Improved eddy flux measurements by open-path gas analyzer and sonic anemometer co-location

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Introduction

Eddy flux is systematically underestimated because of:

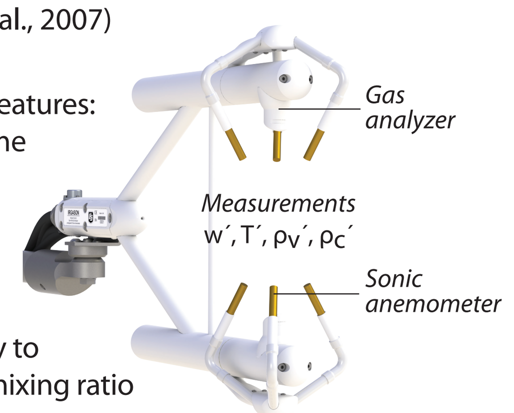
- Spatial separation between measurements of w´ (vertical wind) and ρ´ (gas density)
- Temporal asynchronicity between measurements of w´, T´, and ρ´

Open-path gas analyzers introduce biases in the flux estimates attributed to:

- Variations of air density with temperature T´ and water vapor ρ_v´ (Webb et al., 1980), (Massman, 2004)
- Instrument-induced surface-heat exchange (Grelle et al., 2007)

The IRGASON addresses these problems with the following features:

- Simultaneously measures w´, T´, ρ_v´, and ρ_c´ in the same volume of air
- Reduces instrument self-heating and solar radiation loading due to low power consumption and small-diameter, aerodynamic housing
- Implicitly accounts for air density effects with the ability to compute CO_2 flux using point-by-point conversion to mixing ratio



Research objectives

This study was conducted to:

1. Examine the effect of anemometer and gas-analyzer separation on sensible (Hs), latent (Le), and CO_2 (Fc) fluxes
2. Compare the IRGASON and CSAT3 sonic temperatures
3. Evaluate the influence of instrument induced heat on ambient sensible heat flux measurements
4. Test the concept of calculating fluxes measured by an open-path analyzer using instantaneous point-by-point conversion to CO_2 mixing ratio

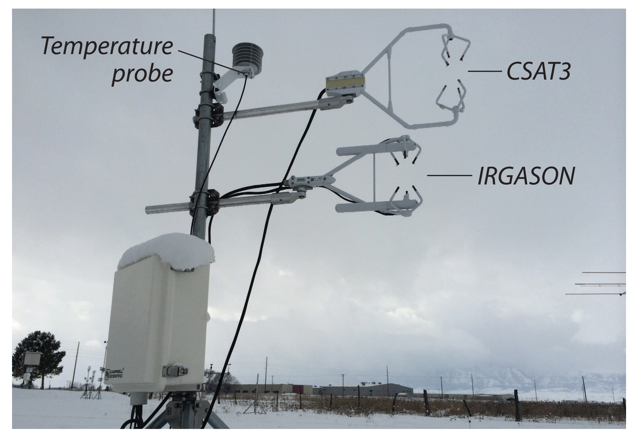


Fig 1. Test setup at a pasture near Logan, Utah

Measurement height:
IRGASON: 1.65 m
CSAT3: 2 m

Spatial separation:
Horizontal: 0.35 m
Vertical: 0.2 m

Sampling rate: 20 Hz

Materials and methods

Operate the IRGASON and CSAT3 in the field over different environmental conditions.

Calculate flux from the IRGASON using instantaneous CO_2 mixing-ratio (MR) based on the provided w´, T´, ρ_v´, and ρ_c´ measurements and the following steps:

a. Correct IRGASON sonic temperature for humidity on-line using the co-located water vapor density:

$$Tair = Ts\frac{1}{\left\{1+0.51\left[\frac{\frac{\rho v}{Patm}}{Rair\left[Ts\frac{1}{1+0.51\left(\frac{\frac{\rho v}{Patm}}{RairTair}+\rho v\right)}\right]}+\rho v\right]\right\}}$$

b. Compute water-vapor pressure and instantaneous CO_2 mixing ratio using:

$$e=\frac{\rho_v RT}{M_v} \qquad \chi_c=\frac{\rho_c RT}{(P-e)M_c}$$

c. Calculate CO_2 flux using the instantaneous CO_2 mixing ratio:

$$F_c^{MR}=\frac{\overline{(P-e)}\cdot m_c}{R\cdot\overline{T}}\cdot\overline{w'\chi_c'}$$

