A comparison of methane emission fluxes quantified using PRISMA hyperspectral satellite data with on-site measurements at a U.S. coal mine

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Methane emissions and coal mines

- Methane is the second most predominant anthropogenic greenhouse gas.
  - More potent than CO_2 in Global Warming Potential (GWP-20), over a 100-year timeframe.
  - The energy sector is responsible for nearly 40% of total methane emissions.*
  - Coal mines account for about 12% of global anthropogenic methane emissions.

(*IEA, Global Methane Tracker 2023)

MRV* of coal mine emissions

- A first step towards mitigation by providing reliable data to policy makers and project developers about mitigation options.

  – Facility level data has lower uncertainty.
  – Lack of monitoring of emissions limit mitigation options to reduce methane emissions.
  – MRV mostly rely on facility-level measurements and modeling (bottom-up).
  – MRV estimations may benefit from remote sensing methods (top-down) as global monitoring tools.
    - Not widely used for official reporting.
    - Reconciliation studies are needed.

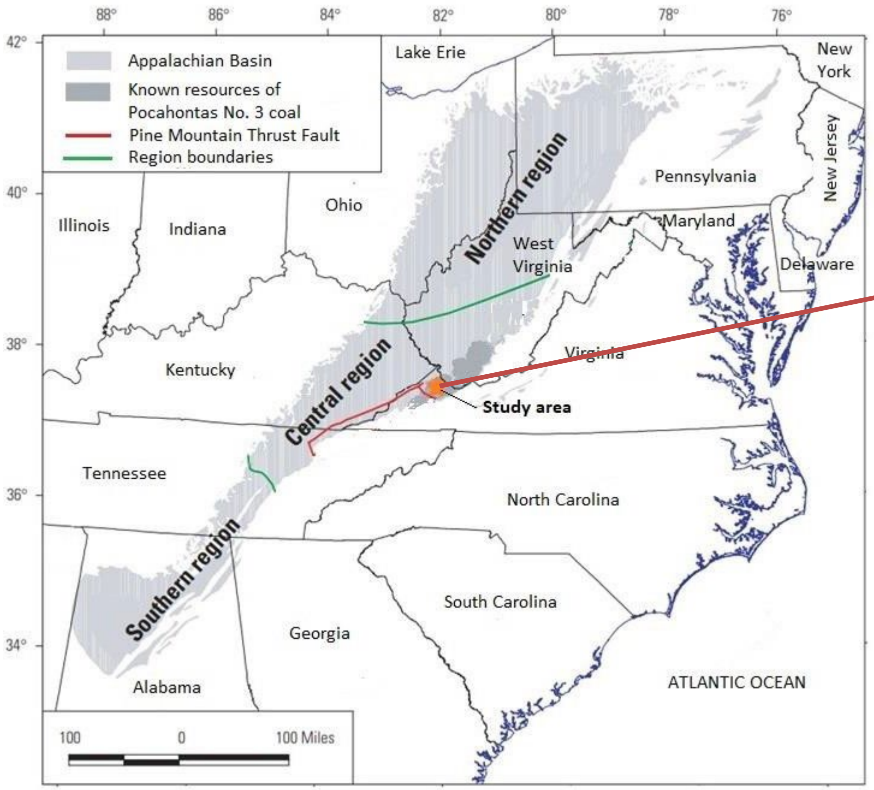
*MRV: Monitoring, Reporting and Verification

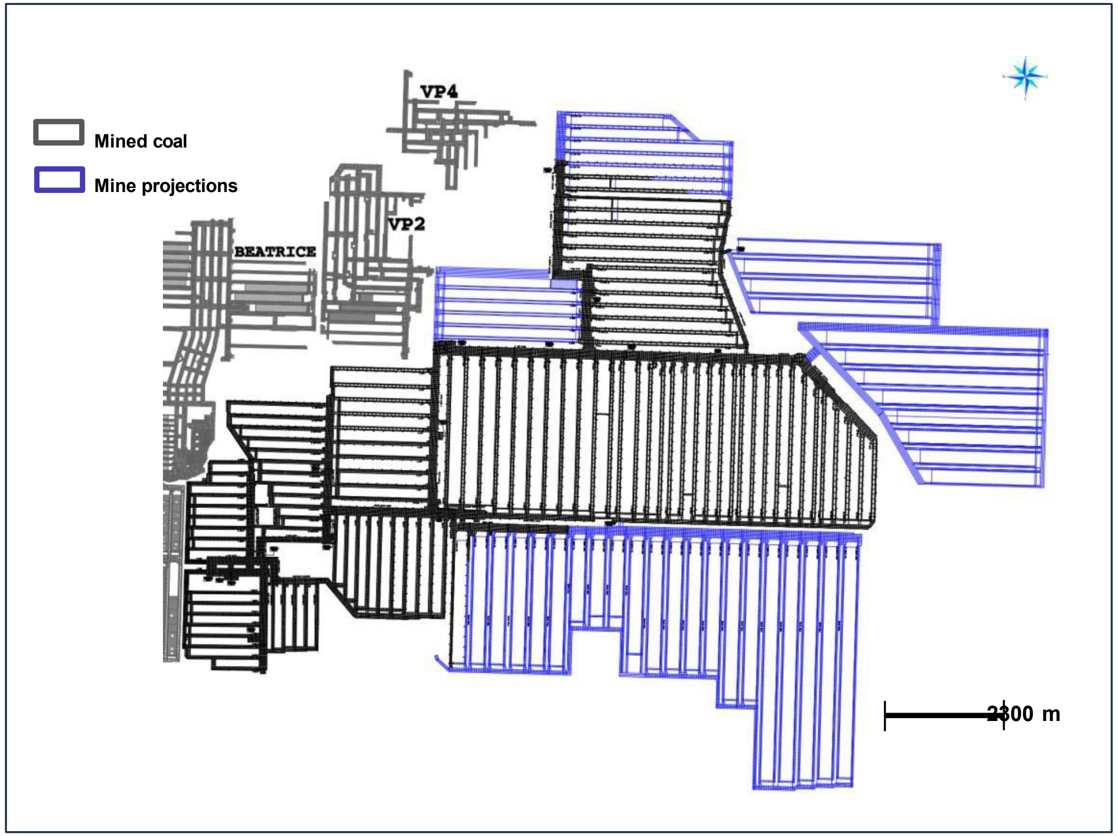
Objectives

- Acquire coal mine monitoring data and satellite measurements at multiple dates between 2020 and 2023.
- Estimate bottom-up (BU) and top-down (TD) methane fluxes from two exhaust fans at the same mine.
- Compare methane emission fluxes.
- Evaluate TD results with two wind reanalysis products.

Location of the longwall mine

- Central Appalachian Coal Basin
- Oakwood CBM Field, Buchanan Co., VA, USA.

