Performance evaluation of an integrated open-path eddy covariance system in a cold desert environment

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Outlines

- Unreasonable CO₂ uptake by open-path eddy covariance (EC) system.
  - Self-heating, spectroscopic effect, bias in CO₂ density.
- Lessons learnt from desert IRGASON experiment.
  - Wind statistics, heat fluxes, CO₂ flux.
- Meta-analysis across 64 FLUXNET sites.
- Results
Typical open-path EC system

LI-7500/7500A+CSAT3

LI-7500/7500A+Gill

EC150

IRGASON
Physiologically unreasonable CO$_2$ uptake observed with open-path EC

<table>
<thead>
<tr>
<th>Period</th>
<th>Landscape</th>
<th>Max ($\mu$mol m$^{-2}$s$^{-1}$)</th>
<th>Mean ($\mu$mol m$^{-2}$s$^{-1}$)</th>
<th>$T_a$ (°C)</th>
<th>Instrument</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>19–20 Feb 2005</td>
<td>Burned boreal forest</td>
<td>−5</td>
<td>−12</td>
<td>−12</td>
<td>CSAT3 + LI-7500</td>
<td>Amiro et al. 2006; Amiro 2010</td>
</tr>
<tr>
<td>9–10 Jan 2005</td>
<td></td>
<td>−4.2</td>
<td>−23</td>
<td>−23</td>
<td>CSAT3 + LI-7500</td>
<td>Amiro et al. 2006</td>
</tr>
<tr>
<td>Jan 2003</td>
<td>Temperature larch forest</td>
<td>−3</td>
<td>−5</td>
<td>−5</td>
<td>TR-61C + LI-7500</td>
<td>Hirata et al. 2007</td>
</tr>
<tr>
<td>27 days in late winter, 2004</td>
<td>Low arctic tundra</td>
<td>−0.9</td>
<td>−10</td>
<td>−10</td>
<td>Gill R3-50 + LI-7500</td>
<td>Lafleur and Humphreys 2008</td>
</tr>
<tr>
<td>9–11 Apr 2003</td>
<td>Drained paddy field</td>
<td>−5.9</td>
<td>12</td>
<td>12</td>
<td>SAT + LI-7500</td>
<td>Ono et al. 2008</td>
</tr>
<tr>
<td>Winter, 2005–2007</td>
<td>Mojave Desert</td>
<td>−0.3 (daily)</td>
<td>−2</td>
<td>−2</td>
<td>CSAT3 + LI-7500</td>
<td>Wohlfahrt et al. 2008</td>
</tr>
<tr>
<td>Oct–Dec 2006</td>
<td>Beech forest</td>
<td>−2</td>
<td>0 to 12</td>
<td>Gill R2 + LI-7500</td>
<td>Metek USA-1 + LI-7500</td>
<td>Järvi et al. 2009</td>
</tr>
<tr>
<td>Jan 2007</td>
<td>Mediterranean alpine shrubland</td>
<td>−2</td>
<td>3</td>
<td>3</td>
<td>Metek USA-1 + LI-7500</td>
<td>Reverter et al. 2010</td>
</tr>
<tr>
<td>Winter, 2006–2008</td>
<td>Eucalyptus plantation</td>
<td>−10</td>
<td>−5 (daily)</td>
<td>15 to 25</td>
<td>CSAT3 + LI-7500</td>
<td>Cabral et al. 2011</td>
</tr>
<tr>
<td>1 Nov 2007–31 Jan 2008</td>
<td>Arctic polyn'ya</td>
<td>−27.95</td>
<td>−4.88 (whole period)</td>
<td>−7.5 to −25</td>
<td>Gill WindMaster Pro + LI-7500</td>
<td>Else et al. 2011</td>
</tr>
<tr>
<td>Winter, 2003–2004</td>
<td>Alpine meadow</td>
<td>−6</td>
<td>0 to −10</td>
<td>Gill R3 + LI-7500</td>
<td>Metek USA-1 + LI-7500</td>
<td>Marcolla et al. 2011</td>
</tr>
<tr>
<td>1 Jan–1 Jun 2004</td>
<td>Sea ice</td>
<td>−14</td>
<td>0 to −35</td>
<td>CSAT3 + LI-7500</td>
<td>Metek USA-1 + LI-7500</td>
<td>Miller et al. 2011</td>
</tr>
<tr>
<td>May–Oct 2008</td>
<td>Subarctic tundra</td>
<td>−4</td>
<td>−0.48 (daily)</td>
<td>−3.5</td>
<td>CSAT3 + LI-7500</td>
<td>Marushchak et al. 2013</td>
</tr>
<tr>
<td>Winter, 2008–2009</td>
<td>Blanket bog</td>
<td>−0.5 (daily)</td>
<td>−3</td>
<td>−3</td>
<td>CSAT3 + LI-7500</td>
<td>Lund et al. 2015</td>
</tr>
</tbody>
</table>

