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**Title:**  
Monthly to annual measurements of land surface CO$_2$ flux integrated by the atmospheric boundary layer.

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Here we describe a method to measure net surface flux of CO$_2$ using concentration measurements in the atmospheric boundary layer (ABL) averaged over monthly to annual time periods. Convective turbulence within the ABL and movement of the ABL over the surface results in a large spatial ($10^4$ – $10^6$ km$^2$) integration of surface processes that effect the CO$_2$ mixing ratio. ABL-flux estimates of net CO$_2$ flux gave close agreement with surface-based, eddy covariance measurements. While the current approach is, in part, tied to smaller-scale measurements (1 km$^2$), our validation site is representative of the larger region. Therefore, our results indicate that the proposed ABL-flux method provides a framework for obtaining regional-scale estimates of net surface flux based solely on measured variables. This approach should allow for precise carbon balance studies at an intermediate scale between the plot and the planet, and could contribute to a stated goal of carbon cycle research; to determine the carbon balance and mechanisms that control it for large geographical regions such as N. America, the USA or Europe (1).
A worldwide, integrated system of measurements and models provides a basis for interpreting and predicting the role of terrestrial ecosystems in the global carbon balance (2-9). Currently, there are more than 150 sites worldwide where carbon balance is assessed continuously using eddy covariance and other methods. The average footprint, or area of surface flux integration, typically does not exceed 1 km². The next larger scale at which adequate closure occurs is at the global scale (ca. 51 x 10⁷ km²), where data from the global flask network enables precise trace gas and isotope balance studies of the world's atmosphere (8,9). While it is possible to map, subdivide and categorize the land surface at many scales in between these two extremes, it has not been possible to conduct precise carbon measurements at these scales. The scale intermediate to these extremes, the regional scale (broadly defined as 10² to 10⁶ km²), is of primary interest in political and climate change considerations of the carbon cycle.

Measurements of mean atmospheric motion, CO₂ mixing ratio, and local surface flux can be used to parameterize inversion models and thus infer net regional surface flux, however the means to test these model outputs is currently limited. Landscape heterogeneity and complex terrain complicates extrapolation from eddy covariance studies to the regional scale. Hence, it is of considerable interest to develop measurement-based methodologies that can estimate net surface flux at the regional scale.

The current analysis focuses on the atmospheric boundary layer (ABL) – a layer of air near the earth’s surface that is separated from the upper atmosphere by a density inversion. At temperate latitudes over the continents, this layer typically develops during the clear weather conditions following a frontal passage and may persist for several days until the next disturbance (10, 11). During the day, this layer is well mixed by convective turbulence. During the night, a shallow nocturnal inversion may form, which typically re-mixes with the ABL the following day. Ecosystems locally modify the ABL through evapotranspiration and physiological processes such as photosynthesis and respiration leading to
changes in the mixing ratios of water vapor and CO$_2$. Meteorological processes such as the entrainment of tropospheric air during boundary layer growth, synoptic-scale subsidence of the troposphere, mesoscale circulations (e.g. sea breezes) and boundary layer cloud formation tend to counter the influence of the land surface by facilitating mixing between the ABL and the, typically drier and warmer, overlying troposphere. The ABL air mass is also moving over the land surface (ca. 500 km day$^{-1}$ under typical fair weather conditions, and dispersing in the horizontal due to divergence and wind shear -12). Hence, the composition of the ABL at any point above the land surface is a function of the initial composition of the air mass when the boundary layer was formed, exchanges with the surfaces over which it has passed, and the composition and quantity of tropospheric air that has mixed with it along its way.

Studies of the CO$_2$ balance of the ABL, therefore, have the potential to provide information on carbon balance of the land surface on a regional-scale. Indeed, the footprint for the concentration of a trace gas of surface origin in the ABL has been estimated to be about $10^6$ km$^2$ (13). Previous mass balance studies have been successful in estimating regional surface flux through the ABL during fair weather conditions (14-18). However, due to both limited sampling in time and a lack of information concerning horizontal advection, it has not been possible to extend these regional flux estimates beyond a few days.