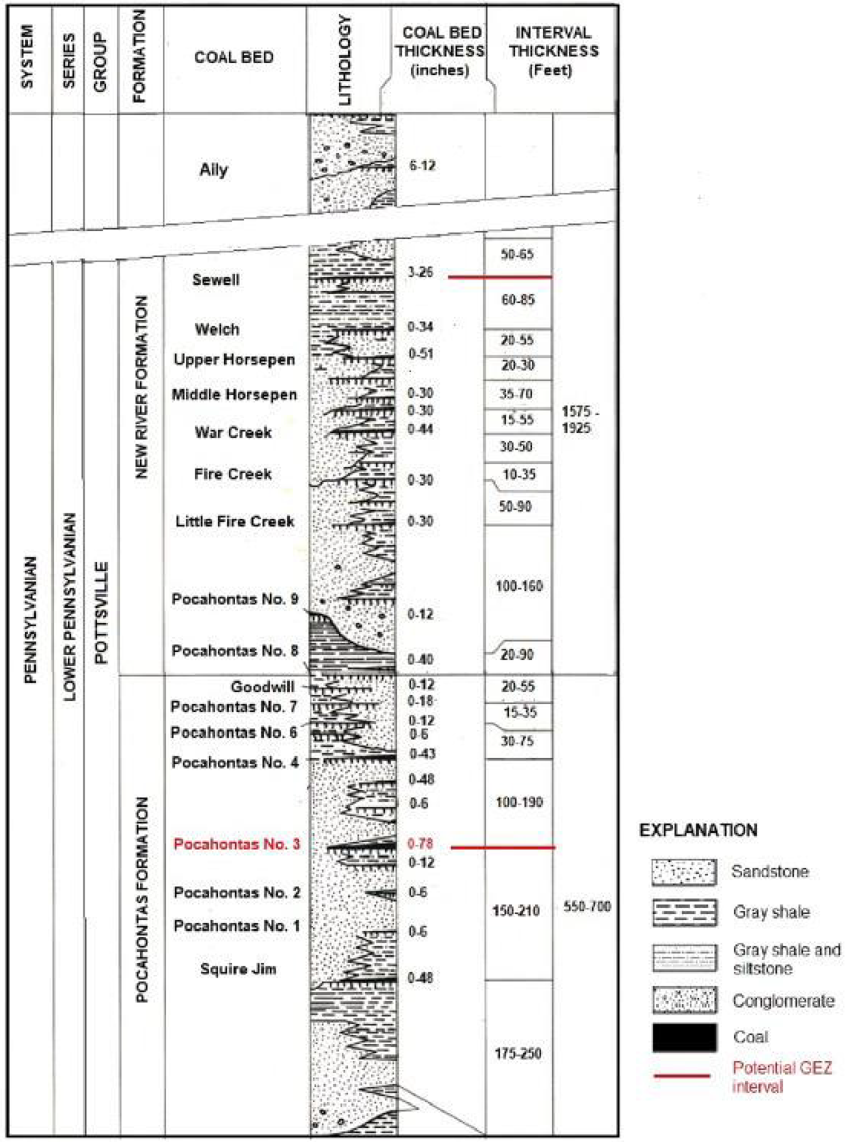




(from Karacan, 2023 - https://doi.org/10.1016/j.coal.2023.104234)

General stratigraphy and mining interval

- Mining in Pocahontas #3 (P3) coal bed.
- Average overburden at the mine site: 488-670 m.
- P3 splits (P31 and P345) and separated by parting layers from P3.
- Splits – when present -are mined together with P3 within 0.6 m parting thickness.



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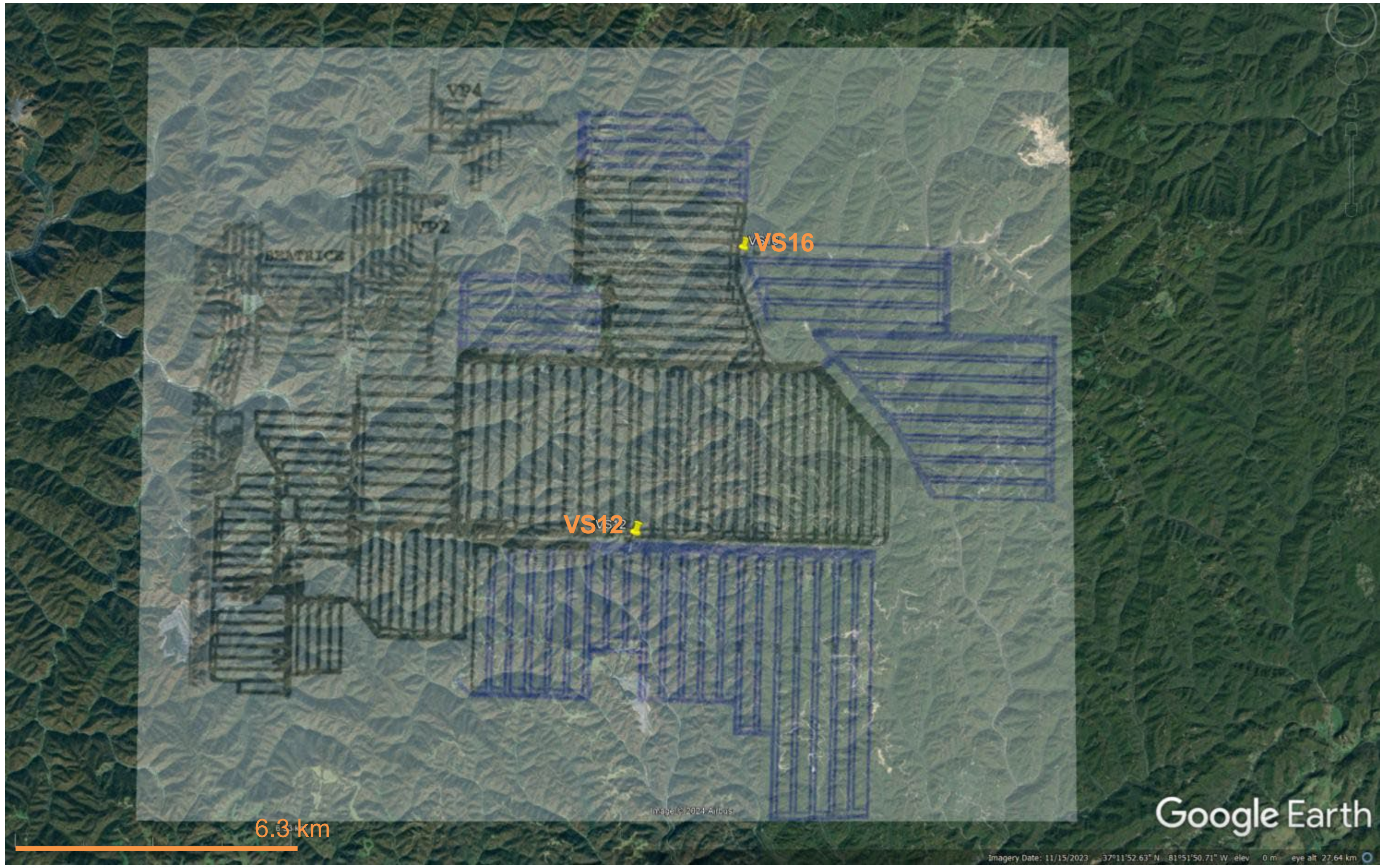
Longwall panels and methane control

- Panel widths ~ 275 m; panel lengths ~1675 – 3350 m.
- Average linear face advance rate ~ 9 – 33 m/day.
- Methane control measures;
  - Fractured vertical degasification wells;
    - Perforated and fractured wells are terminated before start of mining ~ 10 years of production.
  - Gob gas ventholes;
    - ~15 wells are drilled in each panel from surface (12 m to the top of P3, with 275 m open hole section)
  - Horizontal in-seam boreholes (drilled from tailgate).
    - 40-60 are drilled from tailgate side of each of the panels.
  - Remaining 12-35 m^3 methane per m^2 of mining is handled by ventilation air and exhausted through bleeder system.
    - Ventilation air is provided and exhausted by large capacity fans – 14000 m^3/min
- The mine is ranked 203rd out of 1652 mines operating globally by the Global Energy Monitor's Global Coal Mine Tracker* database for methane emissions.