Wang et al., 2016, JTECH
Three possible explanations for unreasonable CO$_2$ uptake

- **Self-heating**: additional heat generated by the instrument electronics or by the solar loading (Burba et al., 2008), such as LI-7500.

- **Spectroscopic effects**: attenuation of temperature at high frequencies and spectroscopic cross-sensitivity (Detto et al., 2011; McDermitt et al., 2011; Bogoev et al., 2014), such as EC150 and IRGASON.

- Errors propagation through density correction procedure by bias in CO$_2$ density (Serrano-Ortiz et al., 2008; Fratini et al., 2014), all IRGAs.
Self-heating of open-path EC

- First interval: low wind, $U'<0$, $U'w'<0$, then $w'>0$, surface warming, air expansion, $\text{CO}_2' < 0$, then $w'\text{CO}_2' < 0$, artificial $\text{CO}_2$ uptake.

- Second interval: strong wind, $U'>0$, $U'w'<0$, then $w'<0$, less surface warming, smaller air expansion, $\text{CO}_2' \approx 0$, no artificial $\text{CO}_2$ uptake.

Burba and Anderson, 2010
Theoretical consideration of self-heating

- WPL density correction algorithm (Webb et al., 1980)

\[ F_c = w' \rho'_c + \frac{\rho_c}{T C_p \rho_a} \left( 1 + \frac{\rho_v M_a}{\rho_a M_v} \right) H + \frac{\rho_c M_a}{\rho_a M_v} \lambda E \]

\[ F'_c = w' \rho'_c + \frac{\rho_c}{T C_p \rho_a} \left( 1 + \frac{\rho_v M_a}{\rho_a M_v} \right) (H + \delta H) + \frac{\rho_c M_a}{\rho_a M_v} \lambda E \]

\[ b = -\frac{\rho_c}{T C_p \rho_a} \left( 1 + \frac{\rho_v M_a}{\rho_a M_v} \right) \frac{\delta H}{H} \]

\[ \frac{\delta H}{H} = 0.14 \text{ (Burba et al., 2008), } \]
\[ b \text{ is } -0.007 \text{ } \mu \text{mol m}^{-2} \text{ s}^{-1} \text{ per W m}^{-2}. \]

Wang, Lee, Lin, et al., in review
Spectroscopic effect due to high-frequency temperature attenuation

\[ A = \frac{N}{(\Delta \nu)} \int_{\nu_1}^{\nu_2} \left\{ 1 - \exp \left( -\frac{S_i \alpha_i CL}{\pi \left[ (\nu - \nu_{0i})^2 + \alpha_i^2 \right]} \right) \right\} d\nu \]

\[ S_i = f_1(T, P) \quad \alpha_i = f_2(T, P) \quad \alpha_i(P, T) = \alpha_0 \frac{P}{P_0} \left( \frac{T_0}{T} \right)^{1/2} \]

Jamieson et al. 1963

\[ F_c' = F_c + 0.014257 H - 0.066828 \]

