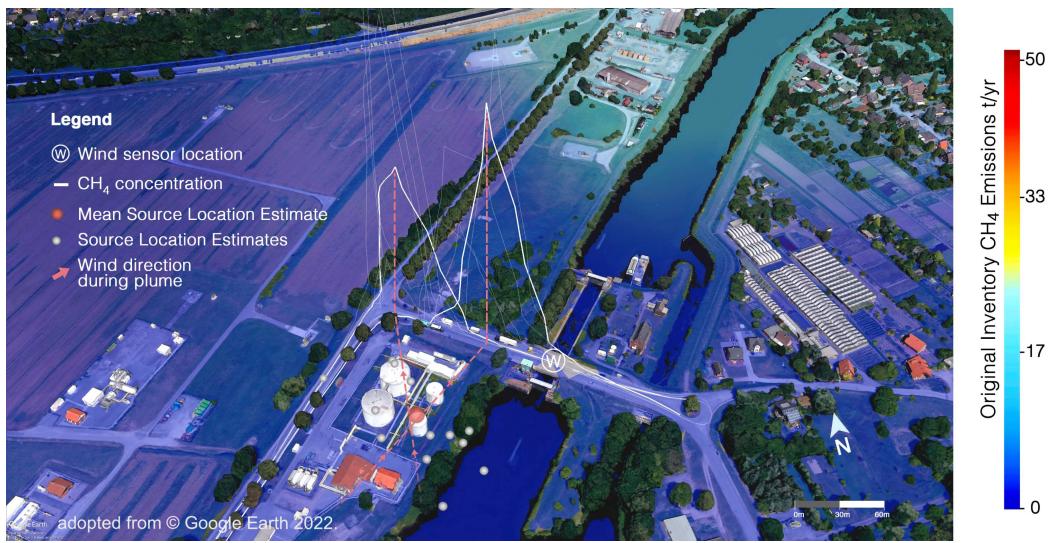
**Figure A3.** Visualization of the mobile measurements around an oil refinery (Location 1) near Bergedorf, Hamburg. The measured $CH_4$ plumes are shown as white lines. Two distinct plumes for slightly different wind directions are highlighted. For all recorded plume-transects a source location estimate has been derived (grey balls). The mean estimate for the source location is shown as a red ball co-located with one of the refinery tanks. The background colors indicate the emissions recorded in the original TNO GHGco inventory. Blue areas indicate zones where the original inventory has low emissions recorded.
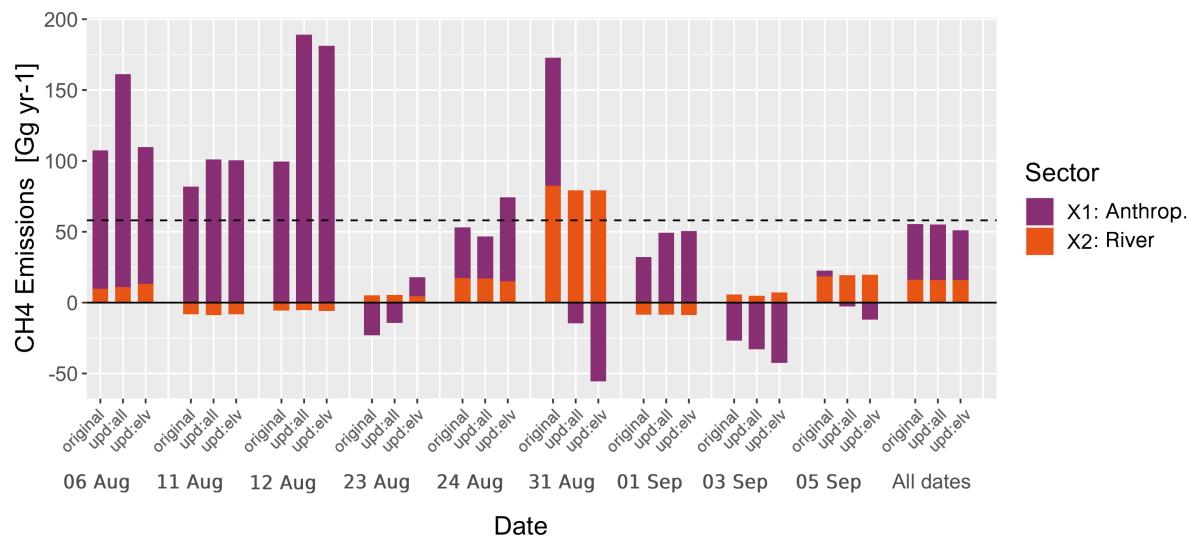
**Figure A4.** This plot shows the results of the inversion split by the two sectors (River and anthropogenic) used in the modelling. Emission estimates are multiplied up to yearly estimates.
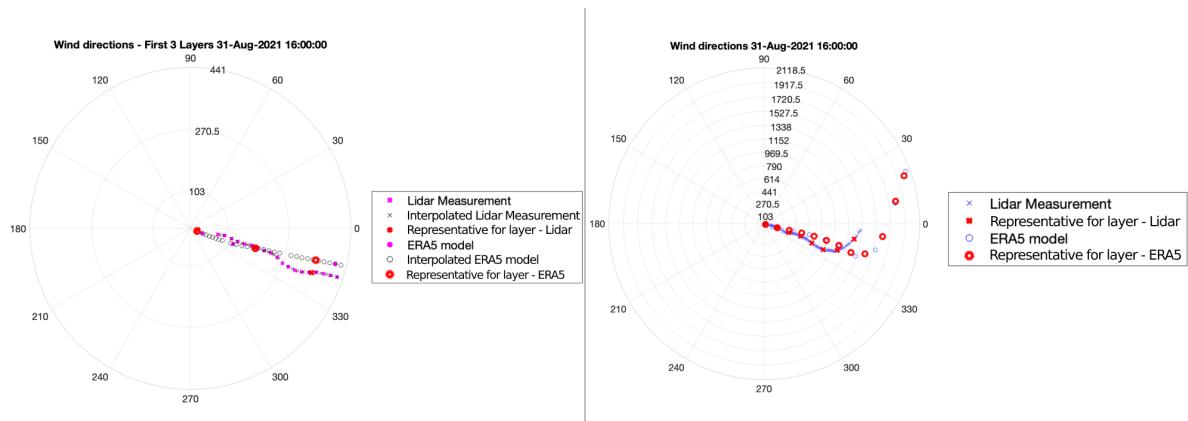
**Figure A5.** Example plot showing the comparison of LIDAR wind data and ERA5 Model on the 31st of August. The circles in the wind-rose plot correspond to different altitudes in meter.