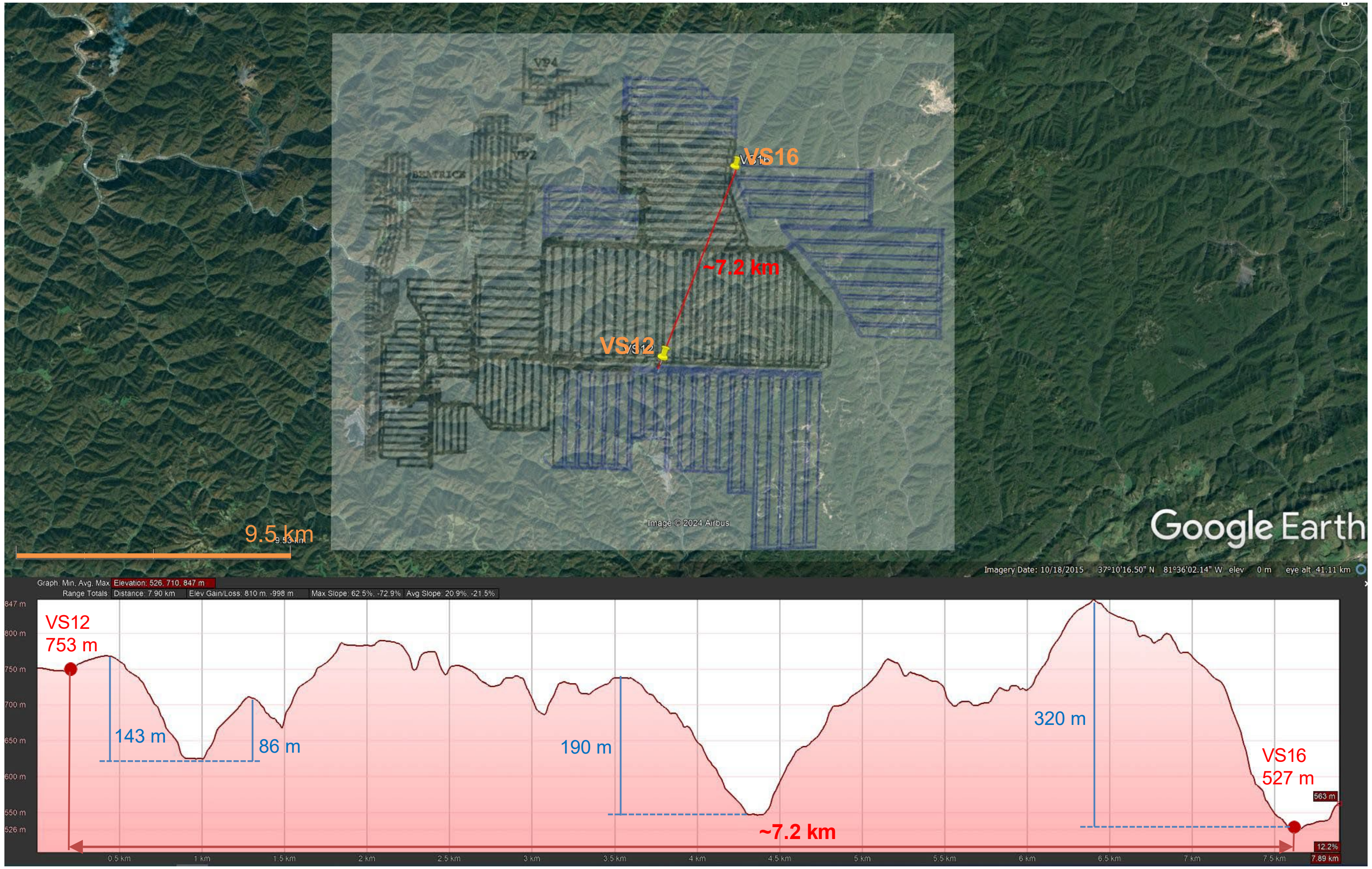
(*https://globalenergymonitor.org/projects/global-coal-mine-tracker/)

Ventilation air shafts

- In this study, VS12 and VS16 monitoring data were used.
- VS16, serving North District panels, has a 4000 m^3/min flow capacity VAMOX unit (Biothermica) that came online in July 2022.
- VS12 served the 3 East Main District and has been idled on Sept 7th, 2023, after completion of mining.



Altitude, terrain and surface coverage

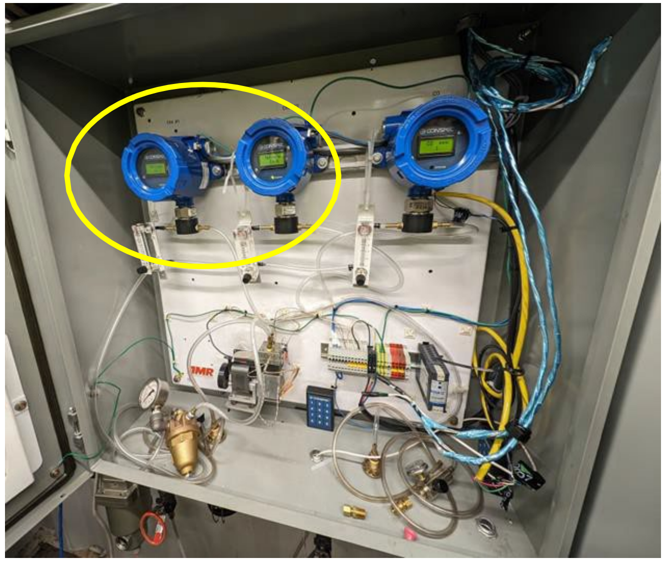


- VS12 and VS16 are ~ 7.2 km apart.
- Their elevation difference is 226 m.
- Rugged terrain with hills and valleys typical of Appalachian Coal Basin.
  - Elevation varies more than 300 m.
  - May affect wind and methane plume.
- Surface is covered with vegetation.
  - May impact detection and quantification of methane plumes.

Ventilation air monitoring – mine fan

- VS12 and VS16 have been monitored by the mine using a continuous monitoring system for flow rate and methane concentration.
  - Flow and gas sampling ports were placed after fan blades for proper mixing.
  - Monitoring performed every minute, later parsed (15 min or hourly intervals) for evaluation.
- VS16 has been monitored by multiple methane sensors for cross-checking.
  - Two Conspec multi-gas monitors for redundancy
  - TAS Unisearch laser spectrometer

Flow sensors

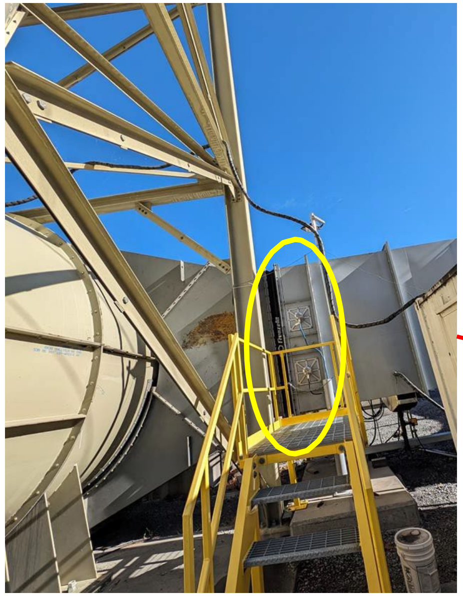


Conspec methane monitors

TAS Unisearch laser spectrometer

Ventilation air monitoring - VAMOX

- VAMOX unit is connected to the VS16 mine vent through a coupling and long ducting that places oxidizer outside of 30 m buffer zone.
- ~30% of flow is diverted to VAMOX - depending on methane concentration.
  - ~90% of incoming methane is oxidized.
- VAMOX has its own sensors to monitor flow every minute.
  - Two Neo Monitor open path laser spectrometer with transmitters and receivers placed 1.5 m from the coupling to mine vent.
  - Flow into VAMOX unit is controlled by a variable frequency pump and flow sensor.

