Geomorphological patterns of remotely sensed methane hot spots in the Mackenzie Delta, Canada

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Abstract
We studied geomorphological controls on methane (CH$_4$) hotspots in the Mackenzie Delta region in northern Canada using airborne imaging spectroscopy collected as part of the Arctic Boreal Vulnerability Experiment. Methane emissions hotspots were retrieved at $\sim$25 m$^2$ spatial resolution from a $\sim$10 000 km$^2$ NASA's Next Generation Airborne Visible/Infrared Imaging Spectrometer survey of the Mackenzie Delta acquired 31 July–3 August 2017. Separating the region into the permafrost plateau and the lowland delta, we refined the domain wide power law of CH$_4$ enhancements detected as a function of distance to standing water in different ecoregions. We further studied the spatial decay of the distance to water relationship as a function of land cover across the Delta. We show that geomorphology exerts a strong control on the spatial patterns of emissions at regional to sub-regional scales: compared to methane hotspots detected in the upland, we find that methane hotspots detected in the lowland have a more gradual power law curve indicating a weaker spatial decay with respect to distance from water. Spatial decay of CH$_4$ hotspots in uplands is more than 2.5 times stronger than in lowlands, which is due to differences in topography and geomorphological influence on hydrology. We demonstrate that while the observed spatial distributions of CH$_4$ follow expected trends in lowlands and uplands, these quantitatively complement knowledge from conventional wetland and freshwater CH$_4$ mapping and modeling.

1. Introduction

Methane emissions from the Arctic are a critical part of the global carbon cycle, particularly due to the positive feedback associated with thawing permafrost (Schuur et al 2015). Arctic CH$_4$ emissions are governed by local environmental and climatic factors such as microtopography (Morrissey and Livingston 1992), surficial geology (Elder et al 2018), soils (Walker et al 1998), hydrologic conditions (Zona et al 2009), and vegetation (Von Fischer et al 2010, Andresen et al 2017). Wetlands are dominant natural sources of CH$_4$, and within wetlands, biogenic CH$_4$ is produced by anaerobic respiration of methanogenic microbes as a by-product of the decomposition of organic matter (O'Connor et al 2010). The CH$_4$ is then transported out of the saturated zone either through diffusion (from sediments/and or the water column), ebullition (methane bubbling from lake sediments), or vegetation-mediated transfer in vascular plants (through the roots) (Jeffrey et al 2019). We define CH$_4$ emission hotspots as discrete areas of intense CH$_4$ emission identified as atmospheric-column-integrated CH$_4$ enhancement by NASA's Next Generation Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG) (Elder et al 2020, 2021).

Understanding the occurrence of CH$_4$ hotspots with respect to the spatial variation and heterogeneity of the environmental factors is important for upscaling CH$_4$ emissions and for improved estimation of CH$_4$ emissions across the pan-Arctic (Schneider et al 2009, Schuur et al 2015, Tan et al 2016, Davidson et al 2017, Peltola et al 2019, Engram et al 2020, Turetsky et al 2020). Methane hotspots could also indicate
areas of lower soil stability, thereby identifying sites highly vulnerable to erosion (Oberle et al 2019) and sites with recent thermokarst or other abrupt thaw processes (Turetsky et al 2020, Elder et al 2021). Identification of CH\textsubscript{4} pathways may therefore help gain better local insights on permafrost integrity and help with erosion prediction models, carbon balance models and other earth system models. Elder et al (2020) identified a two-component power law between CH\textsubscript{4} hotspots and their distance to water bodies, with detections rapidly declining beyond 40 m from standing water. This relationship is influenced by lake and wetland geomorphology and its likely control on the local water table position (Elder et al 2020). Additionally, correlations of CH\textsubscript{4} fluxes with water bodies are not uniform and vary by ecology or structure of the landscape (Kohnert et al 2018). Certain vegetation communities also likely influence CH\textsubscript{4} hotspot occurrence. For example, plant height of sedges in the Arctic coastal tundra was found to be a predictor of higher CH\textsubscript{4} emission rates since taller plants have more extensive root systems that stimulate more methanogenesis and conduct more pore water CH\textsubscript{4} to the atmosphere (Von Fischer et al 2010). In this study we evaluated the regional variability in the CH\textsubscript{4} hotspot power law patterns and their relationship with local geomorphological drivers and presumed water table position over the Mackenzie Delta in the Northwest Territories, Canada. Our objectives are to (a) explore differences between hotspots detected in the permafrost plateau and lowland delta as a function of the proximity to the water table and (b) understand the variability of the power law explaining CH\textsubscript{4} hotspot occurrences by geomorphology (specifically land surface elevation changes) and vegetation distribution across eco-regions in Mackenzie Delta. Knowing whether CH\textsubscript{4} hotspots detected in a geomorphological unit or land cover follow a power law and the strength of the associated spatial decay provides important observational clues about the underlying mechanisms and facilitates statistical extrapolations of the relationship to larger regions. A larger spatial decay rate indicates that the probability of finding a CH\textsubscript{4} hotspot declines rapidly beyond the littoral zone as distances to standing water increases and the water table depth increases. On the other hand, a smaller spatial decay rate may indicate a more gradual decay of hotspot occurrence away from water and the possibility that other factors also influence CH\textsubscript{4} emission.

