IMPERIAL

MEQNet: Deep Learning for Methane Point Source Emission Quantification from Sentinel-2 Observations

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Background

- Mitigating ***methane*** emissions is critical for addressing global warming, and accurate point-source quantification is crucial for identifying super-emitters and targeted mitigation.
- ***Sentinel-2***, with its global coverage, high spatial resolution (10–60m), and frequent revisit cycle, has shown strong potential for detecting and monitoring large methane plumes from super-emitters at regional to global scales.
- Current quantification methods, whether ***retrieval-based physical models*** or ***AI models*** trained on simulated data, are computationally costly, make restrictive assumptions, generalize poorly to real imagery, and are sensitive to surface reflectance, leading to unreliable emission estimates.

Objective - MEQNet

A ***Deep Learning Framework*** for ***Methane Emission Quantification***

- Suppresses surface false positives
- Accelerates large-scale processing
- Generalizes across diverse surface types

Data

Data Source

- **Carbon Mapper (2016-2024):** provides plume masks, column enhancements, and emission rates.
- **Sentinel-2 L1C Imagery:** Co-located multispectral data (13 bands) matched with Carbon Mapper detection.
- **ERA5 (ECMWF):** 10-m wind speed and direction for each sample.

Data Construction

- Matched **Carbon Mapper plumes** with **cloud-free (<10%) Sentinel-2 images** from the same date.
- Each sample includes:
  1. Target Sentinel-2 image (**T**)
  2. Reference Sentinel-2 image (T-1, within 1-10 days)
  3. 10-m wind vectors (u_{10}, v_{10})
  4. Ground-truth column enhancement map
  5. Emission rate (kg/hr)
- Negative samples: cloud-free Sentinel-2 scenes without plumes, with zero emission.

Methodology

- **Enhancement Map Generator (EMG)**

Learns a nonlinear mapping from Sentinel-2 reflectance to methane column enhancement; Leverages spectral and temporal differences between methane plumes and stable background.

Main Components:

1. **NDMI-Guided Branch**
   - NDMI = (B11 − B12) / (B11 + B12)
   - Highlights SWIR methane absorption to guide plume localization.
2. **Cross-Channel Module**
   - Captures **inter-band correlations** across 13 Sentinel-2 bands.
   - Enhances spectral temporal feature learning for enhancement inference.
3. **Change Guide Module**
   - Fuses encoded features using temporal variation attention.
   - Suppresses static background; reconstructs enhancement map.

- **Emission Rate Estimator(ERE)**
  - Inputs: Predicted enhancement map + 10 m wind vectors (u_{10}, v_{10})
  - Structure: Feature Extractor + MLP
  - Output: Methane emission rate (kg/hr)