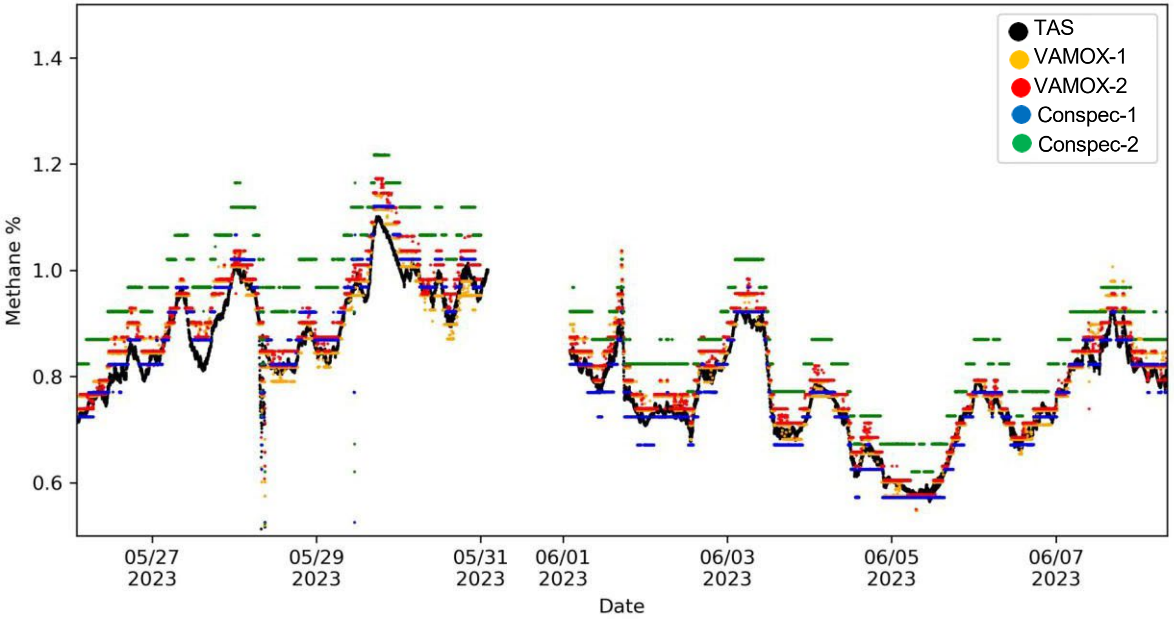

Open path laser monitors


V16 with VAMOX unit


Pump pulling air into the oxidizer

A comparison of methane monitors

- Five sensors on the mine vent and VAMOX duct inlet were compared at two date segments.
- Despite different measurement technologies, they seemed consistent and correlate reasonably.
- However, it should be noted - for 14000 m^3/min mine vent air flow, as an example:
  - Resolution differences between 0.01 ppm and 500 ppm incur flux variation between ~0.006 and ~304 kg/hr.
  - Measurement accuracy deviations between 1% and 30% deviation result in flux differences between ~60 and ~1820 kg/hr.



Correlation Matrix

	TAS	VAMOX-1	VAMOX-2	Conspec-1	Conspec-2
TAS	1.000	0.972	0.982	0.979	0.975
VAMOX-1	0.972	1.000	0.982	0.965	0.961
VAMOX-2	0.982	0.982	1.000	0.977	0.973
Conspec-1	0.979	0.965	0.977	1.000	0.985
Conspec-2	0.975	0.961	0.973	0.985	1.000

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Plume detection and retrieval

- Retrieval of methane from space relies on spectrally-resolved measurements of solar radiation reflected from Earth's surface in the SWIR (Short-Wave InfraRed) part of the spectrum.

- PRISMA satellite, launched by the Italian Space Agency on 22 March 2019, hyperspectral data was used.
  - In orbit at an altitude of 615 km.
  - Equipped with imaging spectrometer, capable of acquiring VNIR (Visible and Near-InfraRed) and SWIR products, and a panchromatic camera with a 5 m spatial resolution.

- PRISMA generates hyperspectral images within 400 – 2500 nm range with a spatial coverage of 30 x 30 km^2 and a spatial resolution of 30 m.
  - Spectral resolution ~10 in the 2300 nm window used for methane retrieval.
  - SNR ~100 for a dark vegetation pixel, ~200 for bright soil surfaces.

Picture from ASI, Italian Space Agency

General bottom-up and top-down approach

- Acquire monitoring and satellite data from VS12 and VS16 at multiple dates:
  - VS12: 10/19/2020, 1/14/2021, 3/20/2023, 8/23/2023.
  - VS16: 2/24/2021, 1/26/2022, 3/2/2022, 11/24/2022, 3/20/2023, 3/25/2023, 6/26/2023, 8/23/2023.

Bottom-up

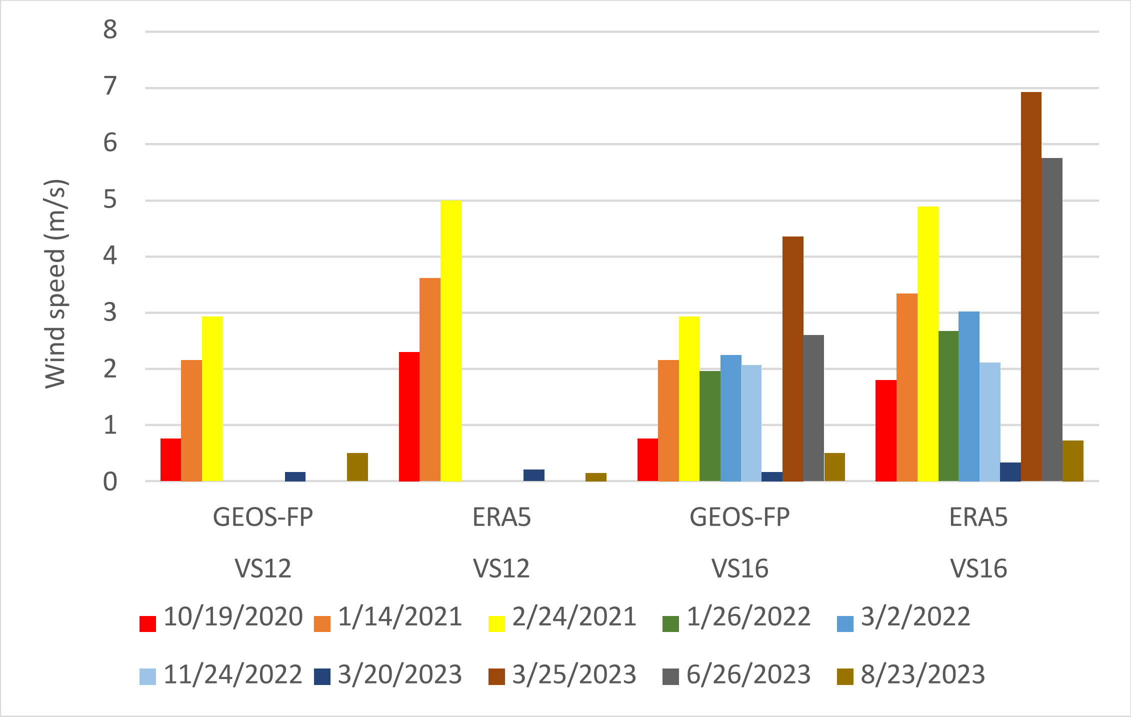
- Methane and flow data were inspected for irregularities.
- Daily data distributions with hourly-averages were generated.
- Hourly mass fluxes of methane were computed.
- For dates when VAMOX was online at VS16, VAMOX flow data were used to calculate fluxes from the mine vent and oxidizer outlet separately and results were combined.
- Uncertainty was quantified.