Compare the results with CO_2 fluxes computed with the traditional WPL approach:

$$F_c^{WPL}=\overline{w'\rho_c'}+\left(\frac{m_d}{m_v}\frac{\overline{\rho_c}}{\overline{\rho_d}}\right)\overline{w'\rho_v'}+\left(1+\frac{m_d}{m_v}\frac{\overline{\rho_v}}{\overline{\rho_d}}\right)\overline{\rho_c}\frac{\overline{w'T'}}{\overline{T}}$$

where the effect of humidity on sonic temperature is corrected with:

$$\overline{w'T'}=\overline{w'T_s'}-0.51\overline{T}\,\overline{w'\chi_v'}$$

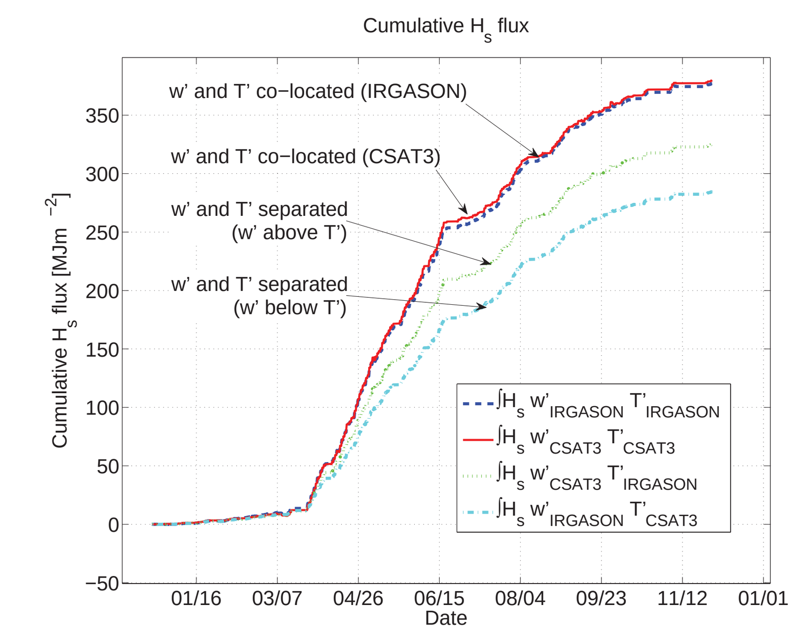
Results

1. Effect of sensor spatial separation on eddy fluxes

Eddy flux is computed when co-located measurements of w´ and T´ from the IRGASON are replaced with equivalent measurements from the CSAT3.

