NET ECOSYSTEM EXCHANGE AT PERMAFROST IN CAMBRIDGE BAY, NUNAVUT, CANADA

J. Yun[1,2 *], M.J. Kwon[1], J.Y. Jung[1], N. Chae[3], B.Y. Lee[1], J. Yoo[1], J. Wanger[4], and T. Choi[1 *]

[1] *Korea Polar Research Institute, Incheon, South Korea*

[2] *Interdisciplinary Program in Agricultural and Forest Meteorology, Seoul National University, Seoul, South Korea*

[3] *Institute of Life sciences and Natural Resources, Korea University, Seoul, South Korea*

[4] *Polar Knowledge Canada, Canadian High Arctic Research Station, Cambridge Bay, Nunavut, Canada*

* *juyeol@kopri.re.kr*

Abstract

There are large uncertainties in understanding the timing and magnitude of the permafrost carbon-climate feedback. This is, in part, due to lack of field measurements. To better understand the mechanisms of exchange processes and to improve climate models, it is important to continuously monitor carbon exchanges at various permafrost locations in the Arctic. In 2012, a study site was established in Cambridge Bay, Nunavut, Canada through a Korea Polar Research Institute (KOPRI) project “Circum-Arctic Permafrost Environment Change Monitoring, Future Prediction and development Techniques of useful biomaterials (CAPEC).” The study site is a dry tundra location situated over permafrost. An eddy covariance system was set up at this site in 2012 to monitor carbon and energy exchanges between the atmosphere and the tundra ecosystem.

This paper presents preliminary results obtained from the study site in 2017. The data acquisition rate for carbon dioxide (CO_2) flux was 44% and that of complementary meteorological data (such as radiation, air temperature, etc.) was 89%. Most of the missing (or low quality) data occurred during the winter. A marginal distribution sampling method was used to fill gaps in missing CO_2 flux data. In mid-June, the site was totally exposed to the atmosphere and the net ecosystem exchange (NEE) became negative (i.e., it was a sink for atmospheric CO_2). In July, the NEE decreased to a minimum of 2.8 grams of carbon per metre squared per day (-2.8 gC/m^2/day). By the end of September, the site was partially covered with snow the NEE went from -2.8 to 0 (increased and fluctuated around zero). The preliminary results represent a period of five months, from May to September 2017. During this period NEE was -100.2 gC/m^2, the gross primary productivity (the amount of CO_2 taken up by vegetation) was 235.4 gC/m^2, and the ecosystem respiration (the amount of CO_2 respired by vegetation an microorganisms in soils)

Suggested citation:

Yun, J., Kwon, M.J., Jung, J.Y., Chae, N., Lee, B.Y., Yoo, J., and Choi, T. 2019: Net Ecosystem Exchange at Permafrost in Cambridge Bay, Nunavut, Canada. Aqhaliat 2019, Polar Knowledge Canada, p. 23-31. DOI: 10.35298/pkc.2019.03

was 135.2 gC/m². With an estimated ecosystem respiration of 9.1 gC/m² based on chamber measurement during non-growing season, the annual accumulated NEE was -91.1 gC/m². These preliminary results indicate that the dry tundra site played a role as a sink for atmospheric CO_2 in 2017. However, due to uncertainty from gap-filling the NEE, particularly in the 2017 winter season data, it is premature to draw such a conclusion at the moment.

Introduction

Arctic tundra has accumulated a large amount of carbon (C) due to low temperature and water availability (Schuur et al., 2015). Due to global warming and its potential climate feedback, there is growing interest in the changes in C exchange rates between permafrost and the atmosphere (McGuire et al., 2012). However, there are large uncertainties in understanding the timing and magnitude of the permafrost carbon-climate feedback, partly due to a lack of field measurements. Therefore, it is both necessary and important to continuously monitor C exchanges. To understand the C dynamics in the Arctic, this must be done over long periods of time at a variety of locations over permafrost. However, harsh environmental conditions such as extreme low temperatures and limited accessibility and power availability make continuous observations difficult in remote permafrost regions in the Arctic (Goodrich et al., 2016). KOPRI has established long-term observation sites in circum-arctic regions for the purpose of continuous monitoring of arctic environmental changes and their feedback to climate change. These sites include diverse tundra types across the Arctic, such as wet, moist, and dry tundra as well as polar desert. The KOPRI research project CAPEC uses an eddy covariance flux system to measure turbulent fluxes of water vapor and carbon dioxide (CO_2) between these study sites and the atmosphere. One study site was established on a dry tundra in Cambridge Bay, Nunavut, Canada in 2012. Dry tundra is common especially in high arctic, including large areas in the Canadian Arctic (Circumpolar Arctic Vegetation Map (CAVM) Team, 2003). This paper presents preliminary results on the variation and magnitude of 2017 CO_2 budget components from the dry tundra study site in Cambridge Bay.