Top-down

- Per pixel enhancement of methane column concentration with respect to the background (ΔXCH_4) was computed.
- Matched-filter based algorithm was applied.
- Plumes were identified and co-registered with wind data (GEOS-FP and ERA5) and high-resolution images of the area.
- Plume was isolated from the background using a polygon.
- Flux was calculated from pixel-based ΔXCH_4 values using the integrated mass enhancement model.
- Uncertainty was quantified.

General bottom-up and top-down approach

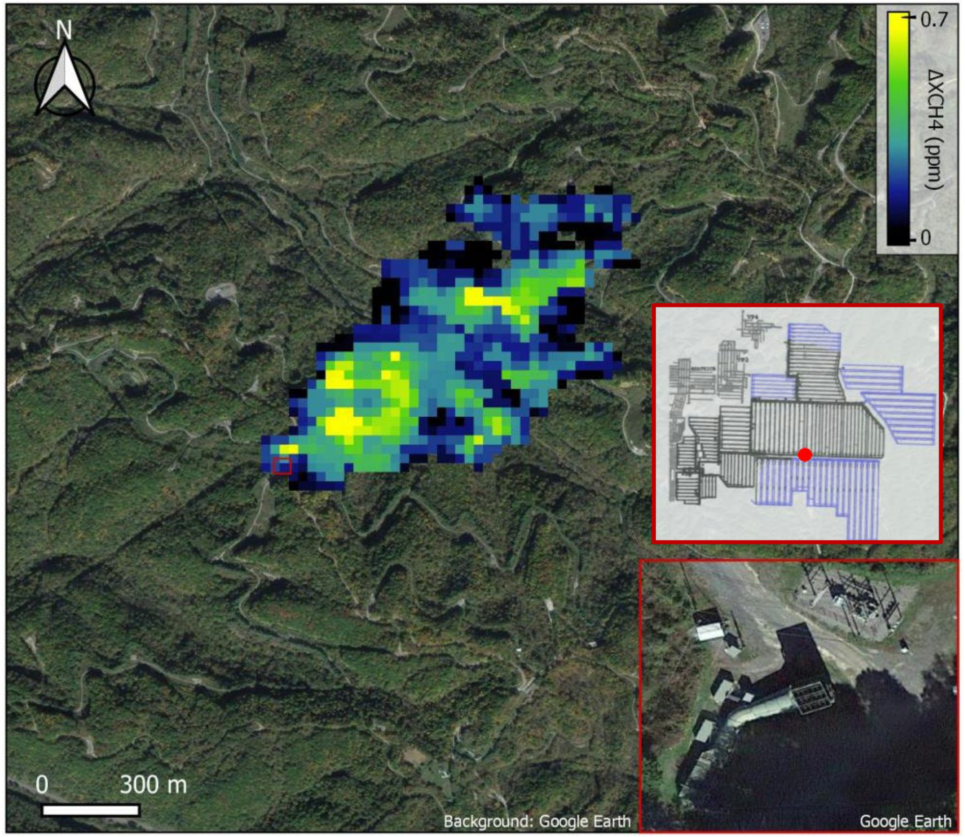
- Wind reanalysis products:
  - GEOS-FP by NASA: Horizontal resolution (0.25° latitude x 0.3125° longitude) and temporal resolution (hourly data).
  - ERA5 by European Centre for Medium-Range Weather Forecasts: Horizontal resolution (0.25° latitude x 0.25° longitude) and temporal resolution (hourly data).



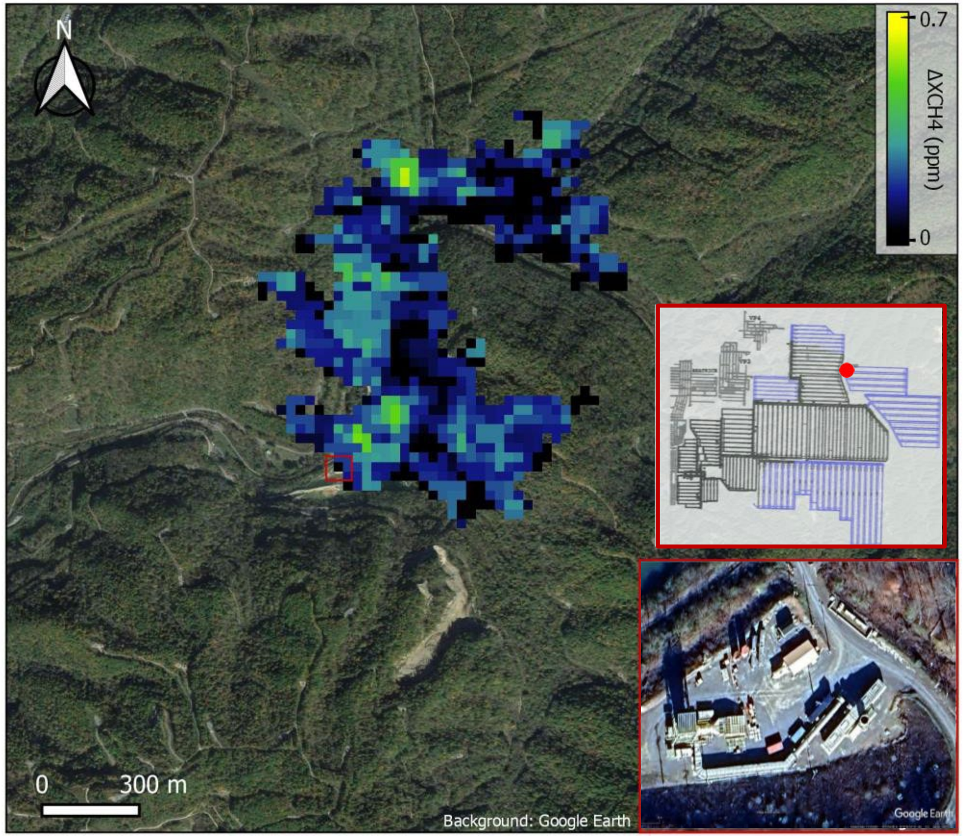
- At VS12 and VS16 locations
  - ERA5 gave generally higher wind speeds than GEOS-FP product.
  - In GEOS-FP, both vent locations fell in the same grid, and therefore read the same wind speed for the dates although they were ~7 km apart.
    - Might be due to spatial resolution

Results

– Plumes with minimum 90 pixels were quantified.