Our analysis shows that quasi-stable differences are established between the ABL and the free troposphere on monthly to annual scales. We hypothesize that these differences reflect carbon fluxes between the land surface, the ABL and the free troposphere, and we propose that simultaneous measurements of water vapor concentration differences along this transport pathway and knowledge of the flux of evapotranspiration can be used to quantify CO$_2$. Lacking information on regional flux to test our proposed method, we report here a comparison of flux
measured at a local site representative of the region to the putative regional flux estimate.

**Methods**

**Study site.** This study was performed in NW Wisconsin, USA, on and around the WLEF television broadcast tower (45.9° N, 90.3° W) as part of the Chequamegon Ecosystem-Atmosphere Study (http://cheas.psu.edu/). The tower is 450 m tall and located within the Chequamegon-Nicolet National Forest and is a NOAA-CMDL CO₂ sampling site (19). The area is largely forested for hundreds of km to the east and west, Lake Superior is approximately 70 km to the north and agriculture begins to dominate about 200 km to the south. The dominant forest types are mixed northern hardwood, aspen, and wetlands. The population density for the area is approximately five people per square km.

**Measurements of ABL CO₂ and H₂O.** Measurements of ABL CO₂ (Cₘ) and H₂O (qₘ) mixing ratios were obtained at 396 m on the WLEF tower (20). Measurements of surface water vapor flux (Fₚ) was obtained from eddy-covariance measurements at 122 m from the tower (20). Note that the flux data was not gap filled and hence comparisons of Fₚ and NEE at 122 m from the WLEF tower were made only when measurements of Fₚ from 122 m were available (Fₚ is required to calculate Fₚ, see Results and Discussion). This resulted in a loss of approximately 14 percent of the annual data.

**Measurements of CO₂ and H₂O in the free troposphere.** On the 23rd and 24th of August, 2000, CO₂ and H₂O mixing ratios were obtained directly from airplane flights through both flask and infra-red gas analyzer measurements (IRGA). Additionally, direct measurements of CO₂ and H₂O mixing ratios from 5 km above the surface were obtained for the 19th of August above the WLEF tower- and for six additional days spanning the month of August for the Midwestern U.S.- through the CO₂ budget and rectification airborne study (COBRA) airplane
The mean of these values, thus obtained, was used for free tropospheric values over the WLEF site for the month of August.

The free troposphere values of CO$_2$ ($C_t$) and H$_2$O ($q_t$) over WLEF were extended to the full year with proxies to supplement the sparse data from aircraft flights. $C_t$, as measured by airplane flights above 5 km in August 2000, was fairly constant over the entire Midwest (366.7 ±1.8 ppm), and the mean value of CO$_2$ was about two ppm different from the monthly mean of CO$_2$ from the marine boundary layer (MBL) at a similar latitude to the WLEF tower (44.4°; data is available from the globalview data set; 22).

Aircraft measurements of $q_t$ in the month of August (1.4 ± 0.9 g/kg) were in close agreement with $q_t$ derived from Rapid Update Cycle (RUC; 1.2 ± 0.5 g/kg) weather-forecasting data from geopotential heights of 3200 to 7600 m (23). RUC is a high frequency weather prediction system developed as a service to provide short-range weather forecasts. The model is updated every 3 h with observations from (but not limited to) surface weather stations, commercial aircraft, various sondes and satellite-derived data for the contiguous U.S. Direct measurements of $q_t$ available for August agreed well with the RUC estimates, and $q_m$ available from the WLEF tower (measured at 396 m) for June through September of 2000 were highly correlated ($y = 0.9383x + 0.2462$, $r^2 = 0.92$, p <0.0001) with $q$ obtained from RUC data (geopotential heights of 300-600 m). We are confident, therefore, that the RUC data provides a good proxy for $q_t$.

Furthermore, the flux estimate are relatively insensitive to $q_t$ as the monthly average $q_t$ was always 1/3 to 1/10 of $q_m$ (Table 1). We used direct measurements of $C_m$ and $q_m$ from the tower and proxies, (the CO$_2$ from the MBL for $C_t$, and the RUC data for $q_t$,) to construct the monthly mean differences in CO$_2$ and water vapor concentration for the full year of 2000 (Figure 3).
Results and Discussion