Materials and methods

Site description and measurements

The study site is located on dry tundra with permafrost ground near Cambridge Bay, Nunavut, Canada (69°7'47.7"N, 105°3'35.3"W). The dominant plant species at the site are *Carex* spp. (*C. scirpoidea*, *C. rupestris*, *C. fuliginosa*, etc.) and *Dryas integrifolia*. The soil type at the site is Orthic Eutric Turbic Cryosol (Soil Classification Working Group, 1998). The organic horizon of the soil is 0.05 to 0.2 metres (m) in depth and the mineral horizon consists of subsoil. The active layer (i.e., thawed top soil layer at the site) reached up to 1.4 m in mid-August, 2017. For long-term monitoring of CO_2 and energy exchange between the atmosphere and the ecosystem, an eddy covariance flux system and a net radiometer, was set up in 2012. These monitoring devices were installed on a meteorological tower owned by Environment and Climate Change Canada, located about one kilometre away from the centre of Cambridge Bay (Figure 1).

A fast response open-path CO_2/water (H_2O) infrared gas analyzer (EC150, Campbell Scientific, USA) and a sonic anemometer (CSAT3, Campbell Scientific, USA) were installed on the tower at a height of 5 m. The two instruments had a separation distance of 0.5 m. To measure surface energy budget components, a net radiometer (CNR4, Kipp & Zonen, the Netherlands) was installed at a height of 4 m on the same tower and two soil flux sensors (HFP01, Campbell Scientific, USA) were installed at a depth of 0.1 m near the tower. Additionally, three soil temperature probes (TCAV-L, Campbell Scientific, USA) were installed at a depth of 0.1 m and two soil moisture sensors (CS650, Campbell Scientific, USA) were set at 0.1 m depth. Three-dimensional wind vectors, temperatures, and CO_2/H_2O densities were sampled at a rate of 10 hertz (Hz). Three components of wind velocity, temperature, and concentrations of CO_2 and H_2O

Figure 1: The study site in Cambridge Bay, Nunavut, Canada.

were measured and stored on a compact flash (CF) card in the data logger (CR3000, Campbell Sci., USA) for post-processing. Half-hourly averaged turbulence statistics and meteorological data were also calculated on a real-time basis and stored on a CF card in the same data logger. The data was retrieved every two months by local staff. In addition, in June and September 2017, the infrared gas analyzer was calibrated at the study site by using CO_2 standard gas and a dew point generator (LI610, LI-COR Biosciences, USA). Forced diffusion chambers (FD chamber, EOSENSE) were also installed at the study site and soil CO_2 emission data from one of the chambers was used to quantify NEE in winter in 2017.

Data processing and gap-filling

The flux data acquired using the eddy covariance method may deviate from those measured in an ideal condition depending on the topography of the observation site, the weather conditions, and the instrument setup including installation height, separation distance between the two fast response instruments, and instrument heading (Baldocchi et al., 2001). In this study, the covariance data were processed by EddyPro version 6.0 (LI-COR Biogeosciences, USA). Several corrective steps were applied to obtain an accurate flux. First, a double rotation method was used as a coordinate rotation to ensure the half-hourly averaged of vertical and lateral wind was zero (Kaimal and Finnigan, 1994). After applying these corrections to the wind data, we calculated the half-hourly averaged covariance data using the coordinate rotated 10 Hz wind data and concentrations of CO_2 and H_2O. “Frequency response correction” (Moore, 1986) and “air density correction” were applied to the calculated half hourly averaged covariance data of CO_2 and water vapor (Webb et al., 1980).

To assure the quality of the post-processed data, the quality control (QC)/quality assurance (QA) process was carried out in accordance with the meteorological data quality regulations set by the World Meteorological Organization. Each measured variable is removed if:

1. it is not within the minimum / maximum value of the measured value shown in Table 1; and

2. the deviation from mean is greater than three times the moving standard deviation of one-week window.

For flux data, abnormal values are removed by using the median absolute deviation on monthly basis. For nighttime turbulent CO_2 flux data, turbulent development was considered for quality control (Papale et al., 2006). The bootstrap method, based on the relationship between friction velocity and nighttime CO_2 flux data with the threshold value (i.e., 0.16 metre per second (m/s)), was used to reduce the uncertainty of the CO_2 data resulting from weak turbulent transport. During the measurement period, the yield of flux data and complimentary meteorological data were on average 44 and 89 %, respectively. Table 2 summarizes the yield rate of each variable. During the winter period (from November to April 2017), eddy covariance data were missing for a considerable period due to technical problems (e.g., equipment failure) or environmental problems (e.g., precipitation, snow, ice, etc.). To address missing data, a standardized gap-filling method proposed by Reichstein et al., (2005)

Table 1: Variables threshold for QC and QA.