2. Study area and methods

2.1. Mackenzie Delta study region

Our study area in the Mackenzie Delta (68.7–69.6 N, 133.5–136.0 W) includes the main delta, which we refer to as ‘lowlands’, and hilly tundra plateau to the east of the delta, which we refer to as ‘uplands’ (figure 1). We differentiated the uplands and lowlands based on an ecoregion classification reflecting the distinctive assemblages of relief, landforms, geology, soil, and vegetation from the terrestrial ecodistricts of Canada (Agriculture and Agri-Food Canada 2013). The delta is a low-level alluvial plain characterized by lakes, wetlands and relatively thin and discontinuous permafrost with seasonally variable levels of hydrological connectivity to the main Mackenzie River channel (Lesack and Marsh 2007). The southern part of Mackenzie Delta is comprised of open spruce woodlands that gradually decline northwards into shrub dominated regions. Tundra in the transition zone is dominated by tall shrubs, but to the north the vegetation communities are characterized by sedges and dwarf shrubs less than 75 cm in height (Burn and Kokelj 2009).

The hilly uplands east of the Mackenzie Delta are incised by numerous depressions containing lakes and water bodies. The northern and central regions of Richards Island are flat topped with steep slopes leading down to lake-filled valleys (Burn and Kokelj 2009). Thaw slumps are widespread in the uplands and are associated with abrupt erosional slopes immediately adjacent to the shorelines of the tundra lakes (Lantz and Kokelj 2008). Some of the factors initiating these slumps include active layer deepening, warming permafrost, wave action, and gullying by surface runoff (Lantz and Kokelj 2008).

2.2. Methane hotspot identification

Methane emissions hotspots have been detected from shortwave infrared (SWIR) CH\textsubscript{4} absorption bands (∼2300 nm) using imaging spectroscopy from aircraft (Thorpe et al 2014, 2016, Thompson et al 2015, Frankenberg et al 2016, Caswirth et al 2019) and orbital sensors (Thompson et al 2016, Irakulis-Loixate et al 2021). Methane hotspots, defined here as column integrated enhancements greater than 2500 ppm m (integrated concentration—path length units), were retrieved from AVIRIS-NG data collected in 2017 as part of the Arctic Boreal Vulnerability Experiment (ABoVE). Methane enhancements above the background were detected for each flight line using a matched filter approach that operates independently on each push-broom column (Thompson et al 2015). Water has extremely low reflectance in the SWIR, including the CH\textsubscript{4} absorption bands, which makes detecting CH\textsubscript{4} above water surfaces challenging (Ayasse et al 2018). We therefore masked water features from the CH\textsubscript{4} detection algorithms. We identified water pixels in each flight line using near zero SWIR reflectances (wavelength ∼ 2220 nm) and delineated water features based on a minimum size threshold for contiguous water pixels. The distance to the closest water feature was computed in 5 m increments (the AVIRIS-NG pixel size for this survey) for all land pixels. We identified the midpoint of the water feature as the farthest point within the water feature from the
Figure 1. Our study region (red outline) superimposed on a land cover classification map for the Mackenzie Delta. The region is roughly bisected into forested lowlands (left) and tundra uplands (right). The green line indicates the upland/lowland delineation based on dominant ecodistrict landforms (Agriculture and Agri-Food Canada 2013). The black lines indicate individual AVIRIS-NG flight lines.

shore, which was computed using the intersection of the major and minor axes of the water features. The elevation at this midpoint was considered to be the elevation of the water feature.