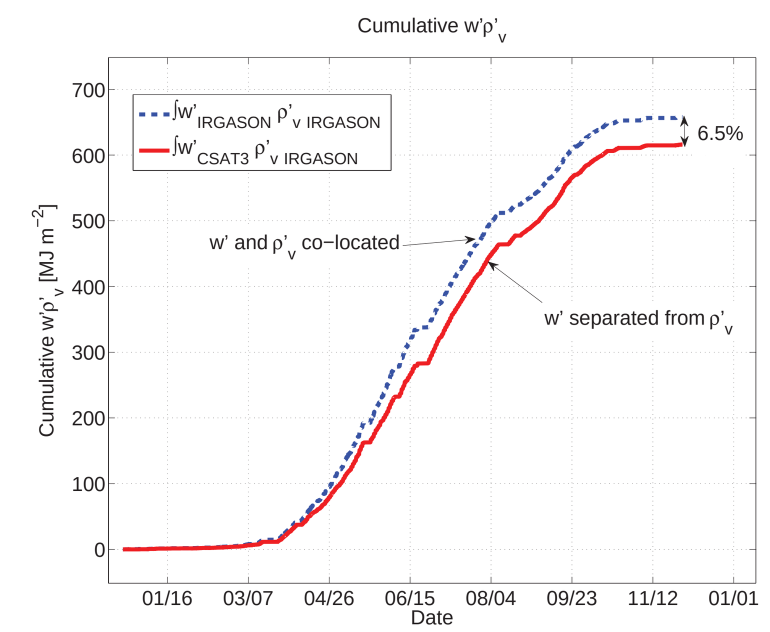
1A. Effect of spatial separation on Hs

A 14.3% loss in cumulative Hs between co-located w´ and T´ and displaced ($w´_{CSAT3}$, $T´_{IRGASON}$) measurements was observed. The loss increases to 25.3% when w´ is underneath the T´ ($w´_{IRGASON}$, $T´_{CSAT3}$).



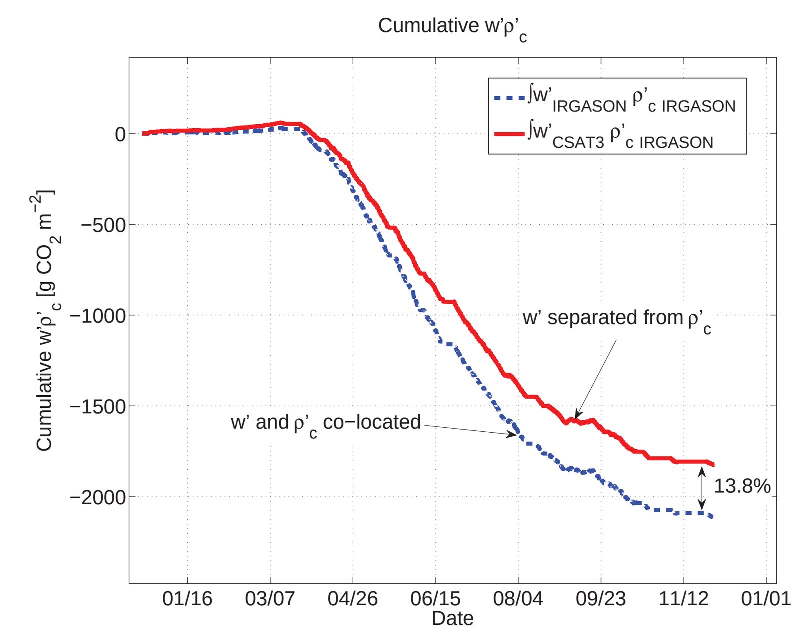
1B. Effect of spatial separation on raw Le

The cumulative uncorrected water vapor flux $w´\rho_v´$ from the IRGASON (w´ and ρ_v´ co-located) is 6.5% higher than the same flux computed using ρ_v´ from the IRGASON and w´ from the adjacent CSAT3.



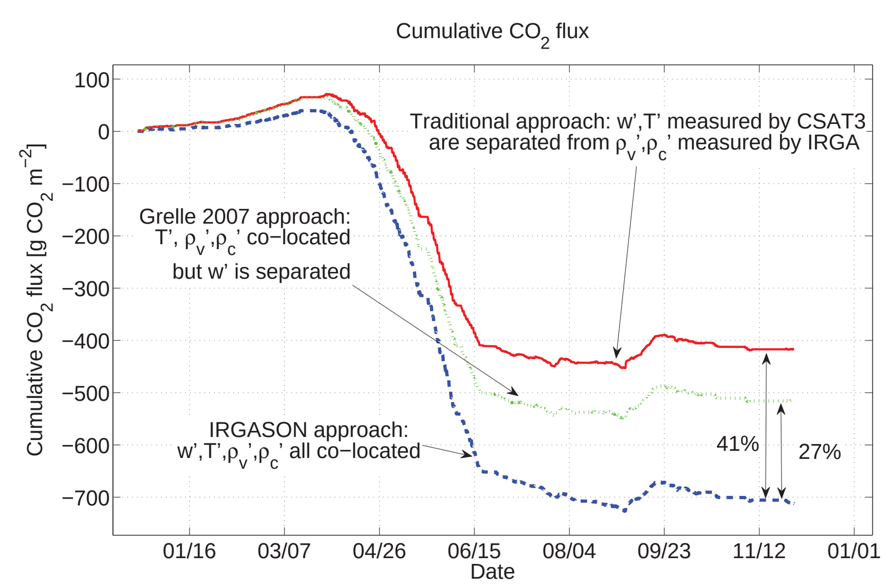
1C. Effect of spatial separation on raw Fc

The magnitude of the cumulative uncorrected CO_2 flux $w´\rho_c´$ from the IRGASON is 13.8% larger than the cumulative flux from the spatially displaced measurements: ρ_c´ IRGASON and w´ CSAT3.



