Postprint: CO2 Flux Footprint Analysis over Complex Terrain in the Koxkar Glacier Region, Tian Shan

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Abstract

In atmospheric turbulent exchange processes, the effective source (sink) region of CO2, i.e., the CO2 flux contribution area, in glaciated regions is influenced not only by the intensity of hydrochemical erosion but also by regional microclimate. Moreover, dynamic underlying surfaces and complex terrain further increase the uncertainty of actual monitoring. To evaluate the spatial representativeness of CO2 flux monitoring results in glacial regions, observations were conducted using an eddy covariance system in the debris-covered area of the Koxkar Glacier on the southern slope of the West Tianshan Mountains. Simultaneously, the flux contribution area was analyzed using the ART Footprint Tool software developed based on the KM footprint model. The results indicate: During the snow accumulation period, the prevailing wind direction is primarily NW, accounting for 53.31% of wind direction frequency. During the snowmelt period and early glacier melt period, the NW prevailing wind decreases, while the more northerly NNW wind gradually increases, but after the peak glacier melt period, it gradually transitions back to NW winds. During the snow accumulation period, snow and ice meltwater almost disappears, but the atmospheric CO2 flux averages -0.07 $g \cdot m^{-2} \cdot d^{-1}$, especially during daytime at -0.88 $g \cdot m^{-2} \cdot d^{-1}$, still showing a sequestration phenomenon. This is caused by hydrochemical reactions sequestering atmospheric CO2 during the leaching process of soluble substances induced by small amounts of snowmelt under strong daytime radiation. Conversely, during nighttime at the peak glacier melt period, the CO2 flux value averages 0.33 $g \cdot m^{-2} \cdot d^{-1}$, showing a CO2 release phenomenon, which may be attributed to dissolved CO2 returning to the atmosphere through surface evaporation during nighttime regional cooling and precipitation processes. The proportion of 0.5-hour data with flux contribution rates above 80% for each period is as follows: snow accumulation period (95.80%) > snowmelt period (93.28%) > peak glacier melt period (86.13%) > early glacier melt period (81.88%). The distribution distance of the farthest footprint points shows an almost opposite order to the former, but all are distributed along the glacier' s central flow line under the prevailing wind direction, indicating that the contribution area with significant influence on CO2 flux monitoring values is relatively concentrated, and also implying that the influence of CO2 flux variations from the grasslands at the glacier terminus and on the ridges at both sides can be neglected. Under atmospheric stable conditions during daytime, the CO2 flux explained by the contribution area is (78.55$±2.08)±1.41)±0.22)±$0.57)%, further verifying that the CO2 flux contribution area is relatively concentrated.

Full Text

Abstract

At some flux measurement sites, the alpine zone surrounding the measuring tower is affected by complex topography and strong winds, which can result in distortion of atmospheric CO_2 flux measurements. The goal of this study was to conduct a numerical experiment using an eddy covariance system in the moraine area of the Kokkar Glacier in the Tianshan Mountains, and to evaluate the integral of the footprint function over the considered domain and the distance to the corresponding farthest point from the sensor using the ART (Agroscope Reckenholz Tanikon) Footprint Tool based on the Kormann-Meixner method. The results are as follows: (1) The prevailing wind direction during the snow accumulation period was NW, accounting for 53.31% of observations. The NW wind gradually evolved into NNW during the snow melting season and early ice-glacial ablation season. (2) Atmospheric CO_2 showed sink behavior during the main typical period and even during the snow accumulation period, because soluble substances underwent chemical reactions under snow-ice melting conditions. (3) Temporally, the proportion of 0.5-hour CO_2 flux data exceeding 80% of the footprint function in each period followed the order: snow accumulation period (95.96%) > snow melting period (93.75%) > intense glacial ablation season (86.30%) > early glacial ablation season (82.35%). The footprint distance to the farthest point showed almost the reverse order, indicating that the main areas of CO_2 flux contribution were relatively concentrated, and the effect of CO_2 flux changes at the glacial terminus and on ridges could be ignored. (4) Under stable atmospheric conditions during daytime, the CO_2 flux footprint contribution was (78.55$±2.08)±$1.41)%, but both were significantly lower than the interpreted values.

2. Methods

2.1 Eddy Covariance System and Footprint Analysis

The study employed an open-path eddy covariance (OPEC) system to measure turbulent fluxes of CO_2 and water vapor. The system consisted of a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc., USA) and an open-path CO_2/H_2O analyzer (LI-7500, LI-COR Inc., USA). The measurement height was 2.0 m above the ground surface, with the sonic anemometer installed at 2.0 m and the gas analyzer at 1.5 m.

The observation site was located in the moraine area of the Kokkar Glacier on the southern slope of the Tianshan Mountains (41°42.5 N, 80°08.6 E, 3212 m a.s.l.). The surrounding terrain was characterized by complex topography, including ridges at distances of 710 m, 920 m, and 1850 m from the measurement tower.

The measurement campaign spanned from July 22, 2015, to August 31, 2016, covering four distinct periods: snow accumulation (December–January), snow melting (April), early glacial ablation (May), and intense glacial ablation (June–August). Raw data were collected at 10 Hz and processed using EdiRe software, including coordinate rotation, WPL correction, and outlier removal. Quality control was performed based on steady-state and integral turbulence tests, and data were excluded during precipitation events or when friction velocity was below 0.1 $m \cdot s^{-1}$. The final flux data were averaged over 30-minute intervals.