Continuous measurements of the mixing ratio of CO$_2$ in the ABL have been conducted at the WLEF tower since 1995 (19). As shown in Figure 1, the (monthly average) CO$_2$ concentration shows a more pronounced seasonal cycle than observed in the marine boundary layer at the same latitude. Bakwin et al. (24) suggest that CO$_2$ at WLEF follows that of the global atmosphere, with an additional contribution arising from continental CO$_2$ exchange, a sink for CO$_2$ during summer and a source during winter. Efforts to separate the local from large-scale influences are complicated by a lack of knowledge about vertical and horizontal differences in CO$_2$ near the tower. Atmospheric CO$_2$ measurements conducted in the summer of 2000 by the COBRA campaign (21) provide important insight into the nature of these differences. Vertical sounding showed that ABL CO$_2$ ($C_m$) was quite variable from place to place and time to time, while that in the free troposphere ($C_t$) (above the ABL) was fairly constant over the entire Midwest (Figure 2), and the latter concentration was similar to that measured in the marine boundary layer. This is not unexpected since strong zonal winds mix the free troposphere at this latitude (25). Mass exchange between the ABL and the free troposphere would tend to force $C_m$ to track that of the zonal atmosphere, while net CO$_2$ exchange occurring at the land surface would tend to cause $C_m$ to depart from that of the free troposphere.

To illustrate the behavior of ABL mixing ratio with time, observations from the tower are plotted together with that of the troposphere (the mean of the COBRA measurements of $C_t$) over several synoptic cycles in August (Figure 2C). The measurement level (396 m) was generally above the nocturnal inversion and well below the daytime entrainment layer at the top of the ABL. At this level, the strong diurnal cycle in CO$_2$ mixing ratio near the surface was not seen, and longer-term trends in the properties of the ABL air mass were evident.
pressure, with associated frontal passage and storms, $C_m$ was very similar to $C_t$. This is expected as there should be strong vertical mixing at such times, and Hurowitz et al (26) presents several case studies of rapid CO$_2$ concentration changes associated with synoptic events. During intervening fair weather intervals when the area was under the influence of high pressure systems, large scale subsidence predominates above the ABL with divergence within the ABL. During these periods, $C_m$ was drawn below $C_t$ over several days. With passage of the next frontal system $C_m$ again approached $C_t$. Over the entire interval, the average $C_m$ was lower than $C_t$. This was consistent with CO$_2$ flux measurements indicating that the land surrounding the tower was a net sink for CO$_2$ (-1.1 $\mu$mol m$^{-2}$ s$^{-1}$) averaged over the month of August. Long-term (monthly averages) mixing ratios show consistent differences in CO$_2$ between the ABL the marine boundary layer (a surrogate for the free troposphere; Figure 1).

Assuming that the mean differences in atmospheric CO$_2$ between the ABL and the free troposphere are generated by net ecosystem exchange, can these be used to estimate the surface flux? Most previous efforts to estimate surface fluxes from ABL studies have attempted to integrate the mass balance of the ABL for CO$_2$ over some interval of time. One of the challenges of this approach is to account for the CO$_2$ fluxes associated with horizontal advection and vertical mixing between the ABL and the free troposphere (for a review see 12). Here, we adopt an approach based on the integration of a boundary layer budget for water vapor and CO$_2$ that satisfies the need for knowledge of atmospheric transport based on easily measured variables. This method assumes knowledge of the flux of water vapor from the surface, and measurements of the differences in water vapor concentration in addition to those of CO$_2$. It is assumed that both water vapor and CO$_2$ are conserved in the ABL, and that both gases respond similarly in atmospheric mixing. It then follows that the information on atmospheric transport required to interpret CO$_2$ differences between the ABL and the free troposphere is implicitly included in the flux-
difference relationship for water vapor (12). It is recognized that during storms water vapor is not conserved, however both the surface flux and the water vapor difference between the ABL and free troposphere are small during these periods.

