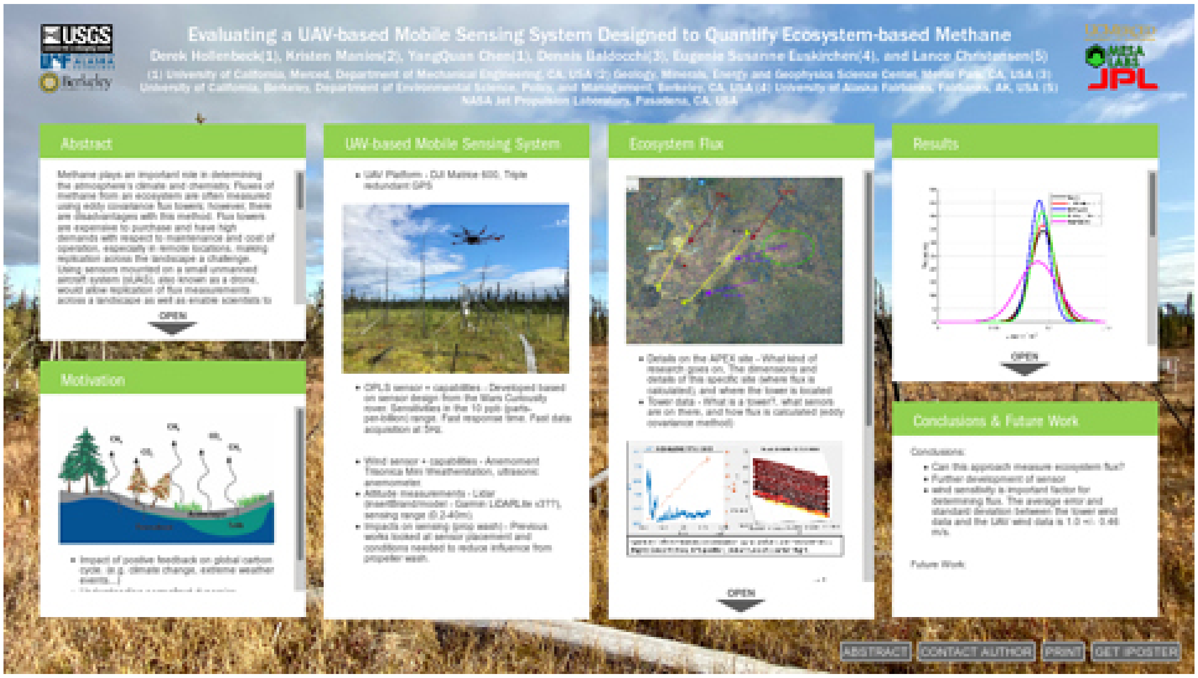
Evaluating a UAV-based Mobile Sensing System Designed to Quantify Ecosystem-based Methane



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RESEARCH QUESTIONS & ABSTRACT

Research Questions:

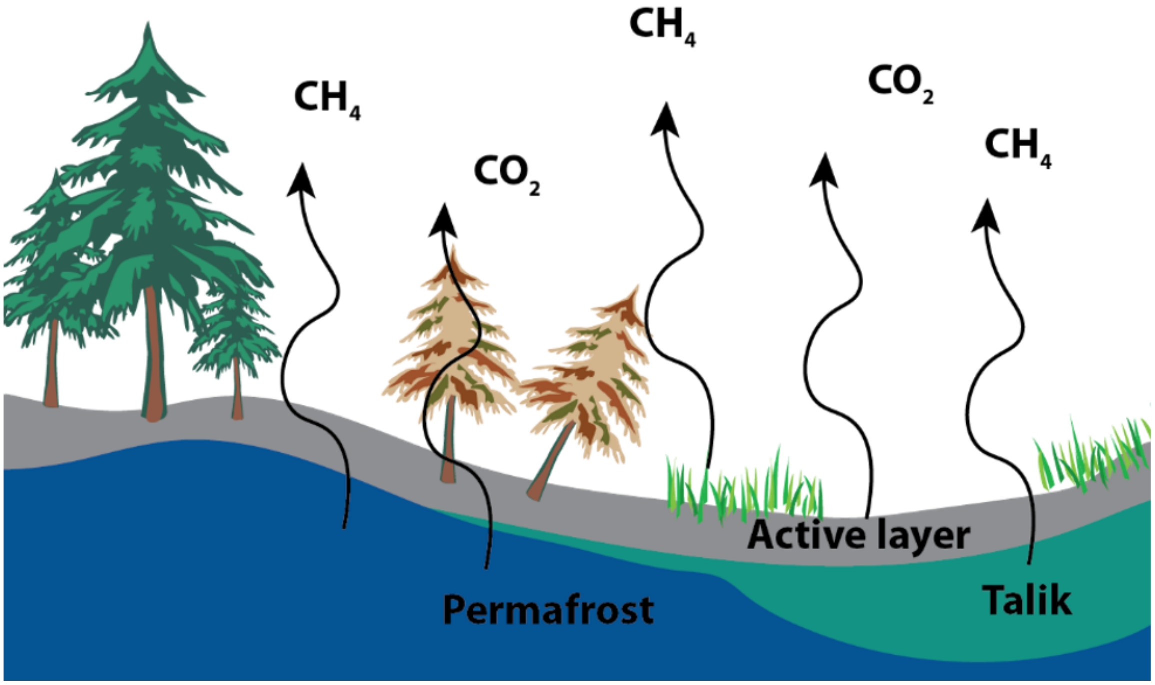
- Can UAV's be used to quantify ecosystem flux?
- What parameters are key in determining flux?
- What’s the best kriging method for calculating flux?