We computed the Poisson rates of CH$_4$ enhancement by distance to water bins (number of CH$_4$ enhanced pixels divided by number of all pixels in each distance bin) for upland and lowland regions. The first two distance bins closest to water features (<10 m) were omitted in the Poisson rate analysis to account for the negligible reflectance of water features in the SWIR bands (Elder et al 2020), which impacts CH$_4$ detection in mixed open water pixels along shorelines. We computed power law parameters for CH$_4$ enhancement by distance to water separately in the upland and lowland regions of the Mackenzie Delta. The power law describes the functional relationship between Poisson rate of CH$_4$ enhancement and distance to water, and takes the form

$$y = kx^{-a}.$$

Here $y$ represents the Poisson rate of CH$_4$ enhancement, $x$ is the distance to water, $k$ is a constant and $a$ is the spatial decay rate.

2.3. Geomorphological analysis

Topography impacts the hydrological, geomorphological, and biological processes in permafrost landscapes (Moore et al 1991). The spatial distribution of topographic attributes can often be used as an indirect measure of the spatial variability of these processes. We used high resolution (2 m) ArcticDEM elevation data (Porter et al 2018) to obtain elevation and topographic variables for the study region. To investigate the influence of variable land surface elevations on CH$_4$ hotspot distribution, we computed the difference in elevation between all terrestrial locations and their closest water body, defined here as $\Delta Z$. We use this $\Delta Z$ metric as a proxy for water table depth, since water table elevation fluctuation is generally negligible over relatively short distances from open water bodies (i.e. < 50 m from water) in relatively flat landscapes such as the Mackenzie Delta. We also derived land slope (degrees) to characterize the change in elevation between each pixel and its neighbors.

To understand the potential variations in CH$_4$ hotspots as a function of land cover, we computed the distance to water power laws for different land cover classes. We used the 2014 Landsat landcover (Wang et al 2019) to identify vegetation classes in the upland...
and lowland regions (figure 1). Since vegetation type varies by proximity to water, we also analyzed the distribution of the different land cover classes by distance to water.

Though the ArcticDEM provides a comprehensive high-resolution dataset to analyze elevation, it is not a bare earth model and can include vegetation height. To evaluate the potential influence of vegetation on our study, we used vegetation height and bare earth elevation derived from the Land, Vegetation, and Ice Sensor (LVIS), an airborne, wide-swath imaging laser altimeter. Since LVIS data was not available within the primary AVIRIS-NG Mackenzie Delta study region, we identified two proxy flight lines 75 km south of the main study region, but still within the upland and lowland ecoregions (figure 2). We computed the power law equations for these flight lines and analyzed the elevation differences based on ArcticDEM and the LVIS waveforms.

3. Results

The spatial distribution of the CH$_4$ hotspots varied by upland and lowland ecoregions (figure 3). The number of hotspots detected in the lowland was consistently higher than in the uplands (1.09% of lowland and 0.63% of upland non-water pixels with CH$_4$ enhancement >2500 ppm m), with a higher proportion of the hotspots closer to water features in both regions (figure 3). Hotspots also clustered nearer the Arctic Ocean coastline than inland.

3.1. Understanding CH$_4$ enhancements in the context of geomorphology

We plotted the Poisson rate of CH$_4$ enhancement and $\Delta Z$ values at different distance bins from water bodies to understand the presumed water table distribution as a function of distance to water for lowland and upland regions (figures 4(a) and (b)). Methane hotspots detected in the lowland follow a power law curve ($y = 0.034 \times ^{-0.325}$, $R^2 = 0.853$), with the point of inflection at about 30–35 m from water features (figure 4(a)). The average $\Delta Z$ value at this point is roughly 1 m. Methane hotspots detected in uplands also follow a power law ($y = 0.139 \times ^{-0.882}$, $R^2 = 0.913$), with the point of inflection at about 35–40 m, and a mean $\Delta Z$ value of 3 m. The rate of spatial decay in uplands (0.882) is more than 2.5 times stronger than in lowlands (0.325), indicating a stronger spatial decay with respect to distance from water in uplands than in lowlands (figure 4(b)). Figures 5(a) and (b) show the Poisson rate of CH$_4$ enhancement and slope at different distance bins from water bodies for lowland and upland regions.
3.2. Understanding CH$_4$ enhancements in the context of land cover

We plotted the distribution of various land cover classes as a function of distance to standing water (figure 7). Compared to shrubs, most of the forest categories were distributed closer to water across the region. Though our analysis excluded ‘water’ pixels based on AVIRIS-NG data, we included a ‘water’ land cover category which indicates pixels identified as water in the Landsat landcover, but not classified as water based on AVIRIS-NG. We also computed the power law equations for each land cover in the upland and lowland regions (table 1).