Evapotranspiration from the land surface adds water vapor to the ABL, and mixing of tropospheric air generally tends to dry the ABL. Over temperature forest systems, it has been shown that the majority of water vapor within the ABL is of surface origin (27), that the principle control over water vapor within the ABL during fair-weather conditions is surface flux (11) and that the ratios of CO₂ to H₂O within the ABL are consistent with leaf-level measurements of the ratio of carbon gained to water lost by plants (18). Over time scales longer than a few days, a quasi-stable differences in water vapor and CO₂ were observed between the ABL and the free troposphere over the WLEF site (Figure 3). We assume that these seasonally varying differences reflect a steady-state balance between surface exchange and atmospheric mixing such that \( F_{\text{NEE}} = (C_m - C_t)/r_a \) and \( F_q = (q_m - q_t)/r_a \), where \( F_{\text{NEE}} \) and \( F_q \) are the net ecosystem exchange (NEE) of CO₂ and water vapor flux averaged over the same time interval, respectively. \( C_m, C_t \) and \( q_m, q_t \) are mixing ratios of CO₂ and water vapor in the mixed boundary layer and troposphere, respectively. The term \( r_a \) is analogous to an aerodynamic resistance for mixing of air from the free troposphere into the ABL. By noting that \( r_a \) is the same for both fluxes we can write that,

\[
F_{\text{NEE}} = \frac{(C_m - C_t)}{(q_m - q_t)} \cdot F_q
\]

This argument is analogous to the flux-gradient relationships commonly used in the atmospheric surface layer (12). ABL-free troposphere mixing on synoptic scales may have analogy to turbulent eddies at smaller scales, and a more detailed study of covariation of mixing ratio and transport might lead to a methodology based on observed or modeled transport.
This method was applied to calculate net CO$_2$ flux over the WLEF study site using $C_t$ and $q_t$ measured from airplane flights, $C_m$ and $q_m$ from 396 m and $F_q$ measured at 122 m on the WLEF tower. Figure 4 shows a comparison of calculated value of $F_{\text{NEE}}$ and a local measurement of net CO$_2$ flux (expressed as a 24 hour average) conducted at 122 m above the ground surface by eddy-covariance (20). The two estimates tracked one another fairly well as the magnitude and sign of net CO$_2$ exchange changed from a sink to a source in late August and early September. The day-to-day variance between the ABL-flux estimate and the eddy-covariance NEE could be, in part, due to differences in advection, storage and mixing associated with the synoptic cycle. If this is the case we would expect the agreement to improve with longer averaging periods (71). The NEE estimated by eddy covariance for the month of August was (35.4 g C m$^{-2}$) or presented as a mean flux density $-1.1 \mu$ mole CO$_2$ m$^{-2}$ s$^{-1}$. Taking the monthly average values for $F_q$, $C_m$, $q_m$ (from the tower), $C_t$, and $q_t$ (from airplane measurements) we calculate an average monthly CO$_2$ flux of $-1.6 \mu$ mole m$^{-2}$ s$^{-1}$. Thus, the ABL-flux method provides a plausible estimate of the average net CO$_2$ flux at the monthly scale.

To extend this test of the ABL flux method to longer periods proxies we estimated the monthly mean differences in CO$_2$ and water vapor between the ABL and the free troposphere for the full year of 2000. These data are summarized in Table 1, and NEE estimates by eddy covariance and the ABL-flux method are summarized in Figure 5. Rainy periods, when advection is strong (26) and water vapor is not conserved, drop out of the analysis since $F_q$ is small and mixing ratio gradients are small due to strong vertical mixing.

The monthly estimates of $F_{\text{NEE}}$ were in close agreement with eddy-covariance measurements of NEE (Figure 5, uncertainties in Table 2). The ABL-flux method also captured the large shift in NEE associated with the seasonal cycle, and
provided similar results to eddy-covariance NEE on an annual basis. This comparison of a local flux measurement with $F_{\text{NEE}}$ is encouraging. However, we suggest some caution in interpreting the absolute value of the flux estimates reported here; first, proxies were used for $C_t$ rather than direct measurements, and second the eddy-covariance estimates are still being processed to correct for missing data (14%) and times with low turbulence. Note that measurements of time rate of change in $CO_2$, or $CO_2$ differences alone would not be sufficient to estimate flux. Information on transport is also needed (24). In the method examined here, information on transport is inferred from measurements of the water vapor flux-difference relationship. Transport statistics from a model could also be used in place of the ABL-flux approach to estimate net $CO_2$ flux. However, the approach proposed here has the obvious advantage that it is observation based.