Abstract:

In this work, we test the ability of a UAV equipped with a highly accurate CH_4 sensor to calculate ecosystem flux using the mass balance method. This method uses data collected with curtains (transects at various heights) flown both upwind and downwind of the area of interest. The concentration of methane within these curtains is then estimated using kriging techniques. The difference in calculated amounts of methane between the upwind and downwind curtains is processed to obtain an estimate of flux. Flights in wetlands that also have eddy covariance towers, providing corroborating flux values, have been flown in Alaska and California. We calculated UAV-based flux for the Alaskan flights using a bootstrap approach from multiple randomly subsampled data points within each full curtain of data. We compare these calculations to the traditional mass balance technique. We tested if these different approaches improve the accuracy of our results, as well as the uncertainty bounds for the small fluxes emitted from these ecosystems.

MOTIVATION & CHALLENGES

Figure 1: Diagram depicting increases in the release of carbon with permafrost thaw (unthawed, left; thawed, right).



Methane plays an important role in determining the atmosphere's climate and chemistry.

Fluxes of methane from an ecosystem are often measured using eddy covariance flux towers; however, there are disadvantages with this method. Flux towers are expensive to purchase and have high demands with respect to maintenance and cost of operation, especially in remote locations, making replication across the landscape a challenge.

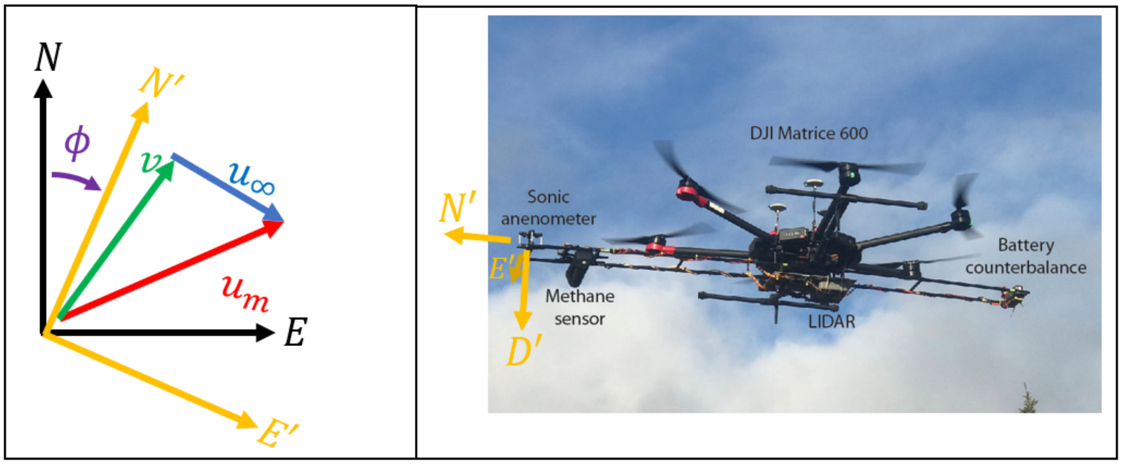
Figure 2: UAV-mobile sensing system above eddy covariance tower in Alaskan peatland bog.

Using sensors mounted on a unmanned aerial vehicles (UAV), also known as a drone, would allow replication of flux measurements across a landscape as well as enable scientists to measure methane at locations where towers are not practical (i.e. sites that are ephemeral in nature, immediately after a disturbance, etc.). This has been done in prior studies looking at controlled release experiments [4,7] and in measuring flux from oil and gas sites [6]. The emission levels found in these cases are typically much greater than ecosystem flux studied here.

If successful, the use of UAV's can help us understand not only how permafrost thaw is impacting the amount of gas transferred from the soil to the atmosphere, but also provide feedback on how climate change impacts the carbon cycle from a variety of ecosystems.

UAV-BASED MOBILE SENSING SYSTEM

Figure 3: Shows the UAV sensors, coordinate system, and wind triangle relationship for calculating the wind speed and direction.



$$\begin{bmatrix} N \\ E \end{bmatrix} = \begin{bmatrix} cos\phi & -sin\phi \\ sin\phi & cos\phi \end{bmatrix} \begin{bmatrix} N' \\ E' \end{bmatrix} = R_{\phi}(t) \begin{bmatrix} N' \\ E' \end{bmatrix}$$

- Measured wind, u_m with a Trisonica anemometer in body fixed frame. The N' is aligned with the vehicle heading.
- Vehicle movement v (GPS-based) in inertial frame
- Actual wind, u_∞ in inertial frame
- Aircraft heading ϕ is used to rotate the wind measurements to inertial frame. $R_{-\phi}(t)$ for different values of $\phi = \phi(t)$.