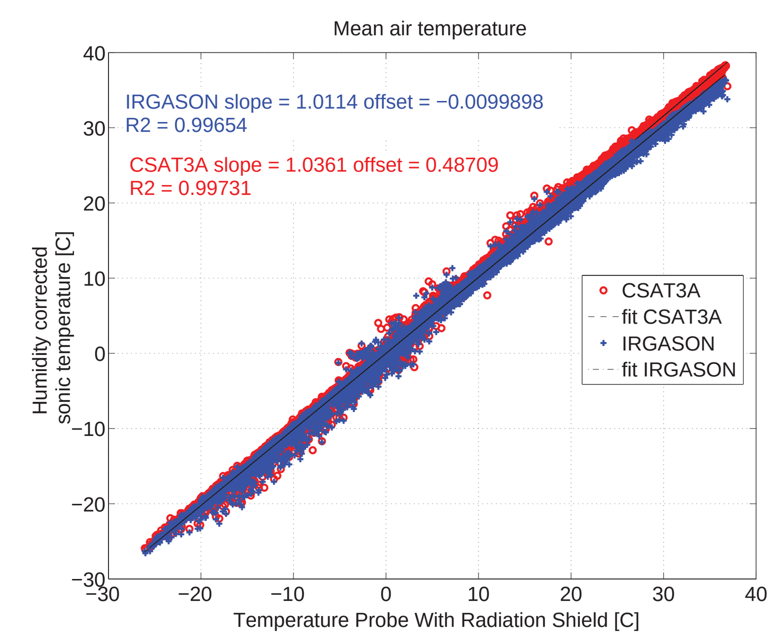
1D. Effect of spatial separation on WPL corrected Fc

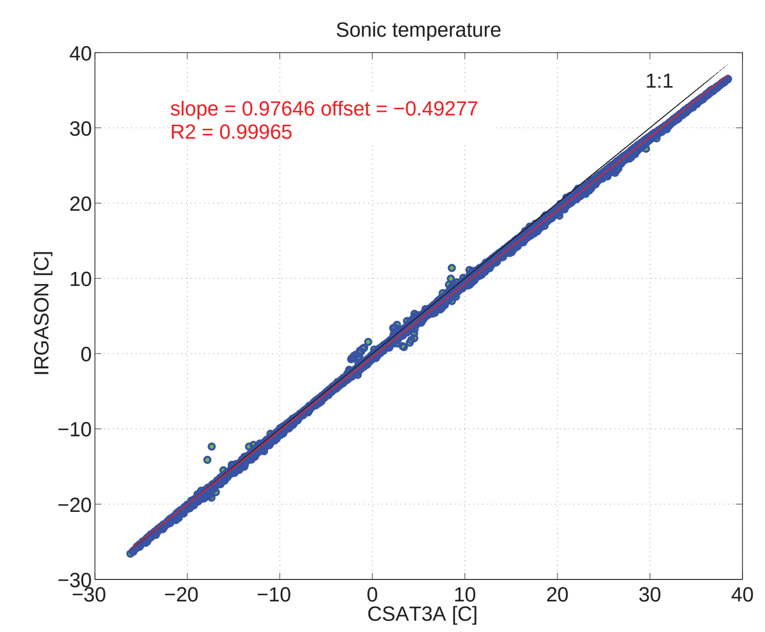
Flux is underestimated 41% when w´ and T´ measurements are separated from the ρ_v´ and ρ_c´. The error is reduced to 27% when T´ is co-located with ρ_v´ and ρ_c´.