For this study, $F_q$ was measured locally and had a footprint no larger than 1 km$^2$. We acknowledge, however, that the footprint affecting the mixing ratio of $C_m$ and $q_m$ is undoubtedly much larger. Gloor et al. (13) estimated that the footprint controlling $C_2Cl_4$ mixing ratio (and by inference, $CO_2$) at the WLEF tower was on the order of $10^6$ km$^2$, and other published estimates of ABL footprints range from $10^2$ to $10^4$ km$^2$.

To explain the observed agreement between the ABL-flux and eddy-covariance estimates of NEE, we propose that air masses passing through the tower from most directions have passed over similar forest, and that NEE and $F_q$ measured locally are fairly representative of the footprint which effects $C_m$ and $q_m$. Hence, the eddy covariance measured at 122 m provides reasonable estimates of the NEE of this region in this special case. While it would be difficult to test the ABL-flux method over more heterogeneous landscapes, it should still be possible to estimate fluxes from such an area provided an adequate estimate of $F_q$ is available.
The importance of each measured variable in calculating $F_{NEE}$ was assessed individually by performing a sensitivity analysis using the standard error of the mean for each variable (Table 3; The standard error of the mean for each month was calculated assuming that each 24 h period was one independent sample for the monthly mean). $F_{NEE}$ was least sensitive to $q_t$, which is not surprising as free tropospheric water vapor is relatively constant and near 1 g kg$^{-1}$ on an annual basis, hence a precise measurement of $q_m$ is more important in calculating the water vapor difference between the ABL and the free troposphere. While the $F_q$ had a substantial effect in the sensitivity analysis, the measurement error associated with eddy covariance measurements is considerably smaller than the standard error of the mean. The most important variable in matching $F_{NEE}$ to eddy-covariance measurements of NEE was $C_m$, followed by $C_t$ and $q_m$. Hence, an accurate measure of $(C_m-C_t)$ is crucial to flux calculation by the ABL-flux method. Note that the standard error of the mean was considerably higher than the measurement precision of $C_m$ (0.01 ppm).

The ABL-flux method can be considered as a variant of the flux-gradient approach used extensively in the past to estimate surface flux from measurement of differences in CO$_2$ and water vapor along an eddy diffusion path in the surface layer above plant canopies (12). The present application considers the ABL and free troposphere as boxes. Mixing between the boxes and fluxes entering the ABL from the surface establish differences in the concentration of CO$_2$ between the boxes. In reality, an idealized steady state is probably not achieved between these boxes on the time scale of hours to days, because surface exchange and entrainment respond to diurnal and synoptic cycles. However, if it is assumed that a reference gas and CO$_2$ are both conserved over the time frame of averaging, and that the initial and final mixing ratios are the same (i.e. storage is negligible), then the average flux should be proportional to the average mixing-ratio difference for each gas. Although water vapor is used here as the reference gas, other gases such as radon, which are produced or consumed in the soil...
might be another option. Variations in surface flux, storage and entrainment velocity are assumed to affect both water vapor and CO$_2$ similarly, and therefore the CO$_2$ flux scales to the water vapor flux. Significant error may be attributed to F$_{\text{NEE}}$ estimates at the monthly scale due to the reliance on proxies for C$_t$. The addition of data from more terrestrial towers and regular airplane flights, in concert with atmospheric transport models of free tropospheric CO$_2$, would no doubt improve regional estimates of F$_{\text{NEE}}$.

We regard the results presented here as a proof-of concept demonstration that flux-difference analysis of ABL transport for water vapor and CO$_2$ can provide useful estimates of carbon balance. It is obvious, however, that the full potential of this method requires more complete and systematic data. While the method was applied here over a fairly homogenous landscape, the estimates could be made over heterogeneous areas including urban or mountainous areas that are unsuitable for eddy-covariance measurements. Furthermore, measurements at this scale could address problems of aggregation in large scale models of the carbon cycle. Indeed, it is not unreasonable to propose that this method could be extended to obtain not only regional, but continental-scale measurements of net CO$_2$ flux.
References


**Acknowledgements**

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Figure legends

Figure 1. Monthly averages of CO₂ in the marine boundary layer (MBL) at 44.4 °N, and from 396 m from the WLEF tower (C_m).

Figure 2. Representative ABL profiles of (A) CO₂ and (B) H₂O during mid-afternoon, and (C) CO₂ and surface pressure for several days of August 2000 at the WLEF tower site. Data for (A) and (B) and C_t in (C) were obtained by airplane flights. C_m values in (C) are 24 h averages of CO₂ at 396 m. The dashed line and shaded area in (C) represent the mean free tropospheric CO₂ mixing ratio and standard deviation for all of August.