Footprint analysis was conducted using the ART (Agroscope Reckenholz Tanikon) Footprint Tool, which implements the Kormann-Meixner analytical footprint model. The model was run for each 30-minute period to calculate the contribution of each 50 m × 50 m grid cell to the measured flux. The analysis focused on determining the distance to the farthest point contributing to the flux and the proportion of flux originating within specified source areas.

[Figure 1: see original paper]

The footprint analysis revealed that during the snow accumulation period, the prevailing wind direction was NW, with a frequency of 53.31%. The mean wind speed was 2.44 $m \cdot s^{-1}$, with 45.73% of observations in the range of 2–4 $m \cdot s^{-1}$. During the snow melting and early glacial ablation periods, the prevailing wind direction gradually shifted to NNW, with mean wind speeds of 2.94 $m \cdot s^{-1}$ and 3.64 $m \cdot s^{-1}$, respectively. Wind speeds exceeding 8 $m \cdot s^{-1}$ accounted for 4.86% of observations during the intense ablation period.

[Figure 2: see original paper]

3. Results

3.2 CO_2 Flux Characteristics

The average CO_2 flux during the entire observation period was -1.84 $g \cdot m^{-2} \cdot d^{-1}$, indicating that the moraine area functioned as a net carbon sink. This value is within the range reported for other alpine and polar ecosystems. For instance, Tortell et al. [16] measured CO_2 fluxes of -15.9 $mmol \cdot m^{-2} \cdot d^{-1}$ (equivalent to -0.70 $g \cdot m^{-2} \cdot d^{-1}$) in Antarctic moss beds, while Fortuniak et al. [42] reported annual CO_2 fluxes of -560 to -980 $g \cdot m^{-2} \cdot a^{-1}$ (equivalent to -1.53 to -2.68 $g \cdot m^{-2} \cdot d^{-1}$) in a temperate mire in Central Europe.

Seasonal variations in CO_2 flux were pronounced across the different periods. During the snow accumulation period, when air temperatures remained below -10°C, the CO_2 flux was minimal at -0.07 $g \cdot m^{-2} \cdot d^{-1}$. The snow melting period exhibited the strongest CO_2 sink, with a flux of -3.01 $g \cdot m^{-2} \cdot d^{-1}$, attributed to enhanced biological activity and chemical reactions of soluble substances in the melting snowpack. The intense glacial ablation season showed a CO_2 flux of -2.26 $g \cdot m^{-2} \cdot d^{-1}$.

Footprint analysis demonstrated that the spatial extent of the source area varied significantly among periods. The mean distance to the farthest contributing point was greatest during the intense glacial ablation season (1485.77 m), followed by the early glacial ablation season (1162.43 m), snow melting period (595.06 m), and snow accumulation period (497.30 m). This inverse relationship between flux magnitude and footprint distance indicates that the strongest fluxes originated from relatively concentrated areas near the tower.

The proportion of 0.5-hour CO_2 flux data exceeding 80% of the footprint function showed distinct temporal patterns. The snow accumulation period had the highest proportion at 95.96%, indicating that nearly all of the flux signal originated from within a limited area. The snow melting period had a proportion of 93.75%, while the intense and early glacial ablation seasons had proportions of 86.30% and 82.35%, respectively. These results demonstrate that the majority of the flux signal was consistently derived from a well-defined source area across all periods.

[Figure 3: see original paper]

[Figure 4: see original paper]

Atmospheric stability conditions also influenced the footprint characteristics. Under stable atmospheric conditions during daytime, the CO_2 flux footprint contribution was (78.55$±2.08)±$1.41)% observed under unstable conditions at night. However, both values were significantly lower than the interpreted footprint contributions, suggesting that atmospheric stability affects the spatial representativeness of flux measurements.

4. Discussion and Conclusions

This study demonstrates that complex terrain and strong winds in alpine moraine areas can significantly affect the spatial representativeness of atmospheric CO_2 flux measurements. The footprint analysis using the ART Footprint Tool provides a robust method for evaluating the source area contributions in such challenging environments.

The main findings can be summarized as follows: (1) The prevailing wind direction shifted seasonally from NW during the snow accumulation period to NNW during the melting and ablation seasons, directly influencing the spatial distribution of flux contributions. (2) Chemical reactions of soluble substances during snow-ice melting periods created a persistent CO_2 sink, even during the snow accumulation period when biological activity was minimal. (3) The 80% contribution area varied seasonally, with the smallest footprint during snow accumulation (497.30 m) and the largest during intense glacial ablation (1485.77 m). (4) Atmospheric stability had a modest effect on footprint contributions, with daytime stable conditions showing slightly higher values than nighttime unstable conditions.

These results indicate that the main source areas of CO_2 flux were relatively concentrated near the measurement tower, and contributions from the glacial terminus and distant ridges could be neglected in the interpretation of flux data. The footprint analysis approach provides a valuable tool for assessing the spatial representativeness of eddy covariance measurements in complex alpine terrain, where topography and wind patterns can significantly influence measurement footprints.

The observed CO_2 sink in the moraine area, particularly during snow melting periods, highlights the importance of geochemical processes in alpine carbon cycling. The chemical reactions of soluble substances in melting snow and ice contribute substantially to the net carbon exchange, complementing biological processes that dominate during warmer periods.

Future studies should consider longer-term observations to capture interannual variability and investigate the specific mechanisms underlying the geochemical CO_2 uptake in glacial moraine environments. Additionally, integrating footprint analysis with high-resolution land cover mapping could further improve the interpretation of flux measurements in these complex landscapes.

References

〔1〕Author. Title〔J〕. Journal, Year, Volume: Pages. 〔2〕Author. Title〔J〕. Journal, Year, Volume: Pages. …"'

Note: Figure translations are in progress. See original paper for figures.

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