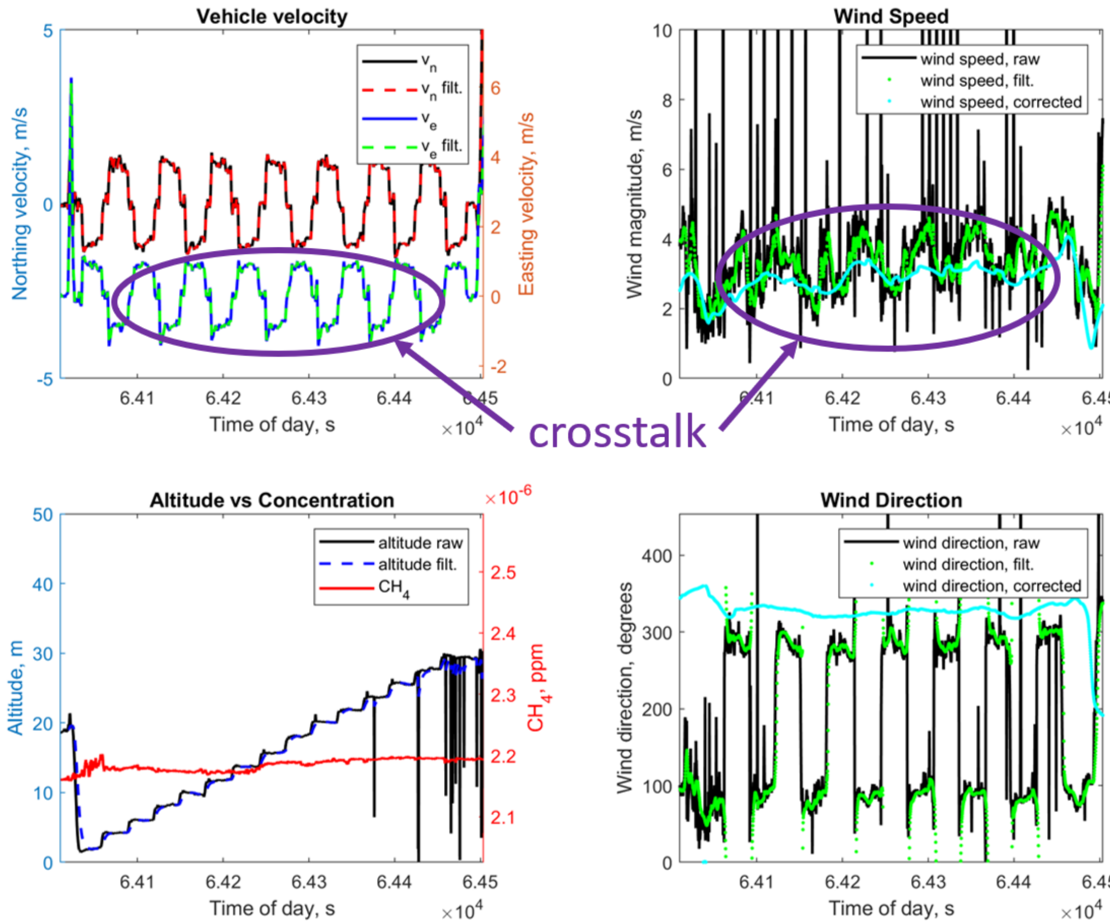
The mobile sensing system is comprised of a UAV platform, a CH_4 detector, a wind speed sensor, and an altitude sensor:

- The UAV platform is a DJI Matrice 600 with triple redundant GPS for calculating latitude, longitude and vehicle velocities;
- The CH_4 detector is an open path laser spectrometer (OPLS) [3], capable of sensitivities in the 10 ppb (parts-per-billion) range with fast response time and data acquisition at 5Hz.
- The wind sensor is an 50g ultrasonic anemometer, namely the Anemoment Trisonica Mini Weatherstation, capable of measuring 3D wind vectors +/- 0.1 m/s and +/- 30 degrees elevation.
- The altitude sensor is a Garmin LiDARLite v3, sensing range (0.2-40m).

Getting good wind data is paramount to calculating accurate fluxes.