3.3. Influence of vegetation on ArcticDEM analysis

The power law functions for the upland and lowland proxy flight lines were ($y = 0.07 \times -0.841$, $R^2 = 0.711$) and ($y = 0.084 \times -0.468$, $R^2 = 0.885$). The difference in upland and lowland spatial decay rates for the proxy region (0.841 for upland and 0.468 for lowland) were similar and consistent to that observed for the primary Mackenzie Delta study region (0.882 for upland and 0.325 for lowland). Additional information and charts on the Poisson rates from the LVIS analysis are presented in the supplemental section. We calculated the difference between elevation from ArcticDEM and the mean elevation of the lowest detected mode from the LVIS waveform ($Z_g$), which represents the bare ground elevation, for the upland and lowland proxy flight lines (figures 8(a) and (b)). The mean difference in elevation across the flight lines are 0.18 m for lowland and 0.1 m for upland. We compared the differences with vegetation height, which was derived from the LVIS variable RH95, which is the height above the ground at which 95% of the waveform occurs. However, there was no significant correlation between the vegetation height and difference in elevation. We suspect the overall elevation differences between the ArcticDEM and LVIS $Z_g$ products are caused by vegetation canopy heights on the broad scale. However, the lack of correlation between these differences and LVIS-derived vegetation heights (RH 95) may also relate to seasonal or interannual changes between observations and/or perceived differences due to mismatched spatial resolution of the observations.

4. Discussion

4.1. Ecodistrict-dependent distance to water patterns

The differences in spatial decay rates for upland and lowland regions are consistent with the idea that topography and geomorphology control the distribution of CH$_4$ hotspots. In lowlands, the hotspots are more spatially distributed, decaying more slowly away from water. An average $\Delta Z$ of less than 1 m across the lowland region (figure 4(a)) points...
Figure 4. The Poisson rate of CH$_4$ enhancement (red circles) and $\Delta Z$ (blue box plots) as a function of distance to water bodies for (a) lowland and (b) upland regions. The $\Delta Z$ is the difference between elevation at a non-water location and the elevation of the nearest water body and can be interpreted as the average position of the land surface relative to the nearest water body. Blue horizontal markers represent the mean $\Delta Z$ by distance bin, and the grey horizontal markers represent the median $\Delta Z$ values.

towards minimal topographic influence on the likely position of the water table, allowing CH$_4$ hotspots to occur at higher rates further from open water bodies. Larger $\Delta Z$ values in the uplands imply a steeper gradient between waterbodies and surrounding land surfaces and a sharper reduction in CH$_4$ hotspot occurrence moving away from standing water (figure 4(b)).

Distances of 30–40 m upland from water represent a critical threshold for the distribution of CH$_4$ hotspots, where on average, hotspots are drastically reduced beyond this distance in both the lowland and upland regions of the Mackenzie Delta and the broader ABoVE domain (Elder et al 2020). Elder et al (2020) also showed that AVIRIS-NG spatial CH$_4$ hotspot patterns are reproducible in non-hotspot fluxes spanning five orders of magnitude. This implies that AVIRIS-NG CH$_4$ hotspot occurrences are dictated by the same environmental controls that regulate the full range of ecosystem fluxes. The critical 30–40 m threshold may represent the average lateral extent of the observed hydrological network’s variable contributing area and its influence on CH$_4$ emissions. A hydrological variable contributing area refers to the zone of dynamically wetting and drying soils which occur near a variable but generally shallow water table (Kirby and Beven 1979) and is commonly used in TOPMODEL-based hydrologic modeling of CH$_4$ fluxes (Melton et al 2013). In these approaches, wetland extents are typically prescribed using a combination of inventory databases, and temporally variable, satellite-derived surface water maps (Bloom et al 2017, Poulter et al 2017). Despite their global coverage, these approaches struggle to account for CH$_4$ emitting areas with sub-surface saturation or inundation beneath closed vegetation canopies. Thus, satellite-derived maps and wetland extent inventories likely underestimate nearshore terrestrial zones
capable of significant CH$_4$ emissions. Our approach reduces these uncertainties by observing CH$_4$ hotspots directly to quantify emergent spatial patterns across our 10 000 km$^2$ study region. Our results imply that large-scale land modeling approaches likely underestimate total wetland CH$_4$ emissions by excluding the fine-scale but widely distributed 30–40 m terrestrial buffer zone of CH$_4$ hotspot occurrence that we observed. Future modeling efforts may improve upscaling of wetland emissions by utilizing the spatial patterns elucidated from our direct CH$_4$ observations.