2. Comparison of sonic temperature

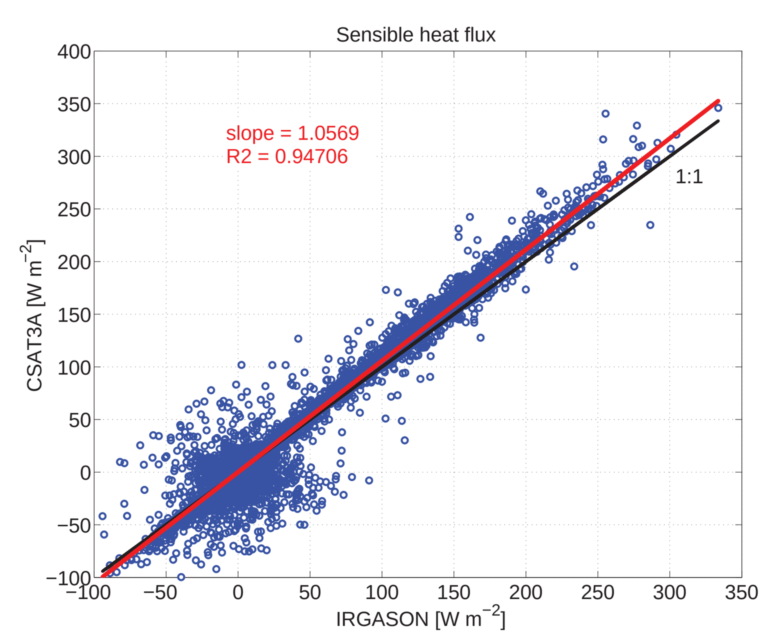
IRGASON and CSAT3 sonic temperatures X-Y slopes agree with the thermistor probe within 1.1% and 3.6% respectively. The CSAT3 overestimated the slope by 2.4% compared to the IRGASON. The CSAT3 has 0.49 °C offset compared to the IRGASON and the air-temperature probe.