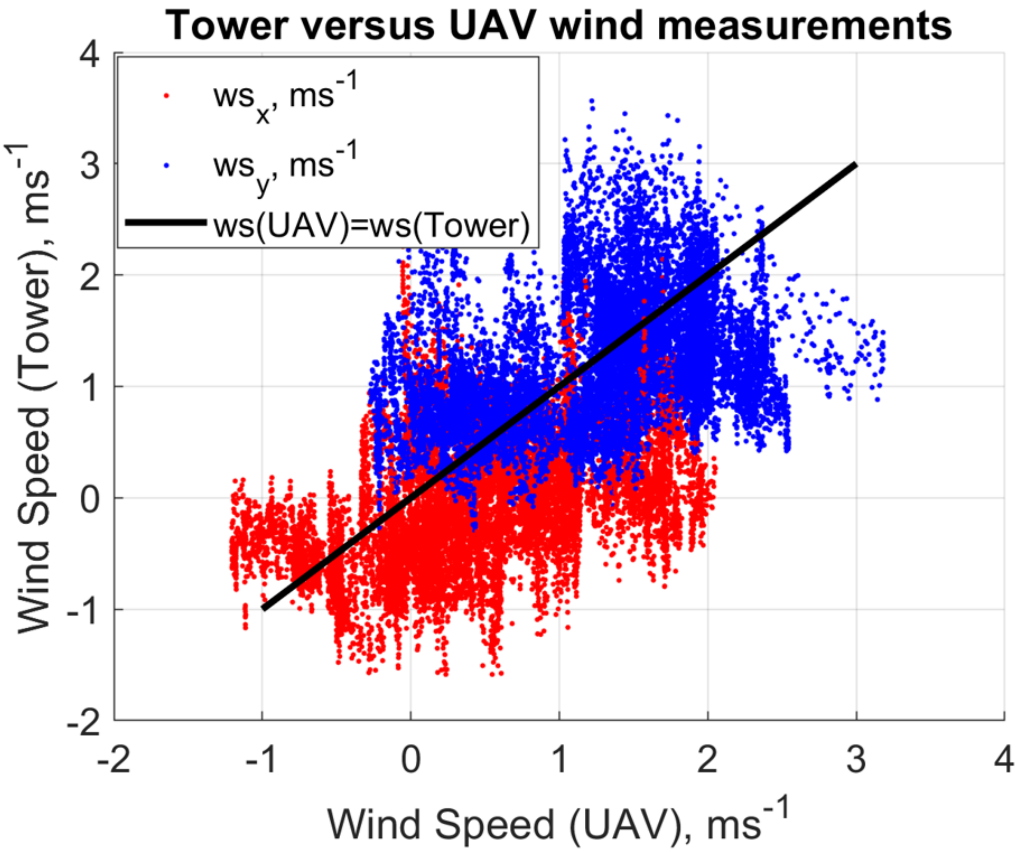
Additional considerations and challenges with sensing on UAV's include:

Figure 4: Quad plot showing example flight data and associated filtering and corrections. Wind speed and direction show some `crosstalk'.



- propeller wash - air intake mixing that causes disruptive air flow near the body of the VTOL aircrafts:
  - Previous works found that sensor placement needed to be ~1 rotor diameter out front just under the body of the UAV under relative 2m/s airflow (wind speed or vehicle 'jousting' movement) [8].
- `Crosstalk' between GPS and wind measurement:
  - Wind speed measurements on UAV's can be solved for using direct 'in situ' wind speed measurements combined with GPS velocity using the wind triangle relationship. [5]
  - The errors can manifest as periodic signals with similar frequencies as the GPS velocities, position or altitude [9].

Figure 5: UAV-based wind speed components plotted against tower-based wind components showing significant noise levels.



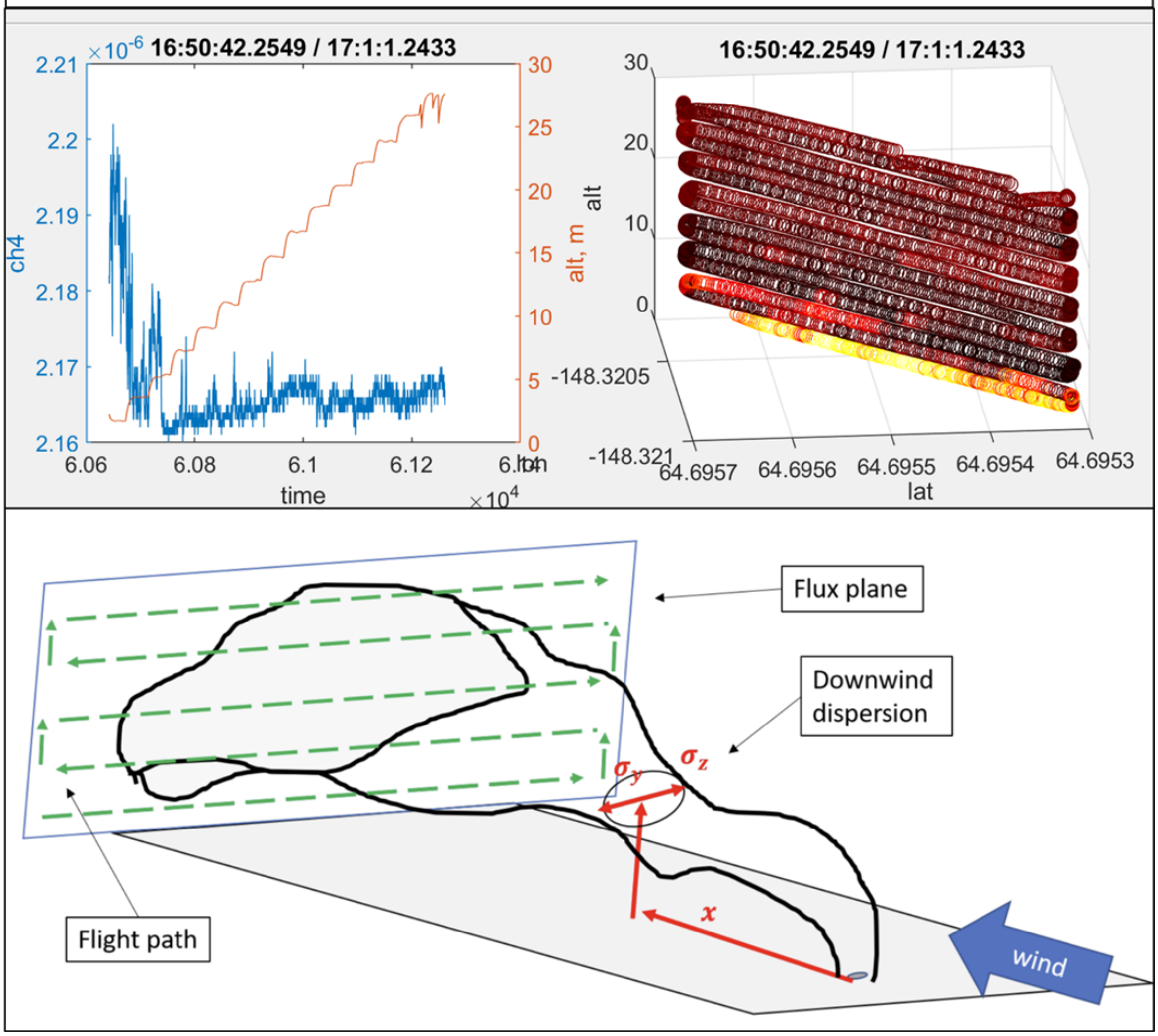
The result of the 'crosstalk' can be seen in the average error and standard deviation between the 2019/9/27 tower wind data and the UAV wind data is 1.0 +/- 0.46 m/s.