In addition to biogenic emissions of CH$_4$ in the lowlands, thawing permafrost can create conduits for seepage of geologic CH$_4$ to the surface (Walter Anthony et al 2012). Furthermore, CH$_4$ seepage is a known phenomenon in the Mackenzie Delta (Kohnert et al 2017). While these emissions are also likely to occur in or near water bodies, we expect widespread biogenic hotspot occurrence to far outweigh spatially isolated geologic hotspot occurrences in our survey area and thus dictate the broad spatial patterns we report here.

4.2. ∆Z and slope
Elder et al (2020) postulated that the ABoVE-domain-wide 30–40 m distance threshold for hotspot occurrence corresponds to the average point where the thickness of overlying oxygenated sediment becomes sufficient to completely oxidize any CH$_4$ produced in the saturated anoxic horizons below, effectively eliminating CH$_4$ emissions to the atmosphere. Elder et al (2020) cited literature values of 15–25 cm (Juutinen et al 2003, Olefeldt et al 2013, Turetsky et al 2014) of aerated sediment above the water table to represent this thickness threshold. Combining the horizontal (30–40 m from water) and vertical dimensions (15–25 cm), and assuming negligible water table elevation change over the horizontal dimension, Elder et al (2020) estimated that
on average ground slopes of 0.5%–1% (0.3–0.6°) have the highest likelihood of supporting \( \text{CH}_4 \) hotspots.

Here, our implementation of the high resolution Arctic DEM allowed us to directly assess relationships between \( \text{CH}_4 \) hotspot distribution and ground position in high emitting areas. Our analysis points towards slightly thicker layers of sediment than previously reported values of 15–25 cm needed to significantly curtail hotspot emissions. Assuming negligible water table elevation change, our calculated \( \Delta Z \) metrics indicate median sediment thicknesses of 90 and 200 cm are needed to fully curtail hotspots in lowlands and uplands, respectively (\( \Delta Z \) at 35 m from water, figure 4). This greater thickness may be the result of a combination of factors both real and artificial. Since the airborne \( \text{CH}_4 \) survey was only sensitive to hotspots of extreme \( \text{CH}_4 \) emission (Elder et al 2020), it is likely that these sites require thicker layers of oxygenated sediment to fully curtail hotspot-level emissions compared to regular \( \text{CH}_4 \) emission magnitudes. Similar thicknesses (120–165 cm) of overlying cover soil are required to fully mitigate \( \text{CH}_4 \) diffusion from highly methanogenic landfill conditions (Abushammala et al 2014), which may have analogous \( \text{CH}_4 \) pore gas concentrations to the ecological \( \text{CH}_4 \) hotspots studied here. As a proof of concept, AVIRIS-NG has recently shown utility for mapping...
hotspot CH$_4$ emissions from relatively diffuse landfill sources in California (Casworth et al 2020).

In the lowland and upland delta regions, the highest slopes are found nearest to open waterbodies (figure 5), a common characteristic of thermokarst geomorphology creating land subsidence and erosion as permafrost degrades. Because of this, higher elevations with higher slopes tend to show greater rates of CH$_4$ hotspot occurrence. This is especially true in the lowland region (figure 6(a)), where CH$_4$ hotspots follow a sigmoid curve with respect to increasing slopes. Specifically, lowland hotspots show a strong positive response to increasing slopes between the values of 0.3–1.3$^\circ$. Most lowland slopes > 1.3$^\circ$ occur in the nearest distance bins to water and thus the CH$_4$ hotspot occurrence ratios level out near peak levels for these relatively high slopes. With much lower overall CH$_4$ hotspot occurrence ratios and steeper rising banks on average, the slight positive relationship between slope and CH$_4$ hotspot occurrence was much weaker in the upland region versus the lowlands (figure 7). In uplands, near-shore saturated littoral zones are unlikely to extend beyond 20–30 m from water, which might explain why slope has a weaker effect on enhancement in uplands. The overall positive relationship between slope and CH$_4$ hotspot occurrence could point to thermokarst activity promoting abrupt landscape change and enhanced CH$_4$ emissions via decomposing permafrost carbon (Walter Anthony et al 2016, Turetsky et al 2020, Elder et al 2021).