Variables	Units	minimum	maximum
Air temperature	°C	-80	60
Relative humidity	%	0	100
Vapor pressure	Pa	0	100
Friction velocity	m s^{-1}	0	2
Air pressure	hPa	600	1 100
Wind speed	m s^{-1}	0	25
CO_2 concentration	ppm	300	500
H_2O concentration	mmol mol^{-1}	0	20
CO_2 flux	µmol m^{-2} s^{-1}	-50	50

Table 2: Acquisition rate of measurement variables in 2017 in Cambridge Bay, Nunavut, Canada.

Variables	Yield (Before QC/QA)	Yield (After QC/QA)
Wind speed	89	89
Air Temperature	89	89
Soil Temperature	78	78
Soil Water Contents	78	78
Solar Radiation	78	78
Sensible heat Flux	89	62
Latent heat Flux COconcentration	45	32
CO_2 Flux	70	38
		* Units (%)

was used. The missing flux value was filled with the average value, under similar meteorological conditions consisting of downward shortwave radiation, air temperature, and vapor pressure deficit within a time window. If no similar meteorological conditions were present within a window of 7 days, the averaging window is extended by 14 days. The gap-filling method was only applied to the growing season, from March to September

To partition NEE into gross primary production (GPP) and ecosystem respiration (R_{eco}), R_{eco} was calculated using Lloyd and Taylor's equation (1994),

$$R_{eco}(T) = R_{ref}\, e^{E_0\left(\frac{1}{T_{ref}-T_0} - \frac{1}{T-T_0}\right)}$$

where R_{ref} is a reference respiration which is site specific. E_0 is a temperature sensitivity which no longer has the theoretical significance of an activation energy. T_{ref} is a reference temperature. E_0 was set at 308.56 kelvin (K), Tref at 283.15 K, and T_0 at 227.13 K based on Lloyd and Talyor (1994). The seasonal course of the reference temperature

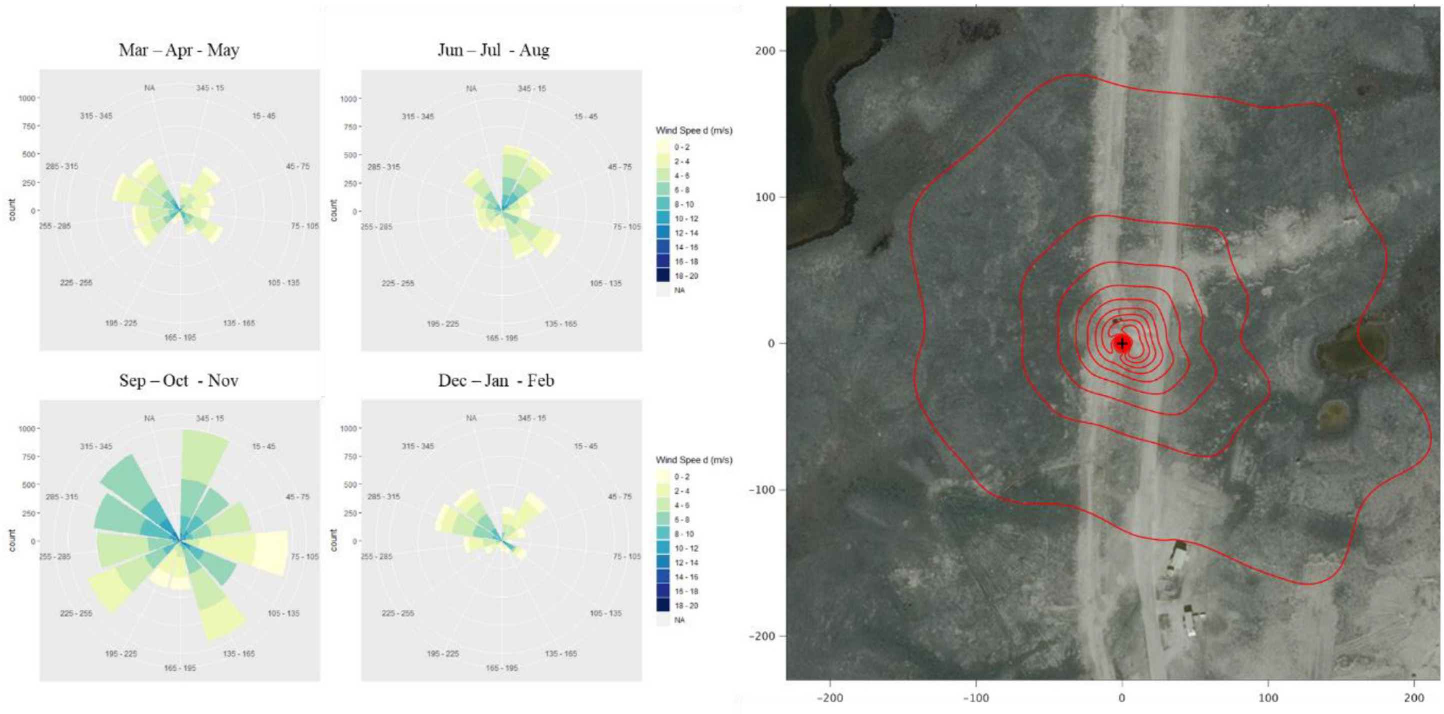

Figure 2: Wind rose and flux footprint of yearly aggregated wind direction and speed in Cambridge Bay, Nunavut, Canada in 2017.