ECOSYSTEM FLUX

Flights were conducted in the Alaska Peatland Experiment (APEX) wetland complex, which is a part of the Bonanza Creek Long-Term Experimental Research Program. This site is located ~33 kilometers southwest of Fairbanks, Alaska. One of the bogs within this complex has both an eddy covariance tower and an autochamber system, providing data checks for both the CH_4 and meteorological measurements.

Within the bog we flew 10 curtain flights (5 upwind and 5 downwind) along the edges of the bog. These curtain flights consisted of horizontal transects at different altitudes (2 m, 4 m, 6 m, etc.), creating a “wall” of data.

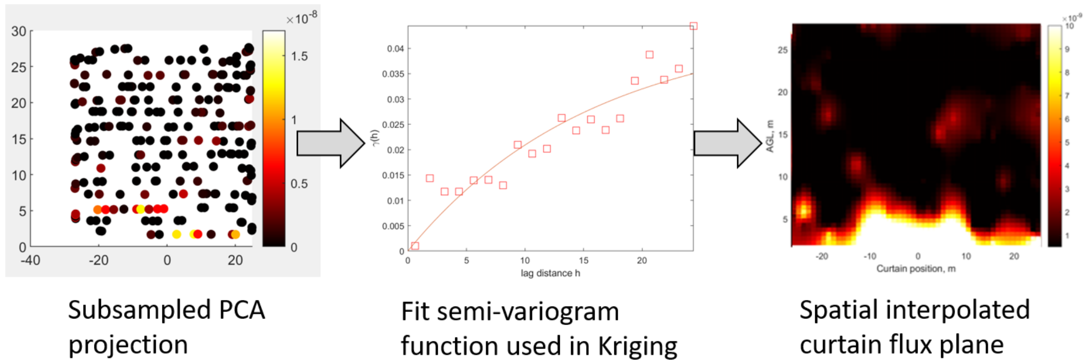
Figure 6: (Left) Timeseries concentration signal and altitude measurements (Right) Concentration, GPS position, and altitude of a curtain flight. (bottom) Typical flight path for a curtain flight down wind of a source.



The challenges and difficulty in implementation of the curtain flight depends on the stability of the predominate wind direction and the available flight paths (e.g. unobstructed with vegetation).

Once the curtain flight is complete, the flux can be calculated using the mass balance method (also referred to as Box method). The sparse curtain data 'wall' is projected into a best fit plane using principal component analysis (PCA) and spatially interpolated. The resulting plane is integrated over the area and multiplied by the average wind speed.

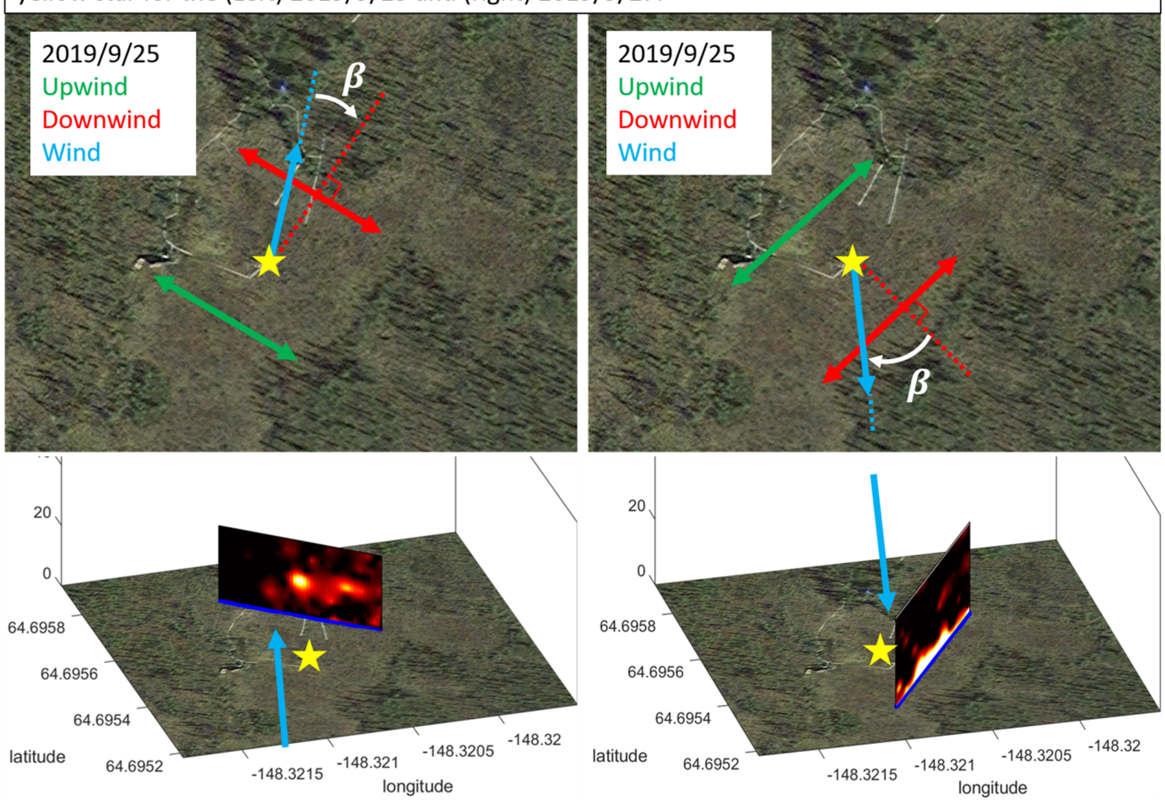
Figure 7: Process for subsampled flight data to flux plane through kriging.