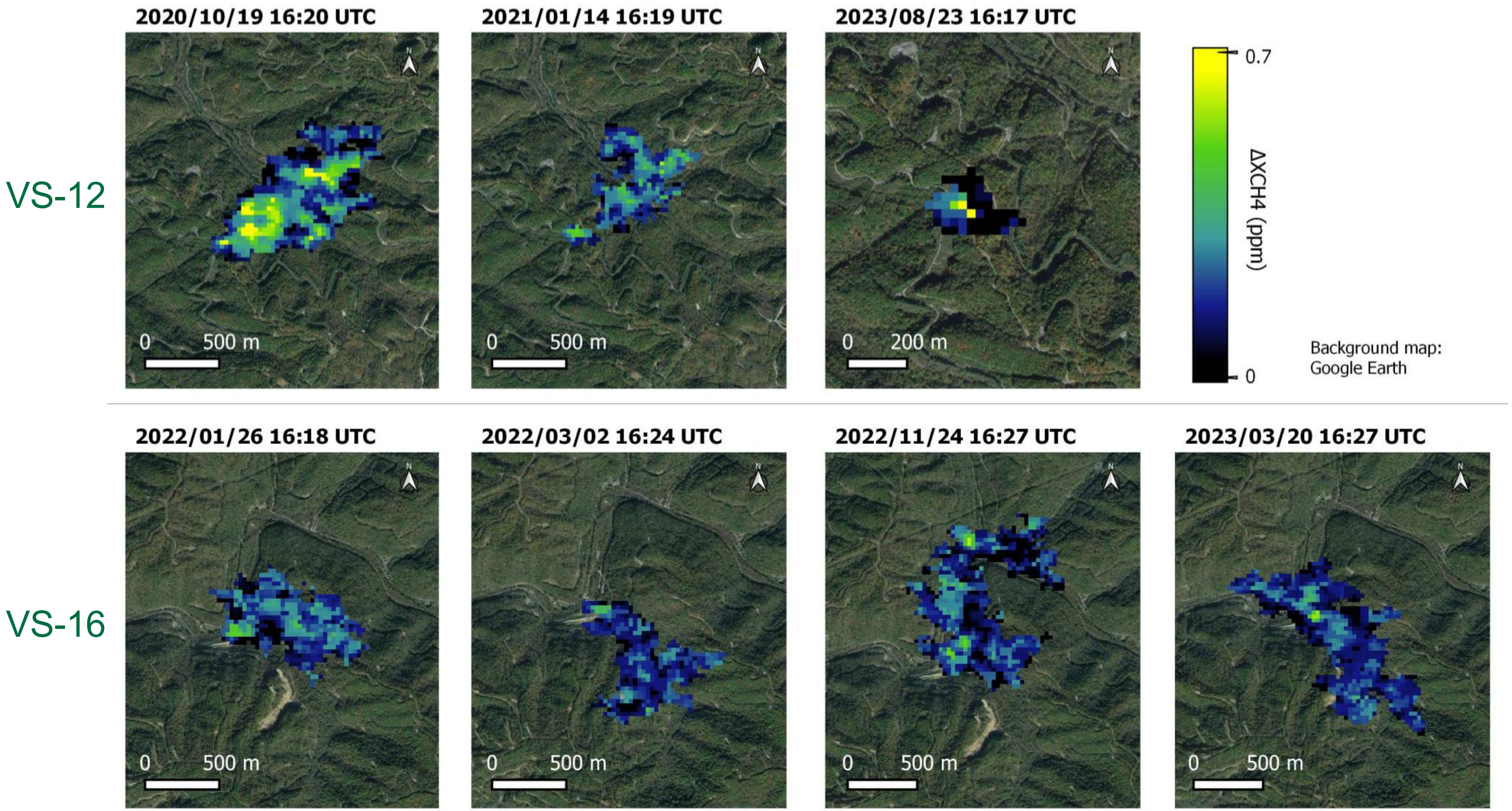


VS12 (10/19/2020)

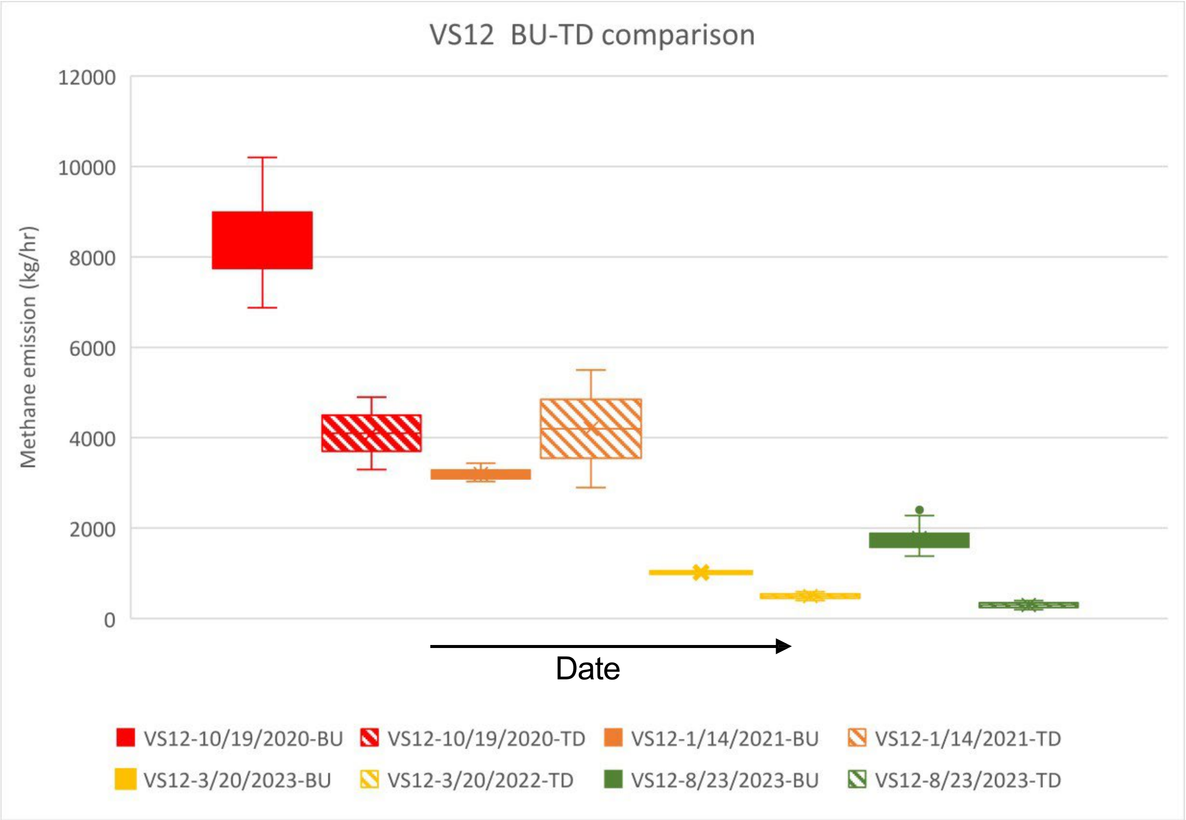


VS16 (11/24/2022)