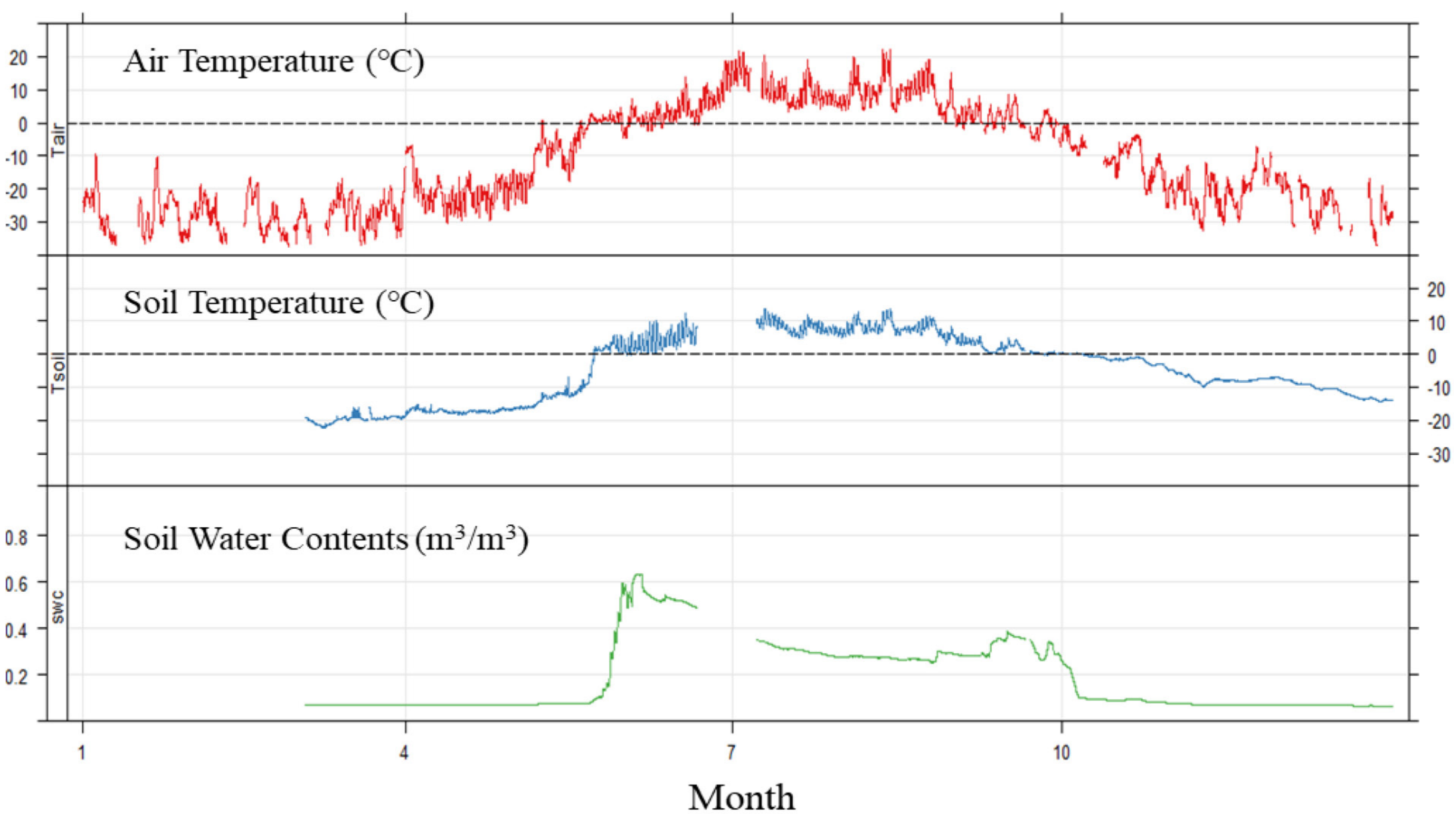

Figure 3: Time series of air temperature, soil temperature, and soil water contents in Cambridge Bay, Nunavut, Canada in 2017.