To check the sensitivity to spatial interpolation methods we apply a bootstrapping approach by uniformly randomly subsampling 1/10 of the curtain data into 100 data sets using:

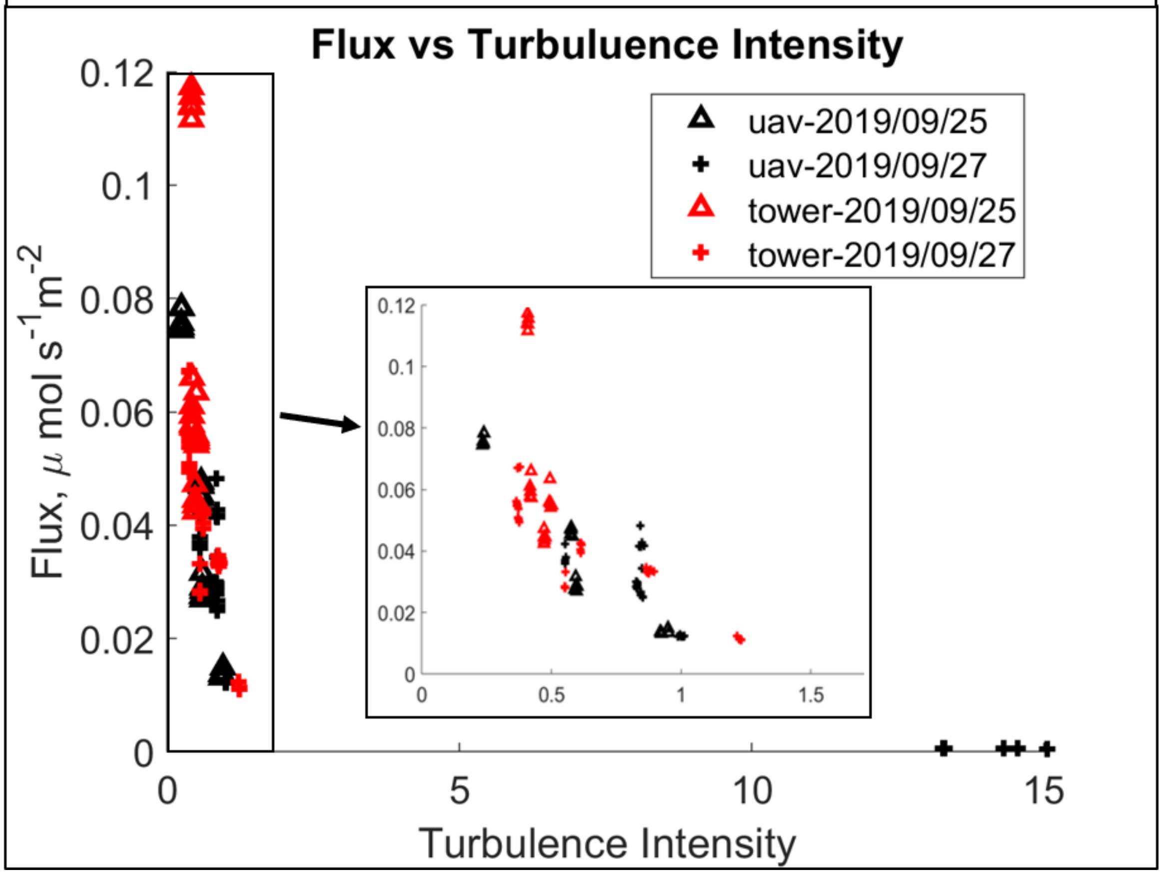
- Kriging [2] with exponential semi-variagram
- Kriging with alpha stable semi-variogram, alpha = 0.7
- Inverse distance weighting (IDW), power = 2.
- Coarse: IDW, power = 1, Fine: Kriging with exponential semivariogram
- Kernel DM+V [1]

Figure 8: APEX bog site showing curtain cosine angle β with reference to the tower indicated by the yellow star for the (Left) 2019/9/25 and (right) 2019/9/27.