The Arctic DEM surface we used to determine $\Delta Z$ was likely positively biased due to incorporation of plant canopy heights and may impart a level of uncertainty to $\Delta Z$ measurements. This is particularly apparent in the 30–50 cm difference between ArcticDEM elevations and LVIS-derived elevations (Zg) in nearshore lowland Mackenzie Delta environments (figure 8), where taller vegetation types are more commonly found closer to water (figure 7). ArcticDEM and LVIS (Zg) surface elevations show negligible differences nearshore environments in the uplands (figure 7). This deviation from the observed offset in lowlands may also represent a fingerprint of amplified seasonal inundation dynamics in the lowlands, where the Mackenzie River has greater influence and thus greater effect on the disparate observation periods for the ArcticDEM and LVIS.
Table 1. Occurrence ratio of CH₄ hotspots and power law parameters (spatial decay rate and $R^2$) by land cover in lowland and upland regions. Land cover classes with $R^2 < 0.7$ have been greyed out. The total number of pixels in each land cover type and the mean ΔZ is also presented for upland and lowland regions.

| Land Cover     | Lowland          | Upland           |
|----------------|------------------|------------------|
|                | Occurrence ratio | Spatial decay rate | $R^2$ | Mean ΔZ | n pixels (x10⁴) | Occurrence ratio | Spatial decay rate | $R^2$ | Mean ΔZ | n pixels (x10⁴) |
| Evergreen Forest | 0.012            | 0.146            | 0.146 | 2.34    | 4.579         | 0.008             | 0.781            | 0.922 | 3.1    | 54.6          |
| Deciduous Forest | 0.014            | 0.944            | 0.921 | 2.07    | 17.18         | 0.014             | 0.55             | 0.426 | 2.49   | 0.904         |
| Mixed Forest Woodland | 0.019            | 0.673            | 0.851 | 1.57    | 118.2         | 0.011             | 0.632            | 0.939 | 4.59   | 17.9          |
| Low shrub       | 0.013            | 0.474            | 0.843 | 1.09    | 317.0         | 0.007             | 0.737            | 0.834 | 4.22   | 211.8         |
| Tall shrub      | 0.016            | 0.384            | 0.843 | 1.31    | 3069          | 0.007             | 0.795            | 0.927 | 5.67   | 1066.2        |
| Open shrub      | 0.019            | −0.009           | 0.00  | 1.79    | 0.943         | 0.008             | 0.596            | 0.297 | 7.06   | 0.693         |
| Herbaceous      | 0.006            | 0.635            | 0.909 | 3.08    | 744.8         | 0.005             | 1.135            | 0.898 | 11.01  | 689.2         |
| Tussock tundra  | 0.004            | 1.866            | 0.868 | 11.74   | 124.8         | 0.005             | 1.292            | 0.878 | 7.88   | 1635.3        |
| Sparsely vegetated | 0.003            | 0.403            | 0.979 | 0.58    | 1039          | 0.005             | 0.552            | 0.716 | 4.0    | 268.05        |
| Fen             | 0.012            | 0.229            | 0.891 | 0.68    | 791.1         | 0.007             | 0.741            | 0.907 | 4.59   | 305.5         |
| Shallows/ Littoral | 0.009            | 0.267            | 0.903 | 0.32    | 403.8         | 0.009             | 0.684            | 0.844 | 1.33   | 91.3          |
| Barren          | 0.004            | 0.47             | 0.923 | 0.4     | 578.5         | 0.007             | 0.705            | 0.849 | 1.43   | 69.3          |
| Water           | 0.011            | 0.375            | 0.873 | 0.08    | 237.2         | 0.012             | 0.785            | 0.868 | 0.57   | 96.68         |

The Poisson rates were not significant in three classes (lowland evergreen, upland deciduous forests, and open shrub), and the lowland spatial decay rate was higher than upland for two classes (tussock tundra and mixed forest). In all cases, a higher ΔZ value, referring to a lower water table, resulted in a higher spatial decay rate among upland/lowland classes, which indicates the lower occurrence of CH₄.

Overall, the higher spatial decay rates in upland compared to lowland persisted in 9 out of 14 classes. The Poisson rates were not significant in three classes (lowland evergreen, upland deciduous forests, and open shrub), and the lowland spatial decay rate was higher than upland for two classes (tussock tundra and mixed forest). In all cases, a higher ΔZ value, referring to a lower water table, resulted in a higher spatial decay rate among upland/lowland classes, which indicates the lower occurrence of CH₄.