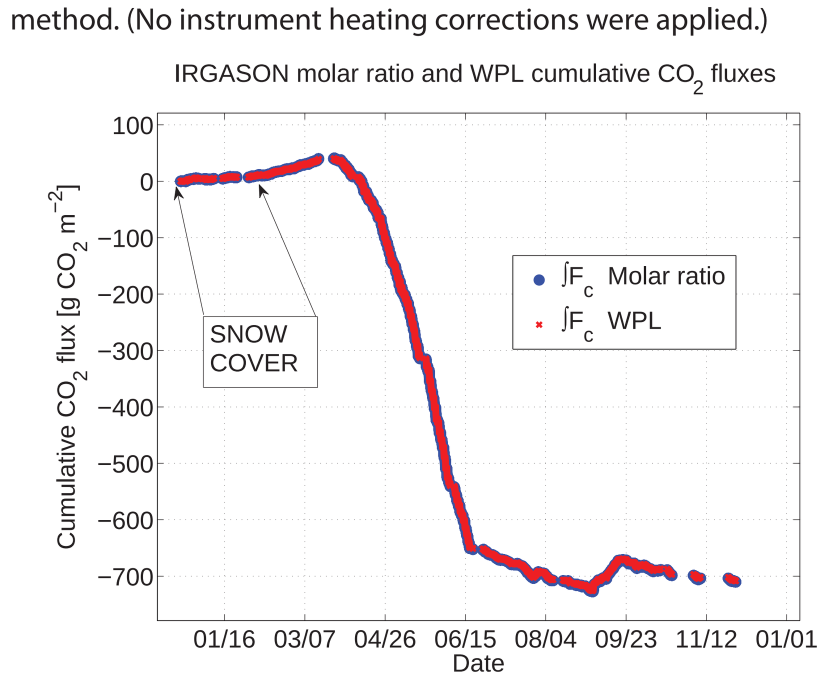
3. Hourly sensible heat flux comparison

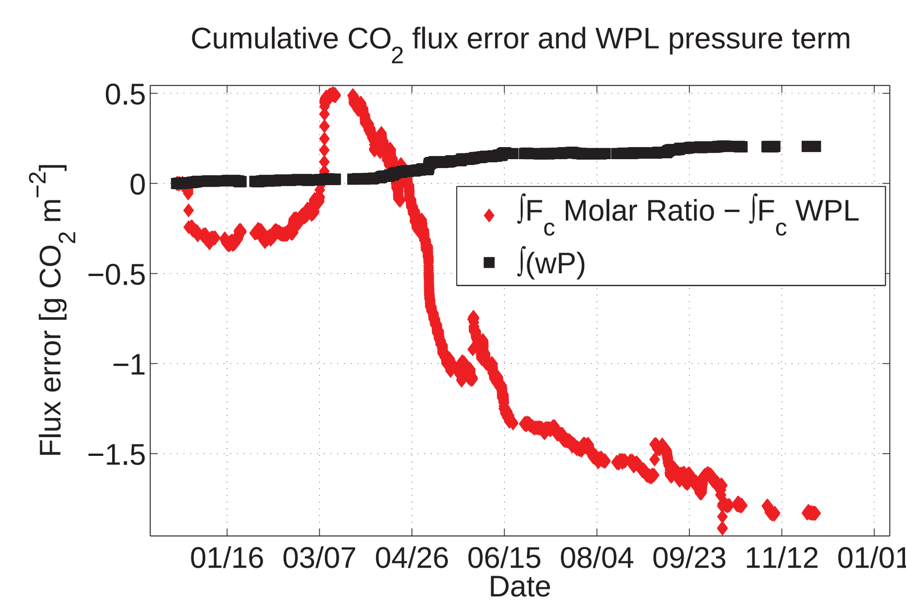
Compared to the CSAT3, the IRGASON underestimates the sensible heat flux by 5.7%. Part of this error is attributed to the 2.4% gain error in the sonic temperature of the CSAT3. Cumulative fluxes agree within 0.7%.



4. Comparison of CO_2 flux computed by the mixing-ratio method to the traditional WPL density-based approach

Both methods yield identical results to within 0.25%. The pressure term (Zhang et al., 2011) is negligible for this site and does not explain the small difference between the two approaches. No apparent CO_2 uptake was observed during off-season and over snow-covered surfaces with either method. (No instrument heating corrections were applied.)





Conclusions

1. **Co-locating the open-path gas-analyzer and sonic measurement volumes preserves the true covariance between all variables associated with the WPL terms and eliminates biases in the eddy-flux estimates.** The correction factors accounting for the loss of correlation due to spatial separation in the individual WPL terms (Massman, 2004) are 6.5% and 13.8% for $w´\rho_v´$ and $w´\rho_c´$ respectively.

2. **IRGASON temperature agrees with the ambient thermistor probe and CSAT3 sonic temperatures to within 1.1% and 2.4% respectively, which indicates that the housing surfaces adjacent to the open-path sensing volume are not appreciably warmer or cooler than the ambient air.** When corrected for humidity, IRGASON sonic temperature is accurate and reliable for calculating CO_2 mixing ratios. It has sufficient frequency response, and it is not affected by solar radiation.

3. **Compared to the CSAT3, the IRGASON underestimates hourly and cumulative sensible heat flux by 5.7% and 0.7% respectively.**

4. **Calculating CO_2 flux using point-by-point conversion to mixing ratio is feasible for an open-path gas analyzer and a co-located sonic anemometer/thermometer. The air density WPL terms can be implicitly accounted for with this approach.** Differences between CO_2 flux calculated using point-by-point conversion to mixing ratio and flux computed following the traditional WPL methodology are less than 0.3%. The pressure term of the density corrections (Zhang et al., 2011) is small for this site and does not explain the difference between WPL and molar-ratio-based fluxes.

No apparent CO_2 uptake was observed during off-season and cold periods over snow-covered surfaces, which also suggests **negligible instrument induced heat flux** in the sensing path of the gas analyzer.

Future work

Validate the mixing-ratio method with flux measurements by a closed-path eddy-covariance system.

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Acknowledgements

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Further information

More details and specifications of the IRGASON instrument can be found at: www.campbellsci.com/irgason.

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