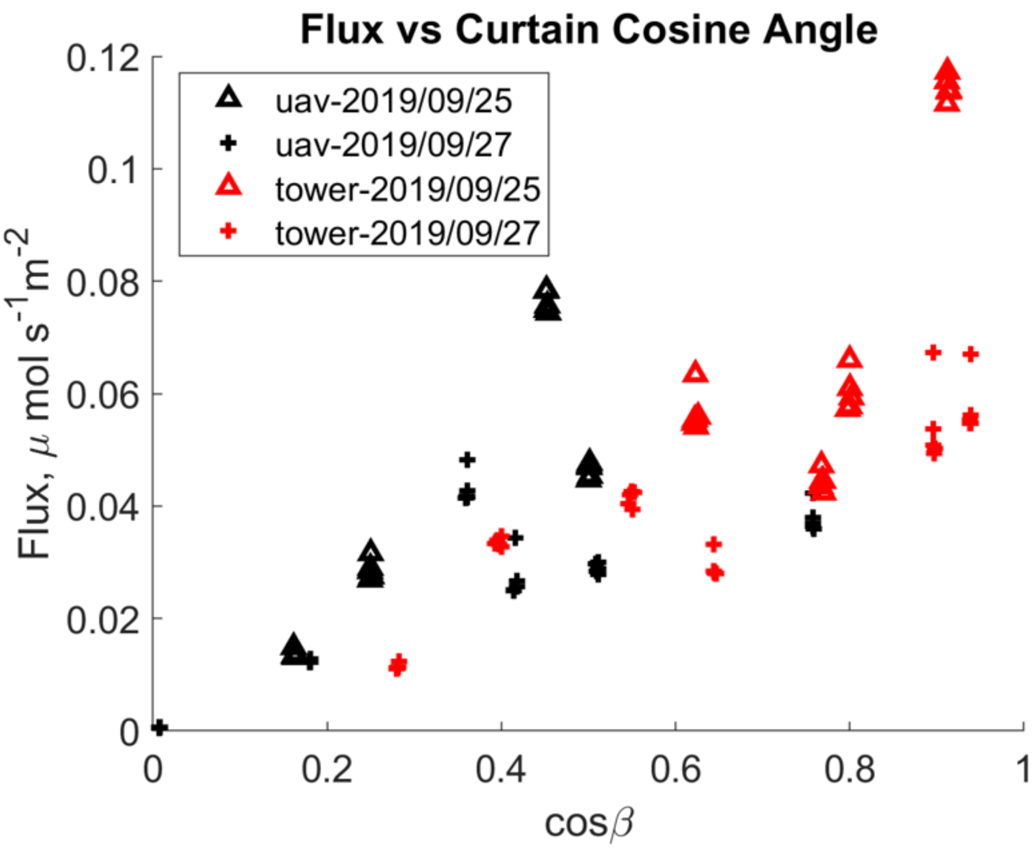
RESULTS

Figure 9: Flux values for each spatial interpolation technique tend to be higher when the turbulence intensity is small.



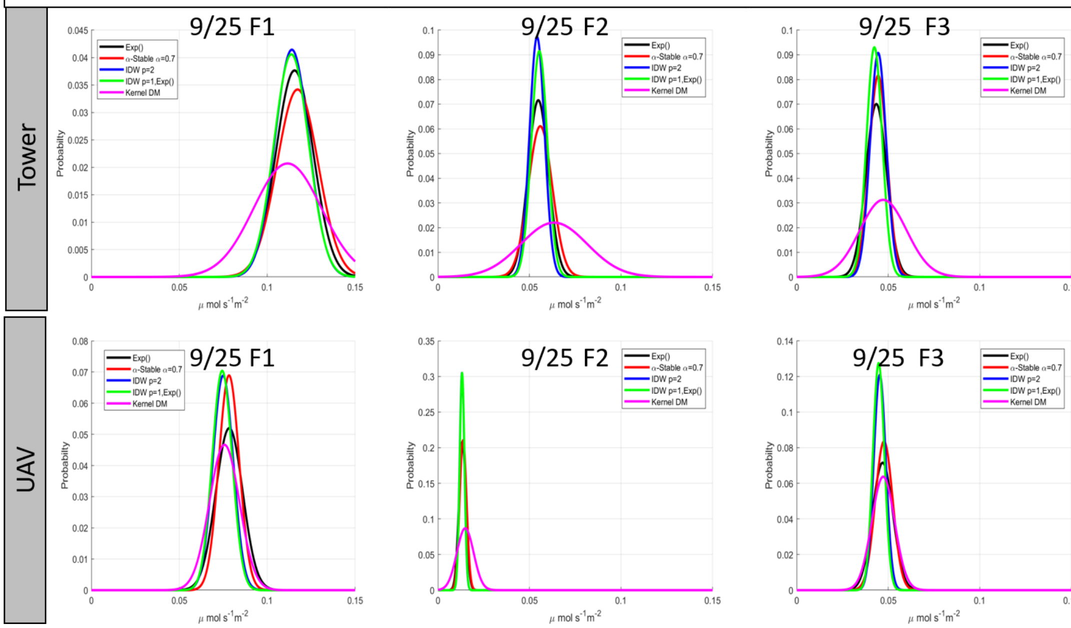
Curtain flux values for each spatial interpolation technique compared to turbulence intensity (measure of how much the wind fluctuates) shows that higher flux values can be measured when the wind is more stable.