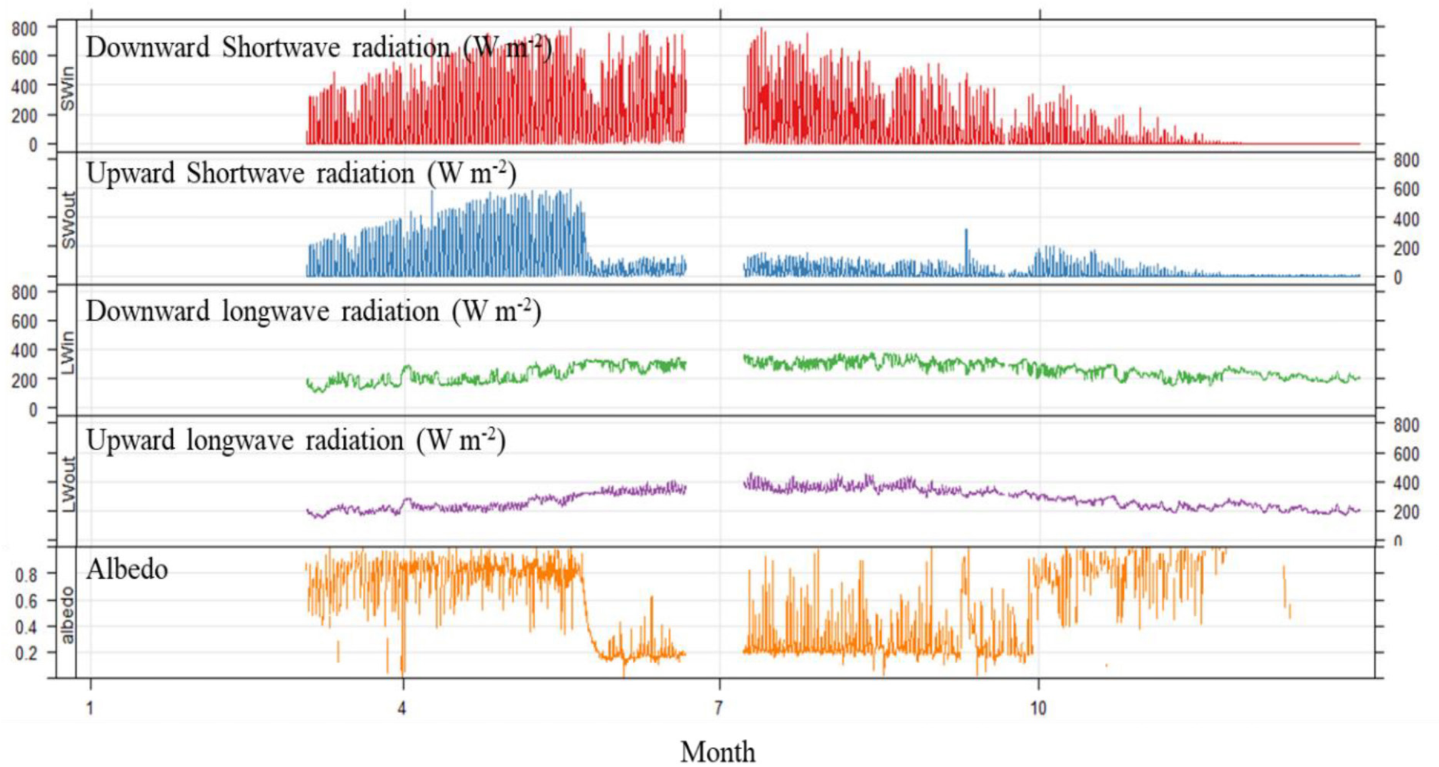

Figure 4: Time series of the surface radiative components in Cambridge Bay, Nunavut, Canada in 2017.

(R_{ref}) throughout the year is estimated from nighttime NEE with a seven-day sliding window in steps of four days. If no R_{ref} could be found, the values are linearly interpolated.

Results

Meteorological conditions

Wind rose is used to show how wind speed and direction are typically distributed at a particular location (Figure 2). The prevailing wind direction over the observation period was westerly. However, from June to August, the wind blew from from the north east. The annual mean wind speed was 4.9 m/s and the maximum instantaneous wind speed of 17.8 m/s was observed in March (Figure 2). The annual mean temperature was -10.7 °C. The highest temperature was 22.1 °C in August and the lowest was -37.6 °C in February (Figure 2). The annual mean soil temperature was -4.8 °C with the highest being 13.7 °C in July and the lowest -22.3 °C in March (Figure 2). While the air temperature and soil temperature showed similar variations, the magnitude of variations in soil temperature was smaller than that of air temperature, particularly during winter. This is attributed to the insulation effect of snow cover in winter.