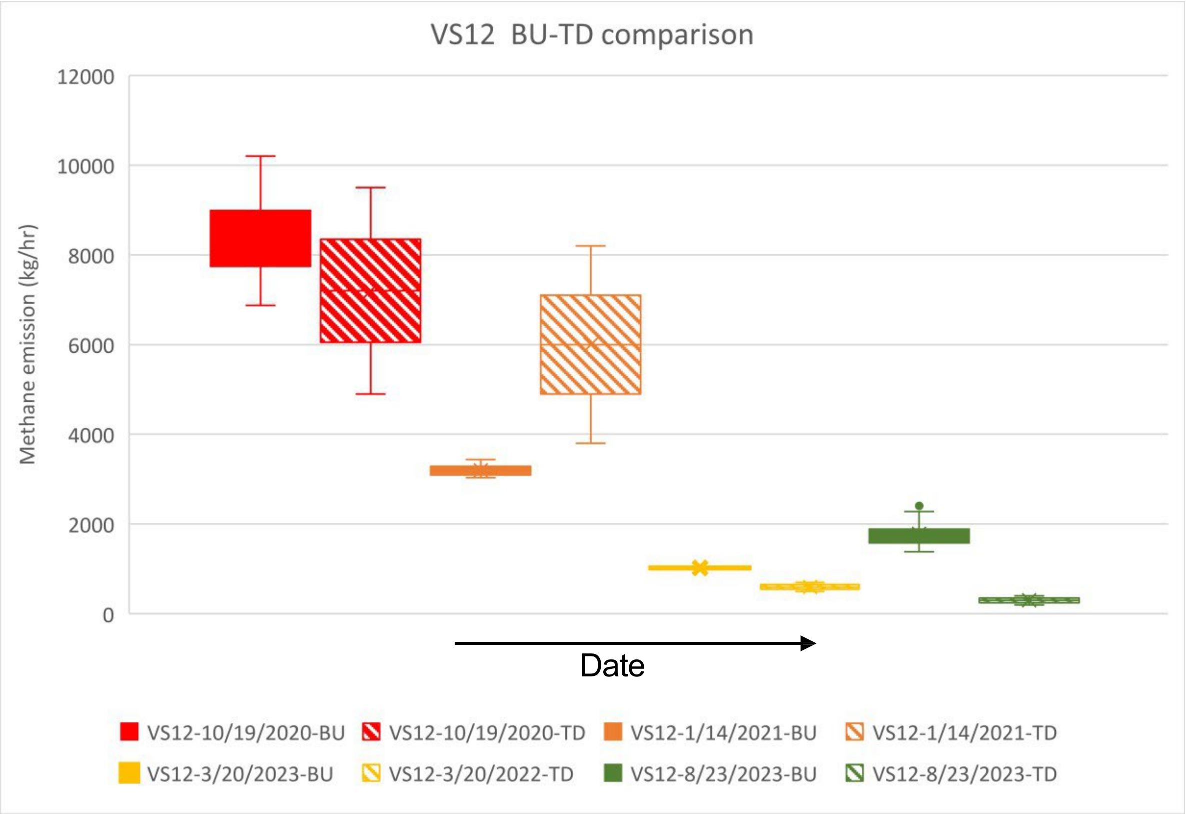
Results - Plumes from sample dates



Results – VS12 BU and TD comparison



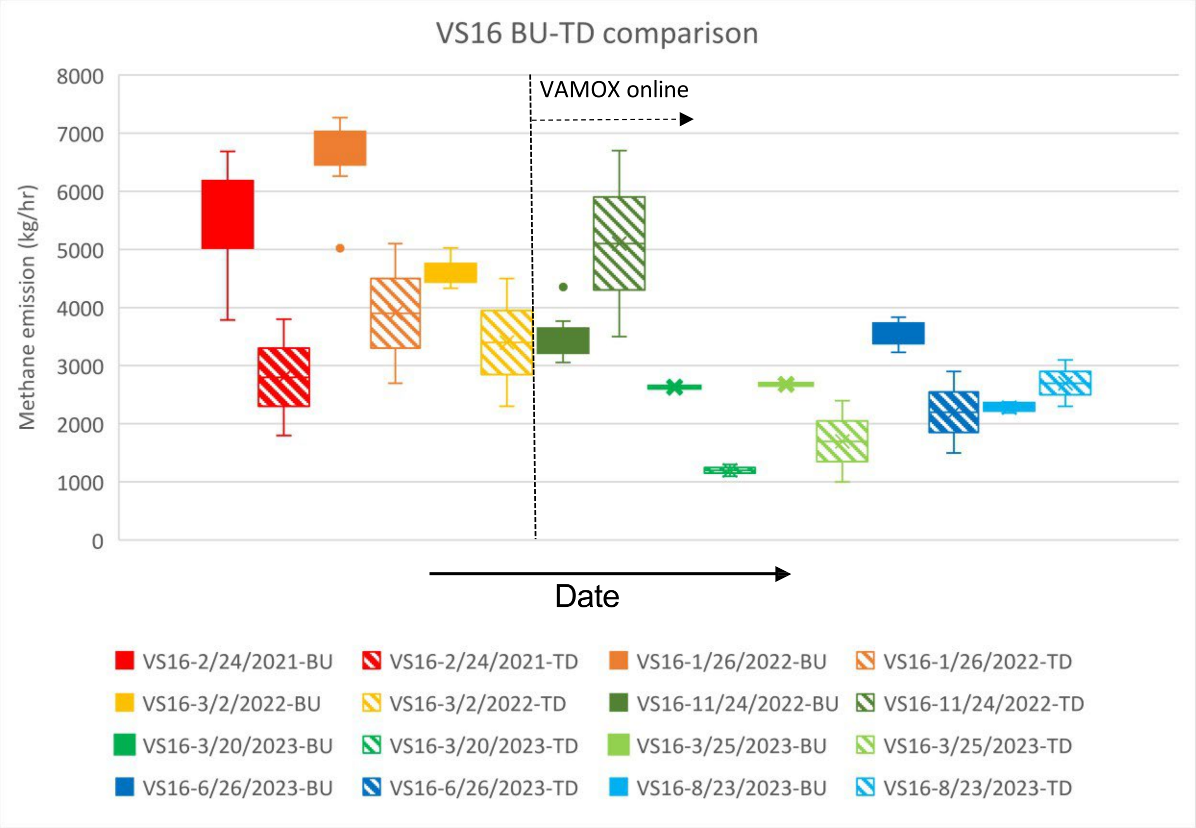
GEOS-FP



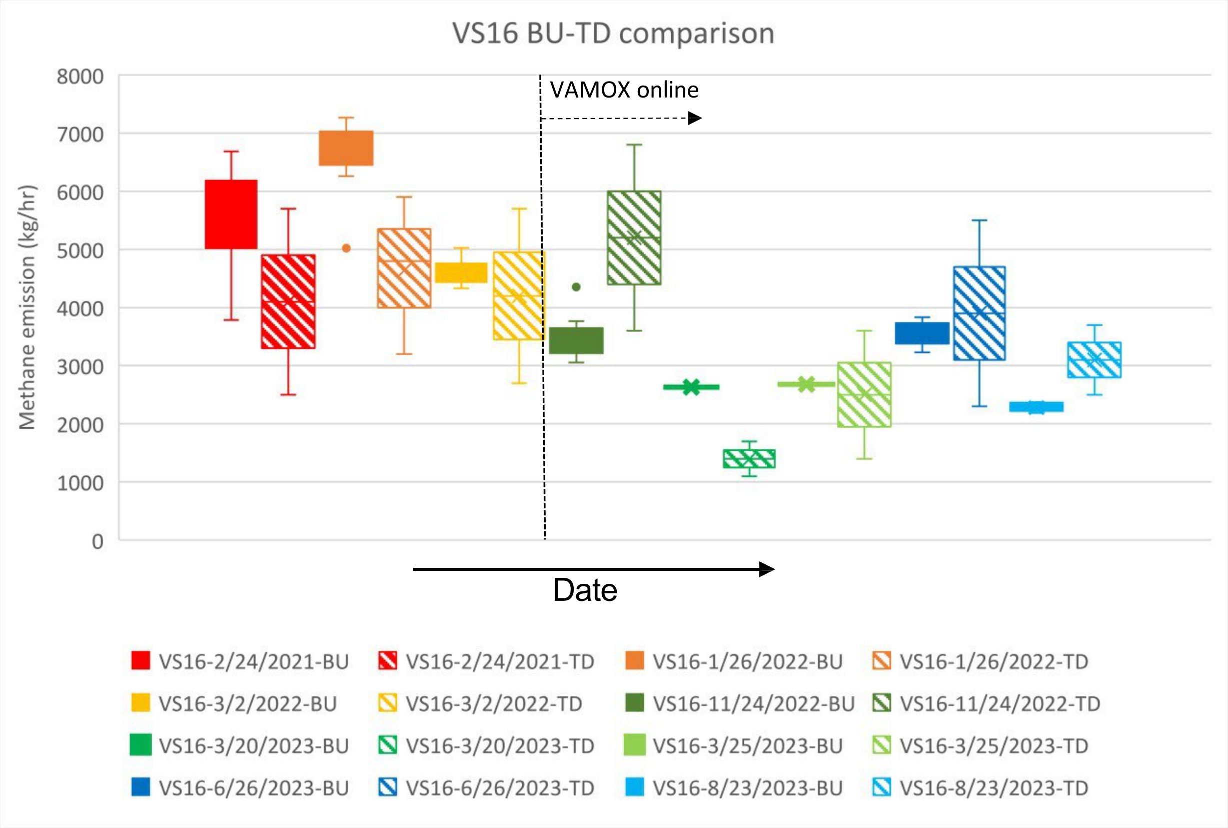
ERA5

- In general, TD estimates are lower than BU.
  - Terrain and surface coverage, formation of plume.
- Estimates with ERA5 seem to be improved.