Bogoev et al. , 2015
Theoretical consideration of spectroscopic effect

\[ \alpha = \tilde{\alpha} + \Delta \alpha, \tilde{\alpha} = \alpha_o \frac{P}{P_o} \left( \frac{T_o}{\bar{T}} \right)^{1/2} \]

\[ \Delta \alpha = -\frac{1}{2} \tilde{\alpha} \frac{T'}{\bar{T}} \]

\[ \Delta A = -\tilde{A} \frac{\Delta \alpha}{\tilde{\alpha}} = \tilde{A} \frac{1}{2} \frac{T'}{\bar{T}}, \quad A = \tilde{A} \left( 1 + \frac{1}{2} \frac{T'}{\bar{T}} \right) \]

\[ C = \tilde{C} \left( 1 + \frac{1}{2} \frac{T'}{\bar{T}} \right) \]

\[ F_c = F'_c + bH \]

\[ b = -\frac{1}{2} \frac{1}{\rho c_p} \frac{\bar{C}}{\bar{T}} \approx -0.025 \ \mu\text{mol m}^{-2} \text{s}^{-1} \]

\[ b \approx -0.014 \ \mu\text{mol m}^{-2} \text{s}^{-1} \]

\[ F'_c \approx F_c + \frac{1}{2} \frac{1}{\rho c_p} \frac{\bar{C}}{\bar{T}} H \]

Wang et al., 2016, JTECH
Universal negative linear relationship between $F_c$ and $H$

Significant and negative linear relationship existed at 37 sites across 64 FLUXNET sites.

Wang, Lee, Lin, et al., in review
Theoretical consideration of bias CO$_2$ density

\[
F_c = \frac{w' \rho'_c}{\bar{T} C_p \rho_a} + \frac{(\rho_c + \delta \rho_c)}{\bar{T} C_p \rho_a} \left( 1 + \frac{\rho_v M_a}{\rho_a M_v} \right) H + \frac{(\rho_c + \delta \rho_c) M_a}{\rho_a M_v} \lambda E
\]

\[
= F'_c + bH
\]

\[
b = \frac{\delta \rho_c}{\bar{T} C_p \rho_a} \left( 1 + \frac{\rho_v M_a}{\rho_a M_v} \right) \left( \frac{\delta \rho_c}{\rho_c} \right) \approx 0.05 \frac{\delta \rho_c}{\rho_c}
\]

- Across 64 sites, \( \frac{\delta \rho_c}{\rho_c} = -5\% \), \( b \) is about \(-0.0025 \mu\text{mol m}^{-2} \text{ s}^{-1} \) per W m$^{-2}$.

Wang, Lee, Lin, et al, in review
Hypothesis

- Integrating the infrared gas analyzer’s sensing heads into the sensing volume of the sonic anemometer has negligible effects on dynamic flows of the IRGASON.

- Inadequate spectroscopic correction by slow response air temperature measurement partly contribute to ecologically unreasonable CO$_2$ uptake with IRGASON.
Site (cold arid desert) and Instrumentation
<table>
<thead>
<tr>
<th>Instrument</th>
<th>Sensor</th>
<th>Height/depth (m)</th>
<th>Variables</th>
<th>Operation period</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC</td>
<td>LI-7500A (LI-COR, Inc.) + WindMaster Pro (Gill Instruments Ltd.)</td>
<td>15</td>
<td>$H, \lambda E, F_c, u, T_a, CO_2, \rho_v, T_s$</td>
<td>Jun 2013–10 Mar 2014</td>
</tr>
<tr>
<td>Radiation</td>
<td>CNR4 (Kipp and Zonen B.V.)</td>
<td>14</td>
<td>$K_\perp, K_\uparrow, L_\perp, L_\uparrow, R_n$</td>
<td>Jun 2013–now</td>
</tr>
<tr>
<td></td>
<td>PAR LITE (Kipp and Zonen B.V.)</td>
<td>14</td>
<td>PAR</td>
<td>Jun 2013–now</td>
</tr>
<tr>
<td>Micrometeorology</td>
<td>HMP155A (Vaisala Inc.)</td>
<td>11, 14</td>
<td>$T_a, RH$</td>
<td>Jun 2013–now</td>
</tr>
<tr>
<td></td>
<td>SI-111 (Apogee Instruments, Inc.)</td>
<td>11</td>
<td>Surface temperature</td>
<td>Jun 2013–now</td>
</tr>
<tr>
<td></td>
<td>TE525MM (Campbell Scientific, Inc.)</td>
<td>11</td>
<td>Precipitation</td>
<td>Jun 2013–now</td>
</tr>
<tr>
<td>Soil</td>
<td>Hukseflux HFP01 (Hukseflux Thermal Sensors B.V.)</td>
<td>0.08, 0.2, 0.5</td>
<td>Soil heat flux</td>
<td>Jun 2013–now</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Period</th>
<th>Date</th>
<th>Populus trees</th>
<th>$T_a$ (°C)</th>
<th>$\rho_v$ (ppm)</th>
<th>$K_\downarrow$ (W m$^{-2}$)</th>
<th>Albedo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>Dec.16, 2013-Jan.3, 2014, dormant season</td>
<td>-6.7</td>
<td>2730</td>
<td>91.1</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>Spring</td>
<td>Mar.12, 2014-Apr.13, 2014, flowering stage</td>
<td>14.1</td>
<td>3390</td>
<td>195.0</td>
<td>0.27</td>
<td></td>
</tr>
</tbody>
</table>
Wind statistics