Flux footprint describes an upwind area “seen” by the eddy covariance system measuring turbulent fluxes (e.g., CO_2 flux) at the site (Figure 2). The flux footprint for the whole measurement period is calculated using flux footprint online data processing (Kljun et al., 2015). Based on the footprint, the study found the east sector (0-180°) contributed significantly to the measured fluxes. Since there is a road to the east of the flux tower, with passing vehicles sometimes, a sector of 90-135° was exempted from the data analysis.

Figure 4 shows the variations in four surface radiative components with albedo. Downward shortwave radiation increased up to about 650 watts per metre squared (W/m^2) in June (Figure 4). Albedo was roughly 0.8 just before snow melted in early May and about 0.2 until late September (Figure 4). The study site was totally exposed to the atmosphere around the middle of

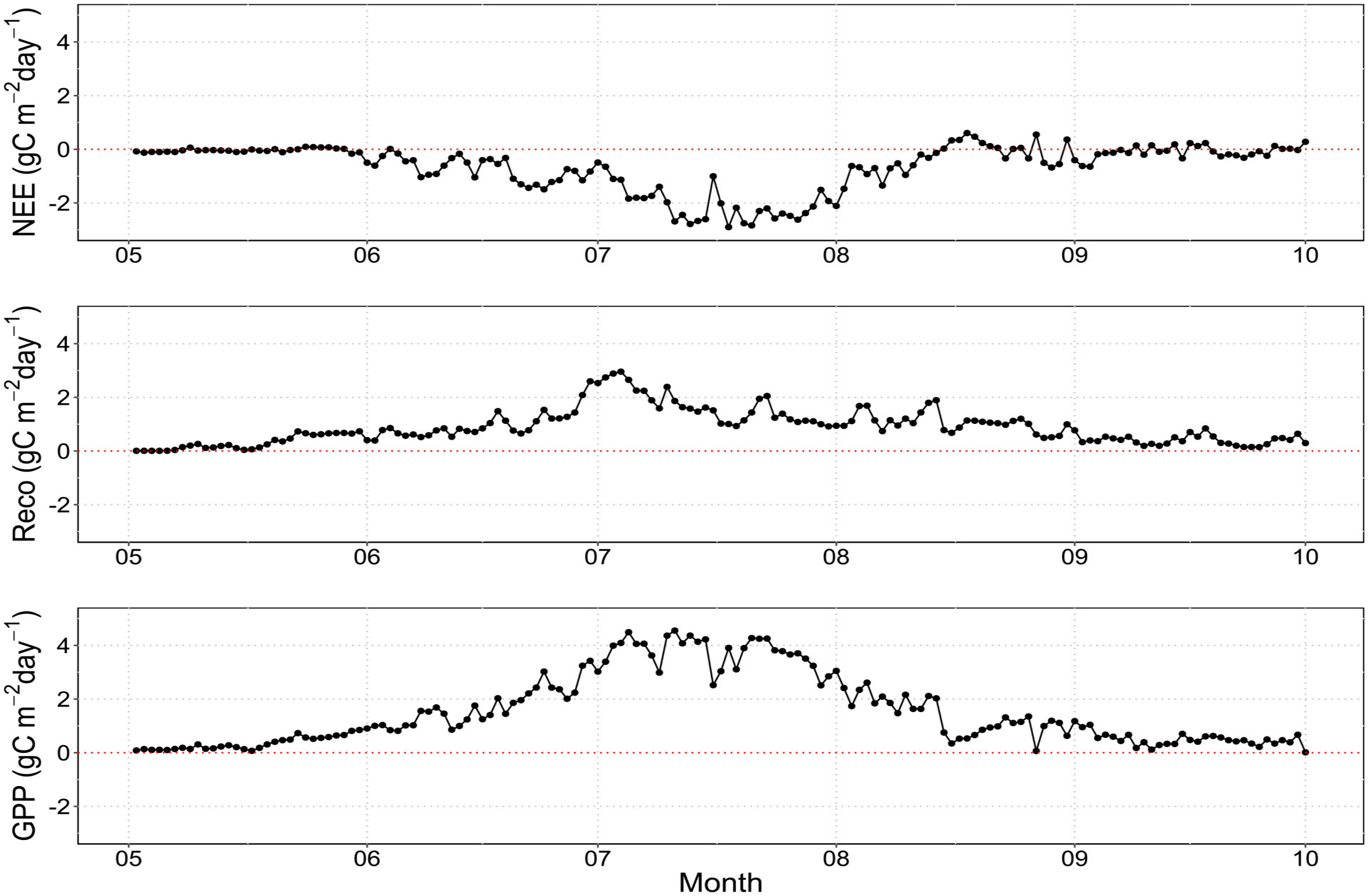

Figure 5: Time series of the net ecosystem exchange (NEE), ecosystem respiration (R_{eco}), and gross primary productivity (GPP) in Cambridge Bay, Nunavut, Canada in 2017.