Results – VS16 BU and TD comparison



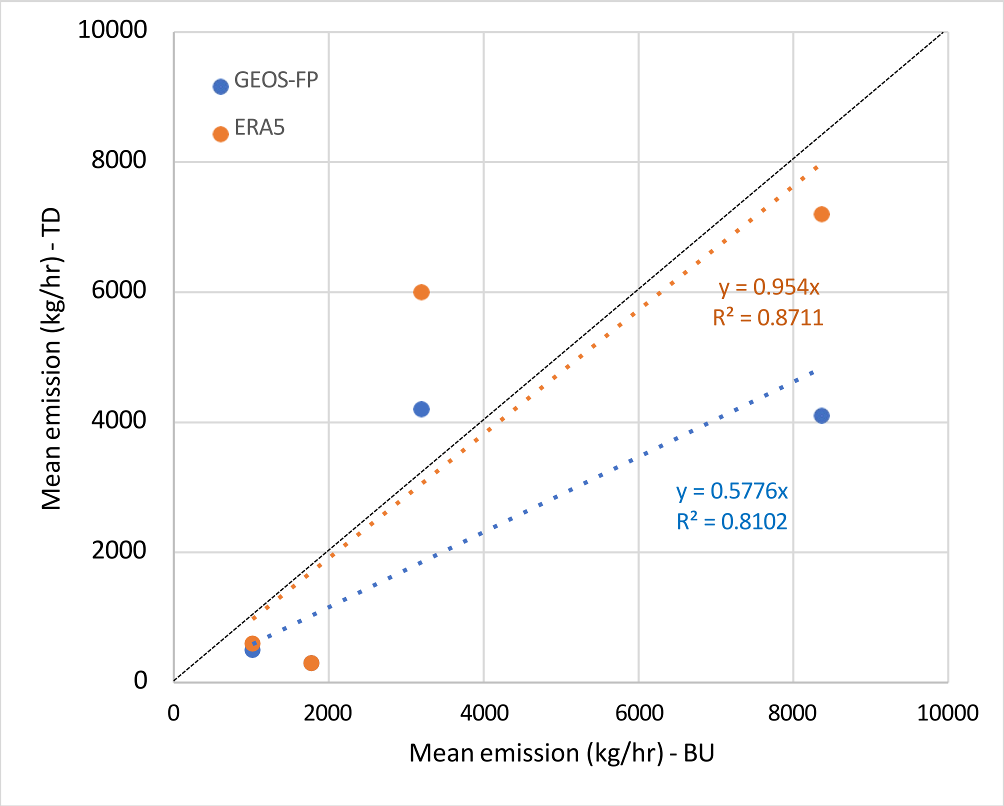
GEOS-FP



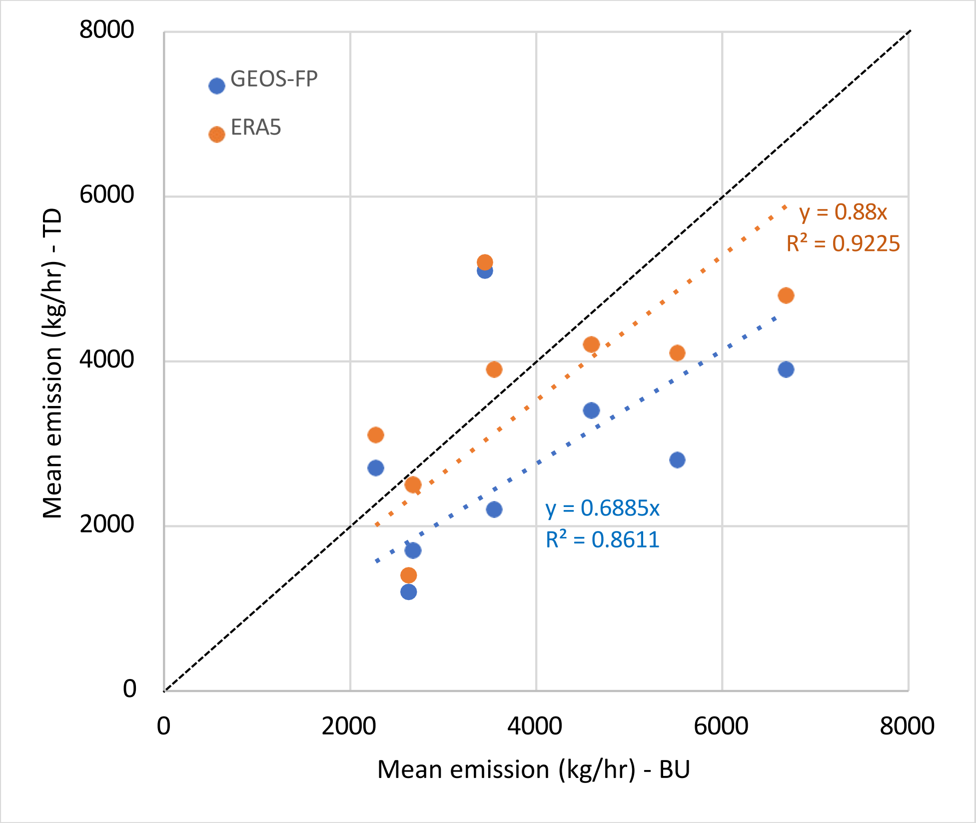
ERA5

- TD estimates are lower than BU as in the VS12 case.
- Data centers and ranges are closer.
- ERA5 results are improved over GEOS-FP.
- Effect of VAMOX unit is visible in BU and TD estimates.

Results – BU and TD mean value comparison



VS12



VS16

- Mean value comparison gives better correlation using ERA5.

USGS

Summary and conclusions

- MRV of coal mine emissions at facility level are important to inform policy makers and project developers.
- Top-down methods can be effective global monitoring and emission quantification tools in support or independent of bottom-up methods through a reconciliation process.
- This work presented a comparison study of emissions evaluated using bottom-up and to-down methods at two ventilation shafts at a mine.
- Bottom-up method showed mean emissions varying ~ 4000-5000 kg/hr during mining. Emissions decrease towards the end of mining, or with VAMOX online.

Summary and conclusions

- Results showed that estimations based on top-down methods were generally lower than bottom-up estimations.
  - Heavy vegetation and the terrain may have affected plume detection and methane enhancement.
  - Despite the departures in mean of distributions, in some cases, either the interquartile range or data range overlapped.
  - Both bottom-up and top-down results should be reported with uncertainties.
- ERA5 product produced closer estimates to bottom-up.
- To improve bottom-up results, sensor locations can be optimized, and potential sensor errors can be included in uncertainty through Gauss' error propagation.
- Top-down methods can be re-evaluated or improved for monitoring complex surfaces to improve detection, as well by selecting the most appropriate weather reanalysis products.

Thank you!

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