\[ y = 1.01(\pm 0.00)x + 0.09(\pm 0.01) \]

\[ R^2 = 0.99, \ P < 0.001, \ I = 1.00 \]

\[ N = 1308, \ RMSE = 0.14 \text{ m s}^{-1} \]

\[ y = 1.07(\pm 0.01)x - 0.02(\pm 0.00) \]

\[ R^2 = 0.96, \ P < 0.001, \ I = 0.99 \]

\[ N = 1302, \ RMSE = 0.05 \text{ m s}^{-1} \]

Wang et al., 2016, JTECH
The Monin-Obukhov scaling relationships

\[
\frac{\sigma_w}{u_*} = 1.25 \left(1 - 3\xi\right)^{1/3} \quad \xi < 0
\]

\[
\frac{\sigma_w}{u_*} = 1.25 \left(1 + 0.2\xi\right) \quad \xi > 0
\]

Wang et al., 2016, JTECH

Garratt 1992; Kaimal and Finnigan 1994
Spectral and cospectral analysis

Wang et al., 2016, JTECH
Sensible and latent heat flux

\[ y = 1.11(\pm 0.01)x - 1.22(\pm 0.41) \]
\[ R^2 = 0.96, \ P < 0.001 \]

\[ y = 0.91(\pm 0.05)x + 0.13(\pm 0.02) \]
\[ R^2 = 0.43, \ P < 0.001 \]

Wang et al., 2016, JTECH
CO$_2$ flux time series

\[ F'_c = F_c + 0.014257H - 0.066828 \]

- Winter mean $F_c$ was -0.25 $\mu$mol m$^{-2}$ s$^{-1}$ and -0.22 $\mu$mol m$^{-2}$ s$^{-1}$ for the separated EC system and the IRGASON, respectively.

Wang et al., 2016, JTECH
After applying correction for spectroscopic effect, the wintertime IRGASON CO$_2$ flux became physiologically reasonable (mean value -0.04 μmol m$^{-2}$ s$^{-1}$). Wang et al., 2016, JTECH
The slope parameter $b$ (μmol m$^{-2}$ s$^{-1}$ per W m$^{-2}$; gray bars) and the $R^2$ value (white bars) of the linear regression between wintertime $F_c$ and $H$. Error bars are ± 1 standard error.

Wang, Lee, Lin, et al, in review
Comparison among geographic regions

Wang, Lee, Lin, et al, in review
Integrating an IRGA into measuring volume of the IRGASON sonic anemometer had negligible effects on its wind statistics.

Both EC systems observed negative CO$_2$ fluxes (-1.6 $\mu$mol m$^{-2}$ s$^{-1}$) in the daytime during the winter experiment. Sensor self-heating was ruled out as the cause of the apparent uptake flux.

After applying correction for spectroscopic effect, the wintertime IRGASON CO$_2$ flux became physiologically reasonable (mean value -0.04 $\mu$mol m$^{-2}$ s$^{-1}$).

The negative linear relationship between observed CO$_2$ flux and sensible heat flux is universal and was confirmed by a meta-analysis of open-path EC data from 64 FLUXNET sites.
Related papers


Data sharing http://yncenter.sites.yale.edu

Yale-NUIST Center on Atmospheric Environment

Thanks for your attention!

Data Access

Follow the link to download the data and the readme file. If you plan to use our data for journal publication, please contact Ms. Zhen Xu at 478766329@qq.com. We will let you know if your plan conflicts with ours and if we should be offered coauthorship.

1) Micrometeorology, water temperature, and radiation and heat fluxes at Meiliangwan, Lake Taihu (2010-2011)