June and was partially covered with snow around the end of September. Upward longwave radiation was greater in the summer and less in the winter than downward longwave radiation. As a result, net radiation varied from -138.9 W/m^2 to 541.1 W/m^2 with the annual mean being 60.8 W/m^2.

Carbon balance

Figure 5 shows the variation of daily averaged NEE, R_{eco}, and GPP from May to September 2017. GPP was calculated by R_{eco} minus NEE. Based on measured and gap-filled data, daily NEE ranged between -2.8 to 0.6 grams of carbon per squared metre per day with accumulated NEE of -100.2 gC/m^{-2}. In June NEE turned negative (i.e., sink for atmospheric CO_2). In July, NEE increased to the maximum (-2.8 gC/m^2/day), after which it decreased. In September NEE fluctuated around zero. While daily R_{eco} ranged between 0 to 3.0 gC/m^2/day, daily GPP was in the range of 0 to 4.6 gC/m^2/day. R_{eco} reached its maximum value in early July, while the peak of GPP appeared in mid-July. This can be explained by the continued growth of vegetation in the summer to achieve maximum leaf-coverage in July. Accumulated R_{eco} and GPP was 135.2 gC/m^2 and 235.4 gC/m^2 for five months from May to September, respectively.

Calculations for R_{eco} during the winter season could not be derived from eddy covariation data due to data missing from a considerable period (November to April 2017). R_{eco} from the winter season was estimated using FD chamber data. Unfortunately, chamber data were not available in winter of 2016. R_{eco} was calculated using only data from October to December of 2017. It was assumed that R_{eco} does not change much in the winter season and that the chamber data was representative of R_{eco}. The average monthly aggregated R_{eco} from October to December was used to represent the monthly aggregated value for the entire winter period (January to April and October to December). From October to December, monthly R_{eco} from the FD chamber was 1.3 gC/m^2. Based on this assumption, R_{eco} was 9.1 gC/m^2 during the winter season. This magnitude is about 7% of the amount of R_{eco} during the growing season. Finally, the annual NEE was estimated to be -91.1 gC/m^2 in 2017.

Summary and conclusions

Based on eddy covariance flux and complimentary measurements, the study reported preliminary results on CO_2 exchange over a dry tundra in Cambridge Bay, Nunavut, Canada in 2017. Overall, the obtained data was reliable. However, there were a lot of missing data (or low-quality data) in the winter season, which resulted in large uncertainty in quantifying annual NEE based on eddy covariance flux data. Therefore, R_{eco} in the winter season was quantified by using FD chamber data, assuming that chamber data represent R_{eco} in the winter. R_{eco} showed the maximum value in early July, while the peak of GPP appeared in mid-July. As a result, NEE was at the maximum in mid-July. Annual GPP, R_{eco} and NEE are estimated 235.4 gC/m^2, 144.3 gC/m², and -91.1 gC/m², respectively. The preliminary results indicate that the dry tundra study site played a role as a sink for atmospheric CO_2 in 2017. However, due to uncertainty in gap-filling NEE, particularly in the winter season in 2017, it is premature to draw such a conclusion.

An arctic-specific environment, including elements such as very small magnitude of C exchange, white nights, and harsh meteorological conditions, make eddy covariance flux measurements and traditional methods for correction difficult. To reduce uncertainty in quantifying annual CO_2 balance other methods are needed for further analysis. These include a neural network method for gap-filling and light response curve for partitioning NEE (Dengel et al., 2013; Runkle et al., 2013). In addition, R_{eco} measurement should be reinforced in the winter season to evaluate annual NEE over this long period. Further analysis will be conducted for better understanding the drivers of seasonal and inter-annual variations in C balance in this ecosystem. Additional analyses of long-term data sets (since 2012) will also enable better understanding of the dry tundra ecosystem response to different environmental conditions.

Community considerations

Cooperation with local community is a key factor for field studies in the arctic tundra. In this regard, KOPRI has communicated closely with local staff in Cambridge Bay, Nunavut, through the CAPEC project. On-site training and continuous communication with KOPRI researchers in South Korea enabled the local staff to perform various tasks, including diagnosing the condition of the instruments and maintaining the research site. In addition, it is expected that long-term monitoring activities of KOPRI in Cambridge Bay, Nunavut, will contribute to the local community directly and indirectly. Local community members may gain a better understanding of local environment changes due to climate change and see the current changes in terms of traditional knowledge.

Acknowledgements

This research was supported by a National Research Foundation of Korea grant from the Korean Government (MSIT; the Ministry of Science and ICT) (NRF-2016M1A5A1901769) (KOPRI-PN19081). The project is titled Circum-Arctic Permafrost Environment Change Monitoring, Future Prediction and development Techniques of useful biomaterials (CAPEC Project). Special thanks to Dr. Donald McLennan for helping with soil classification in the field.