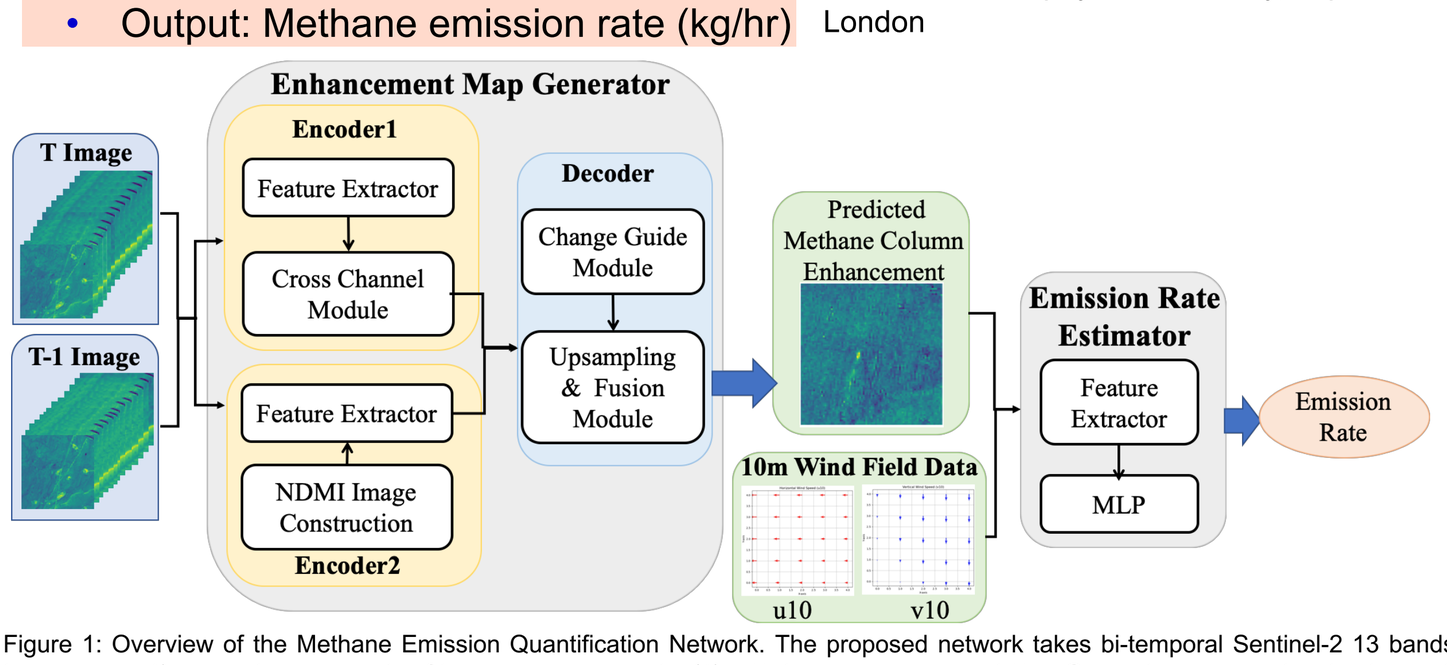

Figure 1: Overview of the Methane Emission Quantification Network. The proposed network takes bi-temporal Sentinel-2 13 bands imagery (at time T and T-1) as input and consists of two main components: (1) a Methane Enhancement Map Generator, which estimates the methane column enhancement via a dual-encoder-decoder architecture integrating spectral and NDMI features; and (2) an Emission Rate Estimator, which combines the predicted enhancement map with 10 m wind field data to estimate the methane emission rate.

Joint Loss Function:

$$L_{total} = \lambda_{EMG} \cdot MSE(E, \hat{E}) + \lambda_{ERE} \cdot MSE(R, \hat{R})$$

Balances enhancement and emission predictions for end-to-end optimization.

Results

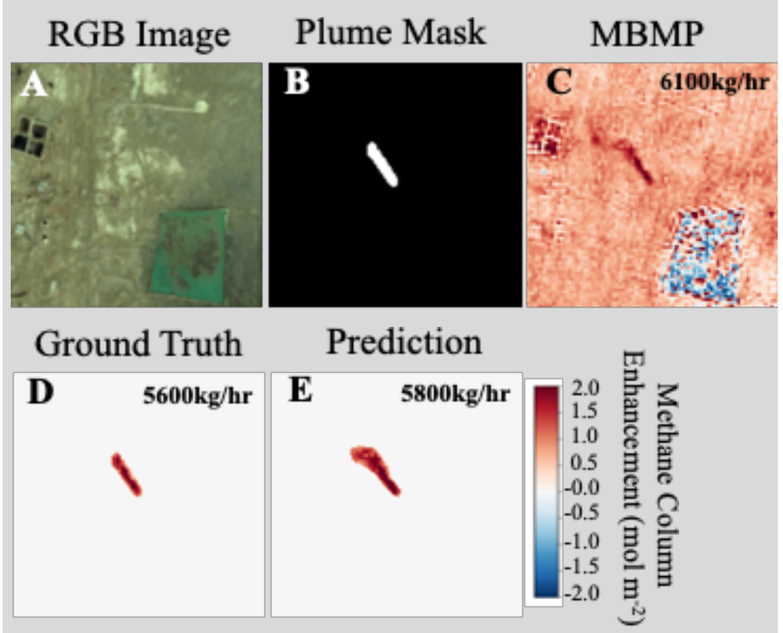

Figure 2: Example visualization of quantification results (location:37.92913◦N, 53.92431◦E) in Turkmenistan. A and B: Sentinel-2 RGB image of the source region and methane plume mask. C: retrieved methane column enhancement map from MBMP [1]. D and E: truth and predicted enhancement by the proposed model.

- **Clearer Plume:** MEQNet suppresses surface interference and produces visually sharper plume patterns.
- **Higher Accuracy:** Achieves R^2 = 0.91 for enhancement and R^2 = 0.94 for emission rate.
- **Faster Inference:** Processes each Sentinel-2 scene in < 2 seconds.

References

[1] Varon, Daniel J., et al. "High-frequency monitoring of anomalous methane point sources with multispectral Sentinel-2 satellite observations." Atmospheric Measurement Techniques Discussions 2020 (2020): 1-21.

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