Figure 3. Monthly averages of ΔC (C_m-C_t; open circles) and Δq (q_m-q_t; closed squares) for 2000. C_m and q_m were obtained through continuous measurements at 396 m from the tower. C_t was obtained by monthly averages of CO₂ collected in the marine boundary layer. RUC weather-forecasting data from the geopotential heights of 3200 to 7600 m was used to obtain q_t.

Figure 4. Daily CO₂ flux for August and September. The solid lines represent regional flux-difference measurements and the dashed lines represent eddy-covariance measurements at 122 m. C_t and q_t were obtained from monthly averages of airplane flights over the midwest, F_q, C_m and q_m were obtained by averaging the 24 h observations from the WLEF tower. The three dashed circles represent days when values of C_t and q_t were obtained directly by airplane flights over the WLEF tower. Missing data points represent periods of time when there was no data collection from the tower.

Figure 5. Monthly and annual NEE for 2000. Hatched bars represent tower eddy-covariance measurements from 122 m. F_NEE was calculated using C_t from the marine boundary layer (black bars). q_t was obtained from RUC data, F_q, C_m and q_m were obtained by averaging the 24 h observations from the WLEF tower for a
given month.

Table 1. Monthly means and standard error of the mean of PBL and free tropospheric values for CO₂ (C), water vapor (q).

<table>
<thead>
<tr>
<th>Month</th>
<th>Cᵢ (ppm)</th>
<th>Cₓ (ppm)</th>
<th>qᵢ (g/kg)</th>
<th>qₓ (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>371.9 ± 0.2</td>
<td>376.4 ± 0.5</td>
<td>0.6 ± 0.02</td>
<td>1.7 ± 0.2</td>
</tr>
<tr>
<td>February</td>
<td>372.4 ± 0.2</td>
<td>376.8 ± 0.4</td>
<td>0.6 ± 0.03</td>
<td>2.8 ± 0.3</td>
</tr>
<tr>
<td>March</td>
<td>373.1 ± 0.2</td>
<td>377.9 ± 0.6</td>
<td>0.7 ± 0.04</td>
<td>3.5 ± 0.4</td>
</tr>
<tr>
<td>April</td>
<td>374.4 ± 0.2</td>
<td>376.6 ± 0.2</td>
<td>0.7 ± 0.05</td>
<td>3.1 ± 0.2</td>
</tr>
<tr>
<td>May</td>
<td>373.9 ± 0.2</td>
<td>372.5 ± 0.8</td>
<td>1.1 ± 0.07</td>
<td>7.2 ± 0.4</td>
</tr>
<tr>
<td>June</td>
<td>370.8 ± 0.1</td>
<td>365.6 ± 0.7</td>
<td>1.2 ± 0.09</td>
<td>8.7 ± 0.4</td>
</tr>
<tr>
<td>July</td>
<td>366.8 ± 0.3</td>
<td>357.6 ± 0.7</td>
<td>1.3 ± 0.07</td>
<td>10.8 ± 0.4</td>
</tr>
<tr>
<td>August</td>
<td>363.9 ± 0.2</td>
<td>358.3 ± 0.9</td>
<td>1.2 ± 0.08</td>
<td>10.8 ± 0.4</td>
</tr>
<tr>
<td>September</td>
<td>363.7 ± 0.3</td>
<td>366.1 ± 0.7</td>
<td>1.1 ± 0.08</td>
<td>7.4 ± 0.4</td>
</tr>
<tr>
<td>October</td>
<td>366.9 ± 0.1</td>
<td>371.9 ± 0.8</td>
<td>0.8 ± 0.06</td>
<td>5.1 ± 0.4</td>
</tr>
<tr>
<td>November</td>
<td>370.7 ± 0.2</td>
<td>375.9 ± 0.4</td>
<td>0.7 ± 0.05</td>
<td>3.2 ± 0.2</td>
</tr>
<tr>
<td>December</td>
<td>372.8 ± 0.2</td>
<td>375.6 ± 0.4</td>
<td>0.5 ± 0.02</td>
<td>1.5 ± 0.1</td>
</tr>
</tbody>
</table>