References

Baldocchi, D., Falge, E., Gu, L., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, C., Davis, K., Evans, R., Fuentes, J., Goldstein, A., Katul, G., Law, B., Lee, X., Malhi, Y., Meyers, T., Munger, W., Oechel, W., Paw, K., Pilegaard, K., Schmid, H., Valentini, R., Verma, S., Vesala, T., Wilson, K., Wofsy, S. 2001. FLUXNET: A New Tool to Study the Temporal and Spatial Variability of Ecosystem–Scale Carbon Dioxide, Water Vapor, and Energy Flux Densities. Bulletin of the American Meteorological Society, 82(11):2415–2434. doi: 10.1175/1520-0477(2001)082<2415:fantts>2.3.co;2.

CAVM Team. 2003. Circumpolar Arctic Vegetation Map. Conservation of Arctic Flora and Fauna (CAFF) Map No. 1. U.S. Fish and Wildlife Service: Anchorage, Alaska. ISBN: 0-9767525-0-6, ISBN-13: 978-0-9767525-0-9.

Dengel, S., Zona, D., Sachs, T., Aurela, M., Jammet, M., Parmentier, F., Oechel, W., Vesala, T. 2013. Testing the applicability of neural networks as a gap-filling method using CH4 flux data from high latitude wetlands. Biogeosciences, 10(12):8185–8200. doi: 10.5194/bg-10-8185-2013.

Goodrich, J.P., Oechel, W.C., Gioli, B., Moreaux, V., Murphy, P.C., Burba, G., Zona, D. 2016. Impact of different eddy covariance sensors, site set-up, and maintenance on the annual balance of CO2 and CH4 in the harsh Arctic environment. Agricultural and Forest Meteorology, 228:239–251. doi: 10.1016/j.agrformet.2016.07.008.

Kaimal, J., Finnigan, J. 1994. Atmospheric boundary layer flows: their structure and measurement. Quarterly Journal of the Royal Meteorological Society. doi: 10.1002/qj.49712152512.

Kljun, N., Calanca, P., Rotach, M.W., Schmid, H.P. 2015. A simple two-dimensional parameterisation for Flux Footprint Prediction (FFP). Geoscientific. Model Development, 8(11):3695–3713. doi:10.5194/gmd-8-3695-2015.

Lloyd, J., Taylor, J. 1994. On the Temperature Dependence of Soil Respiration. Functional Ecology, 8(3):315–323.

McGuire, A., Christensen, T., Hayes, D., Heroult, A., Euskirchen, E., Kimball, J., Koven, C., Lafleur, P., Miller, P., Oechel, W., Peylin, P., Williams, M., Yi, Y. 2012. An assessment of the carbon balance of Arctic tundra: comparisons among observations, process models, and atmospheric inversions. Biogeosciences, 9(8):3185–3204. doi: 10.5194/bg-9-3185-2012.

Moore, A. 1986. Frequency Response Corrections for Eddy Correlation Systems. Boundary-Layer Meteorology, 37(1):17–35 doi:10.1007/BF00122754.

Papale, D., Reichstein, M., Aubinet, M., Canfora, E., Bernhofer, C., Kutsch, W., Longdoz, B., Rambal, S., Valentini, R., Vesala, T., Yakir, D. 2006. Towards a standardized processing of Net Ecosystem Exchange measured with eddy covariance technique: algorithms and uncertainty estimation. Biogeosciences, 3(4):571–583. doi: 10.5194/bg-3-571-2006.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grunwald, T., Havrankova, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J.-M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., Valentini, R. 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. Global Change Biology, 11:1424–1439. doi: 10.1111/j.1365-2486.2005.001002.x.

Runkle, B.R.K., Sachs, T., Wille, C., Pfeiffer, E.-M., Kutzbach, L. 2013. Bulk partitioning the growing season net ecosystem exchange of CO2 in Siberian tundra reveals the seasonality of its carbon sequestration strength. Biogeosciences, 10(3):1337–1349. doi: 10.5194/bg-10-1337-2013.

Schuur, E., McGuire, A., Schädel, C., Grosse, G., Harden, J., Hayes, D., Hugelius, G., Koven, C., Kuhry, P., Lawrence, D., Natali, S., Olefeldt, D., Romanovsky, V., Schaefer, K., Turetsky, M., Treat, C., Vonk, J. 2015. Climate change and the permafrost carbon feedback. Nature, 520(7546):171–179. doi: 10.1038/nature14338.

Soil Classification Working Group. 1998: The Canadian System of Soil Classification – 3rd edition. Agriculture and Agri-Food Canada. Ottawa, Ontario. ISBN 0-660-17404-9.