 **A2 Tables**

**Table A1.** Assignment of inventory sectors to the categories biogenic and fossil

| Inventory | Fossil | | Biogenic | |
|---|---|---|---|---|
| | *Abbreviation* | *Description* | *Abbreviation* | *Description* |
| | CHE | Chemical processes | AGS | Agricultural soils |
| | ENE | Power industry | AWB | Agricultural waste burning |
| | FFF | Fossil fuel fires | ENF | Enteric fermentation |
| | IND | Combustion for manufacturing | MNM | Manure management |
| | IRO | Iron and steel production | SWD | Solid waste |
| EDGAR | PRO | Fuel exploitation | | |
| | RCO | Energy for buildings | WWT | Waste water handling |
| | REF TRF | Oil refineries and | | |
| | | Transformation industry | | |
| | TNR | Aviation, shipping, railway | | |
| | TRO | Road transportation | | |
| | A | Public Power | K | Agricultural Livestock |
| | B | Industry | L | Agricultural Other |
| | C | Other Stationary Combustion | J | Waste |
| | D | Fugitives | | |
| TNO | E | Solvents | | |
| | F1-3 | Road transportation | | |
| | G | Shipping | | |
| | H | Aviation | | |
| | I | Off-road | | |

Classification of the different source sectors in the TNO and EDGAR inventory in
biogenic and fossil emissions. Given that the TNO inventory does not separate waste
into sub-categories, we treated all the sources from waste in the EDGAR inventory as
one for consistency

**Table A2.** Transport Error in ppm

| Date | Elev. | Raw | Original |
|---|---|---|---|
| 06 Aug 2021 | 0,00072 | 0,00062 | 0,00066 |
| 11 Aug 2021 | 0,00071 | 0,00068 | 0,00070 |
| 12 Aug 2021 | 0,00056 | 0,00053 | 0,00053 |
| 23 Aug 2021 | 0,00056 | 0,00053 | 0,00056 |
| 24 Aug 2021 | 0,00074 | 0,00068 | 0,00082 |
| 31 Aug 2021 | 0,00073 | 0,00074 | 0,00073 |
| 01 Sep 2021 | 0,00098 | 0,00101 | 0,00105 |
| 03 Sep 2021 | 0,00078 | 0,00066 | 0,00075 |
| 05 Sep 2021 | 0,00119 | 0,00101 | 0,00110 |

Average transport error in ppm as calculated for each day and each of
the three inventories ("Upd:all" and "Upd:elv", as well as the original
TNO GHGco inventory), by rotating the trajectories of the particle
files according to the standard deviation of the Lidar vs. ERA5 Model
miss-match

*Author contributions.*

**Table A3.** Comparison ERA5 vs. lidar wind data

| Date | Mean W. Spd. (m/s) | | Mean W. Dir. (ºCW) | |
| --- | --- | --- | --- | --- |
| | lidar | model | lidar | model |
| 06 Aug 2021 | 6,1 | 5,0 | 157,5 | 159,9 |
| 11 Aug 2021 | 4,1 | 4,1 | 273,0 | 261,4 |
| 12 Aug 2021 | 4,2 | 4,2 | 192,3 | 197,1 |
| 23 Aug 2021 | 7,5 | 6,8 | 55,3 | 49,4 |
| 24 Aug 2021 | 4,0 | 3,9 | 72,6 | 59,8 |
| 31 Aug 2021 | 4,6 | 4,6 | 8,2 | 353,6 |
| 01 Sep 2021 | 5,4 | 4,3 | 312,0 | 314,4 |
| 03 Sep 2021 | 6,3 | 5,1 | 297,5 | 291,2 |
| 05 Sep 2021 | 2,8 | 2,5 | 101,6 | 88,8 |

Daily mean wind direction and windspeed (model and lidar data) for selected campaign days that were used to estimate emissions.

JC, AF and FD designed the concept and organized the campaign. AF, FD, JB, JC, HM, CS, and CV have carried out the measurements. AF, FD, JC, DW, JB have contributed to the writing. AF, JB, FD, DW, JC, HM, CS, MM, XZ, AU, FK have analysed the data. TJ created the inversion framework and provided support. JC and FD acquired the funding and supervised
535 the project. TR, NW have provided extra funding and instruments.

*Competing interests.* The authors declare that they have no conflict of interest.

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