4.3. Land cover

Analyzing the differences in Poisson rates across the land cover classes shows the spatial variability of CH₄ hotspots across the landscape. The differences in spatial resolution of the datasets (30 m for Landsat and 5 m for AVIRIS-NG) likely caused some classification issues and difficulty in interpreting the results. For example, the water category includes regions identified as water from Landsat, but not identified as water from the AVIRIS-NG bands, which could be due to seasonal inundation differences. This also implies that relatively thin nearshore terrestrial environments (i.e. < one 30 m Landsat pixel) may be misclassified in our approach. Future studies would benefit from land classifications based on native AVIRIS-NG pixels and spectra. Some of the power law differences across land-cover types can also be related to atmospheric mixing differences, e.g. different roughness lengths for each land cover type especially for taller vegetation, or greater air stagnation allowing greater near-surface CH₄ accumulation. Despite these differences, there were patterns in the spatial decay rate of CH₄ hotspots among land cover categories and upland/lowland regions, which are primarily a function of the proximity to water, the presumed water table height, and geomorphological differences, reflected in the land cover.

Overall, the higher spatial decay rates in upland compared to lowland persisted in 9 out of 14 classes. The Poisson rates were not significant in three classes (lowland evergreen, upland deciduous forests, and open shrub), and the lowland spatial decay rate was higher than upland for two classes (tussock tundra and mixed forest). In all cases, a higher ΔZ value, referring to a lower water table, resulted in a higher spatial decay rate among upland/lowland classes, which indicates the lower occurrence of CH₄.
hotspots away from water. The following are some of the differences observed across broad land cover classes:

- **Forests:** The evergreen, deciduous and mixed forests in the study region are predominantly south of the tree line in the lowlands (figure 1). The ecological transition across the tree line is associated with a climatic gradient through the region (Burn 1997, Burn and Kokelj 2009). Open-spruce woodlands with thick surface peat layers characterize the delta south of the tree line. These white spruce forests occupy elevated surfaces on channel levees, lake shores and the delta plain (Pearce et al 1988). Tree stems from wetlands and floodplains have been known to produce and emit CH$_4$ (Pangala et al 2017, Barba et al 2019, Flanagan et al 2021). Within the study region 80% of the forest pixels are within 50 m of a waterbody (figure 7). The proximity to water features helps explain the higher occurrence ratio of CH$_4$ hotspots in lowland forest pixels (table 1).
- **Shrubs:** Low shrubs include closed tundra vegetation cover usually less than 30 cm height dominated by formations of dwarf shrubs. Within the study region, most of the low shrubs are present in the uplands and very few parts of the lowlands (figure 1). The spatial decay rates for proximity to water are similar in lowlands and uplands since they represent similar plant conditions. Tall shrubs in the study region are characterized by willows (Salix), alder (Alnus), dwarf birches (Betula), and a mix of ericaceous shrubs (Ledum, Vaccinium, and Arctostaphylos) (Lantz et al 2010). Towards Figure 8. Difference in elevation derived from ArcticDEM and ground elevation derived from LVIS Zg (lowest detected return) by distance to water bins for the lowland and upland proxy flight lines. Blue horizontal markers represent the mean difference by distance bin, and the grey horizontal markers represent the median difference. The red dotted line indicates the mean difference across all regions in each flight line.
the northern latitudes, dwarf shrub tundra (Betula, Salix, Vaccinium, Ledum, Empetrum, and Dryas) and sedges (Carex and Eriophorum) replace these tall shrubs. The occurrence ratio of tall shrubs in lowlands is 0.016, which is among the highest ratios for shrubs in the region (table 1). The mean $\Delta Z$ of tall shrubs (1.31 m) is lowest among upland and lowland shrubs, emphasizing the importance of higher water tables for CH$_4$ hotspot occurrence.

- Wetland: The spatial decay rate of CH$_4$ hotspots in wetland categories (fen, shallows/littoral and water) was higher in upland compared to lowland (table 1). However, the occurrence ratio of CH$_4$ hotspots was not as high as that over the shrubs and riparian trees. We attribute this due to classification errors in the courser resolution land cover, and the possibility of missing the influence of these land cover classes within 15 m from water. Wetland classification from the Landsat data is known to have a lower classification accuracy due to short-term changes in climate that may cause misclassification of wetlands as shrubs (Wang et al., 2020).

- Tussock tundra: The low-lying outer delta plain is colonized by sedge-tussock wetlands (Mackay, 1963; Johnstone and Kokelj, 2008). The tussock tundra in the study area is predominantly in the uplands, with a small proportion of area identified along the river channel and in the transition zone to lowlands. The spatial decay rates for proximity to water are high in lowlands compared to uplands (1.866 and 1.292). The distribution of tussock tundra in lowland with respect to distance to water is broader, with the 80th percentile distribution being close to 450 m from water (figure 7). The mean $\Delta Z$ of tussock tundra in lowlands (11.74 m) are also higher than that of uplands (7.88 m). Some of these tundra sites may exist in the hummock and hollow microtopography, and these ‘very small’ surface water sites are not detected by 5 m resolution remote sensing data, but can still be wet.