Cₓ and qₓ values are from continuous measurements of CO₂ from the WLEF tower (396 m). Cᵢ values are from the marine boundary layer. qᵢ values are from RUC data.
<table>
<thead>
<tr>
<th>Month</th>
<th>Tower NEE $\mu$mol m$^{-2}$ s$^{-1}$</th>
<th>$F_q$ mmol m$^{-2}$ s$^{-1}$</th>
<th>$F_{NEE}^*$ $\mu$mol m$^{-2}$ s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>0.2 ± 0.04</td>
<td>0.1 ± 0.03</td>
<td>0.5 ± 0.17</td>
</tr>
<tr>
<td>February</td>
<td>0.3 ± 0.04</td>
<td>0.1 ± 0.03</td>
<td>0.3 ± 0.06</td>
</tr>
<tr>
<td>March</td>
<td>0.5 ± 0.04</td>
<td>0.3 ± 0.03</td>
<td>0.5 ± 0.05</td>
</tr>
<tr>
<td>April</td>
<td>0.4 ± 0.08</td>
<td>0.6 ± 0.05</td>
<td>0.5 ± 0.08</td>
</tr>
<tr>
<td>May</td>
<td>-0.4 ± 0.22</td>
<td>1.4 ± 0.11</td>
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</tr>
<tr>
<td>June</td>
<td>-1.8 ± 0.24</td>
<td>2.0 ± 0.19</td>
<td>-1.4 ± 0.10</td>
</tr>
<tr>
<td>July</td>
<td>-1.8 ± 0.24</td>
<td>2.4 ± 0.19</td>
<td>-2.3 ± 0.23</td>
</tr>
<tr>
<td>August</td>
<td>-1.1 ± 0.21</td>
<td>2.0 ± 0.16</td>
<td>-1.2 ± 0.14</td>
</tr>
<tr>
<td>September</td>
<td>0.2 ± 0.19</td>
<td>1.5 ± 0.14</td>
<td>0.6 ± 0.05</td>
</tr>
<tr>
<td>October</td>
<td>0.6 ± 0.08</td>
<td>0.6 ± 0.07</td>
<td>0.7 ± 0.07</td>
</tr>
<tr>
<td>November</td>
<td>0.6 ± 0.07</td>
<td>0.2 ± 0.04</td>
<td>0.5 ± 0.10</td>
</tr>
<tr>
<td>December</td>
<td>0.4 ± 0.05</td>
<td>0.1 ± 0.02</td>
<td>0.4 ± 0.08</td>
</tr>
</tbody>
</table>

*Propagated error was determined from the monthly s.d. for all variables in equation 1. sem is standard error of the mean for a given month.
Table 3. Sensitivity analysis for ABL flux method (equation 1).

<table>
<thead>
<tr>
<th>month</th>
<th>$F_q$ + sem</th>
<th>$q_m$ + sem</th>
<th>$C_t$ + sem</th>
<th>$C_m$ + sem</th>
<th>$q_t$ + sem</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>25</td>
<td>4</td>
<td>12</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>February</td>
<td>20</td>
<td>3</td>
<td>8</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>March</td>
<td>10</td>
<td>3</td>
<td>13</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>April</td>
<td>9</td>
<td>9</td>
<td>10</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>May</td>
<td>8</td>
<td>14</td>
<td>56</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>June</td>
<td>9</td>
<td>3</td>
<td>13</td>
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<td>5</td>
</tr>
<tr>
<td>July</td>
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<td>4</td>
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<tr>
<td>August</td>
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<td>4</td>
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</tr>
<tr>
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<td>13</td>
<td>29</td>
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<tr>
<td>Mean (year)</td>
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<td>6</td>
<td>17</td>
<td>1</td>
<td>7</td>
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<tr>
<td>Mean (may-sep)</td>
<td>8</td>
<td>7</td>
<td>24</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

One standard error of the mean was added to each input individually while holding the other inputs constant to calculate the percent change in $F_{\text{NEE}}$ relative to the values presented in Fig. 5.
Fig 1.
Fig 2.
Fig. 3

[Graph showing data points for time (months) with corresponding values for ∆C and ∆q (ppm, g/kg).]
Fig 4.
fig. 5