Figure 10: Average flux given $cos\beta$ for different dates using UAV (black) versus tower-based (red) wind tend to be higher when the curtain is more perpendicular to the dominant wind direction.



Additionally we can observe that the curtain flux values for each spatial interpolation technique tend to be higher when the curtain is perpendicular to the dominant wind direction.

Figure 11. Large deviations in flux values can be seen due to differences between the tower-based wind (top) and the UAV (bottom). Several flights are shown here as an illustrative example where the x-axis is flux in $\mu mol\ s^{-1}m^{-2}$ and y-axis is the associated probability.



Comparing the flux measurements using the tower-based wind data versus the UAV-based wind calculations show large discrepancies. These differences seem to be the result of 'crosstalk' between the GPS velocity and in situ wind measurements. This shows the resulting flux sensitivity to wind measurements, indicating wind accuracy as an important parameter.

CONCLUSIONS & FUTURE WORK

Conclusions:

- While UAV-based flux estimates are possible, these measurements are sensitive to meteorological conditions (turbulence intensity) and the curtain cosine angle.

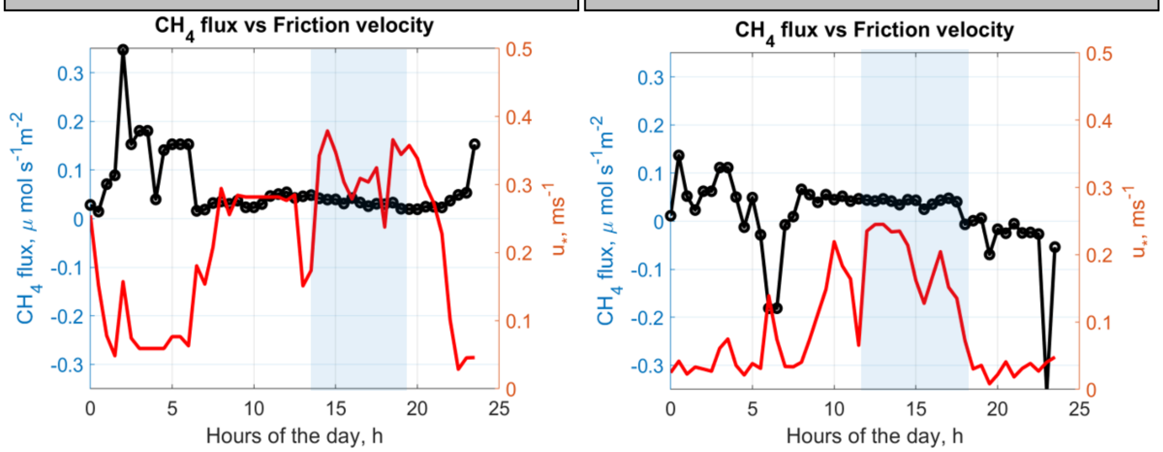
- UAV-based flux estimates are not very sensitive to the type of spatial interpolation technique used

Due to the issues of crosstalk, final ecosystem fluxes were calculated using tower-based wind measurements and compared to the tower-based flux calculations (shown here in micro-mol s-1 m-2).

DATE	AVG TOWER FLUX $\mu mol\ s^{-1}m^{-2}$	AVG UAV FLUX $\mu mol\ s^{-1}m^{-2}$	UAV FLUX-1 $\mu mol\ s^{-1}m^{-2}$	UAV FLUX-2 $\mu mol\ s^{-1}m^{-2}$	UAV FLUX-3 $\mu mol\ s^{-1}m^{-2}$
9/25	0.0338 ± 0.0054	0.0220 ± 0.0278	0.061 ± 0.0162	-0.0180 ± 0.0116	-
9/27	0.0411 ± 0.0063	0.0097 ± 0.0254	0.0078 ± 0.0094	0.0170 ± 0.0035	0.0045 ± 0.0126

Figure 12: Tower-based flux measurements with highlights for hours during flight campaign.

2019_09_25 Tower Data | 2019_09_27 Tower Data



Future Work:

- Explore data fusion techniques to improve in situ wind measurements.
- Explore different wind sensor placement locations to avoid impact from propellers.
- Explore alternate curtain flight paths to improve flux accuarcy and uncertainty.

ABSTRACT

In this work, we test the ability of a UAV equipped with a highly accurate CH_4 sensor to calculate ecosystem flux using the mass balance method. This method uses data collected with curtains (transects at various heights) flown both upwind and downwind of the area of interest. The concentration of methane within these curtains is then estimated using kriging techniques. The difference in calculated amounts of methane between the upwind and downwind curtains is processed to obtain an estimate of flux. Flights in wetlands that also have eddy covariance towers, providing corroborating flux values, have been flown in Alaska and California. We calculated UAV-based flux for the Alaskan flights using a bootstrap approach from multiple randomly subsampled data points within each full curtain of data. We compare these calculations to the traditional mass balance technique. We tested if these different approaches improve the accuracy of our results, as well as the uncertainty bounds for the small fluxes emitted from these ecosystems.

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