- Other vegetation: Herbaceous land cover in the upland are closed tundra vegetation with herbs and dwarf shrubs. These land cover types are common at the transition between exposed uplands and low-lying plains and creeks (Ullmann et al., 2014). The sparsely vegetated land cover includes closed tundra vegetation cover dominated by formations of grasses, mosses and small herbs. In general, these low shrubs are dry and present in exposed areas such as hill tops (Ullmann et al., 2014). These land cover classes show spatial decay trends similar to the overall region with higher decay rates for upland than lowland implying lower probability of CH$_4$ emission away from water sources in upland.

4.4. Vegetation influence based on LVIS analysis
Based on the mean difference in elevation between ArcticDEM and LVIS-derived bare ground elevation, an average vegetation bias correction of 0.18 m for lowland and 0.1 m for upland is suggested for any error due to the vegetation height. Elevation offsets are likely higher nearer to waterbodies (figure 8). In lowland regions, the largest differences are closest to the water bodies and systematically decrease with increasing distance from water (figure 8(a)). We found that it was not straightforward to compare elevation from ArcticDEM and LVIS and associate the differences only to vegetation height. Seasonality and lidar signal waveforms, especially over water bodies are significant in causing differences (Fayne et al., 2020). The difference in acquisition time (LVIS in 2019 and ArcticDEM is a from a mosaic of tiles between 2012 and 2017 in the study region) may have caused additional sources of error in the differences. Some of the larger differences were found to be because of clouds in the original ArcticDEM tiles which led to overestimation of the ArcticDEM elevation (additional information in appendix (available online at stacks.iop.org/ERL/17/015009/mmedia)).

5. Conclusion
We compared CH$_4$ hotspots across ecoregions in the Mackenzie Delta and found differences in spatial decay rates for upland and lowland regions that can be attributed to topography and geomorphology controls on the distribution of CH$_4$ hotspots. In lowlands, the hotspots are more spatially distributed, decaying more slowly away from water, which is a function of the shallower water table. In upland areas, there a steeper decline in hotspot detection as the distance to water increases. The greater slope and deeper water table moving away from water features is a function of the geomorphology of the region. These differences further indicate the fingerprint of different thermokarst regions. In uplands, abrupt thaw occurs as thaw slumps, gullies and active layer detachments, while in poorly drained areas abrupt thaw creates collapse scar wetlands and thermokarst lakes (Turetsky et al., 2020). Carbon released from abrupt thaw features reflects several biophysical processes including inundation with lake/wetland expansion, release of geological CH$_4$, which is known to escape in relatively huge quantities from a very small number of thermokarst lakes and microbial decomposition of thawed permafrost soil organic matter at depth (Turetsky et al., 2020).

The variable contributing area concept provides a framework with which to expand CH$_4$ hotspot analyses to other portions of the ABoVE domain. Distances of 30–40 m upland from water represent a critical threshold for the distribution of CH$_4$ hotspots, and this threshold may represent the average lateral extent of the observed hydrological network’s variable contributing area and its influence on CH$_4$ emissions. Furthermore, this CH$_4$ observation-derived spatial
metric represents an improvement over indirect land modeling techniques which cannot perfectly map terrestrial zones of significant CH$_4$ emission. As a result, large scale land models may underestimate CH$_4$ emissions from terrestrial environments proximal to perceived wetland extents.

We found distinct differences in hotspot pattern behavior of the forested land, shrubs, wetland and herbaceous region of upland and lowland regions, and most of the patterns can be explained by the proximity to water and the height of the water table. Previous studies have found that CH$_4$ emissions are driven by location-specific factors (proximity to water features and higher water tables) rather than by vegetation (Turner et al 2020). Vegetated area has more CH$_4$ production and less oxidation, due to the chimney effect of plant stems (direct emission, less oxidation), inhibited oxidation from root exudates (less oxidation), and higher dissolved organic carbon content (more production) and these effects of vegetation operate on top of these location specific factors (Turner et al 2020). However, since vegetation type is also a function of the geomorphology, hydrology and other contextual variables, quantifying the vegetation dynamics associated with thermokarst be useful for accurate accounting in large-scale vegetation-based models. Comprehending the spatial variability of the Poisson power law has future potential to calculate freshwater CH$_4$ emission (especially for the Delta geomorphological region where the waterbody is small and dense) than upscaling from process-based models.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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