Student thesis series INES nr 332

Land- atmosphere exchange of carbon dioxide in a high Arctic fen: importance of wintertime fluxes

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2015
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Anna Lindstein (2015). Land- atmosphere exchange of carbon dioxide in a high Arctic fen: importance of wintertime fluxes.
Master degree thesis, 30 credits in Physical Geography and Ecosystems Analysis
Department of Physical Geography and Ecosystems Science, Lund University

Level: Master of Science (MSc)

Course duration: September 2014 until January 2015

Disclaimer

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Acknowledgements

Firstly, I would like to thank my brilliant supervisor Magnus Lund for supporting and inspiring me while writing this Master Thesis. I am very happy that I got the opportunity to visit Zackenberg and would like to thank GeoBasis as a part of the Zackenberg Basic program. Furthermore I would like to thank Maria Rask Mylius for preparing me for the field work and also thanks to Kirstine Skov for letting me borrow her warm clothing. Finally I would like to thank Søren Kyed who always was ready to help in Zackenberg, and for making very delicious cakes.

Abstract

Global warming is predicted to have a major impact on the ecosystems over the polar latitudes including the Arctic region which is thought to be especially sensitive to changes in climate. So far, the research studying greenhouse gases in the Arctic has primarily been focused on the short and intense growing season when carbon flux is mostly driven by plants and soil microorganisms. Regarding winter time little is known about what factors that influence the carbon flux between the land and the atmosphere (Net Ecosystem Exchange, NEE) and how big impact it has on the annual carbon budget.

This study investigated the importance of wintertime CO_2 fluxes (Net ecosystem exchange; NEE) on a net annual exchange basis and which environmental variables that affected CO_2 flux during wintertime. If seasonality (i.e. early winter, dark winter, late winter) affected relationships between carbon flux and the driving variables was also examined. The study was based on two years of data (August 2012- October 2014) from an eddy covariance tower on the fen in Zackenberg, Greenland. It was found that winter time flux in the year 2012/2013 was 67.6 g C m^{-2} (emission of CO_2 to the atmosphere) and for the year 2013/2014 the winter time flux was 31.4 g C m^{-2}.

The early winter time (September -7th of November) was the winter season where the strongest relationship between environmental variables and NEE was seen for both years. Here NEE increased exponentially with air temperature and soil temperature (-10 cm) but the relationship was strongest with air temperature. Air temperature, PAR, soil temperature and snow depth were factors that affected CO_2 flux during wintertime but no clear relationship could be seen with snow temperature. Seasonality clearly had an impact on the relationship between carbon flux and the driving variables.

In this study only a few environmental variables were tested and to be able to cover the complete pictures of what factors that affect NEE more studies have to be done, for example of soil and snow temperatures at more depth, water table depth, thaw depth, day of snowmelt and air pressure. A longer time series would also have been valuable but it is certain that winter time carbon flux is important when making an annual carbon budget in the Arctic.

Keywords: geography, physical geography, NEE, eddy covariance, Arctic, CO_2, wintertime flux, Zackenberg

Sammanfattning

Det är förutspått att den globala uppvärmningen kommer att ha ett stort inflytande över polarområdena, inklusive Arktis som anses vara extra känsligt för klimatförändringar. Forskningen gällande växthusgaser i Arktis har hittills mest fokuserat på den korta och intensiva växtsäsongen på sommaren när kolflödet till största delen drivs av växternas fotosyntes och mikroorganismer i jorden. När det gäller kolflödet under vinterperioden saknas tillräcklig kunskap om vilka faktorer som driver kolflödet mellan marken och atmosfären (Net Ecosystem Exchange, NEE) och hur stort inflytande det har på den årliga kolbudgeten.

Den här studien undersökte hur stor del vinterns kolflöde hade över ett år och vilka miljöfaktorer som påverkade vinterflödet av CO_2. Vintern delades upp i olika tidsperioder: tidig vinter, polarnatt och sen vinter och relationen mellan miljöfaktorer och NEE undersöktes också för dessa enskilda perioder. Studien baserades på två års data från ett eddy covariance torn på en myr i Zackenberg, Grönland. Vinterflödet av kol (NEE) under vintern 2012/2013 var 67.6 g C m^{-2} (utsläpp av kol till atmosfären) och kolflödet till atmosfären året 2013/2014 var 31.4 g C m^{-2}.

Den tidiga vintern (september till 7:e november) var den vinterperiod som hade störst inflytande på sambandet mellan miljöfaktorerna och NEE för båda år. NEE ökade exponentiellt med lufttemperaturen och marktemperaturen (-10 cm) och sambandet var starkast med lufttemperaturen. Lufttemperatur, PAR, marktemperatur och snödjup var faktorer som påverkade CO_2 flödet under vintertid men inget tydligt samband hittades med snötemperatur. Variabler som styr kolflödet skiljde sig åt över de olika tidsperioderna på vintern.

I den här studien har sambandet mellan NEE och miljö endast testats på ett fåtal faktorer och för att få en heltäckande bild krävs mer studier med andra faktorer som till exempel med mark- och snötemperatur på fler djup, grundvattennivå, smältdjup, första snöfria dag på våren och lufttryck. En längre tidsperiod än två år hade också varit intressant men det är tydligt att kolflödet på vintern är viktigt för den totala årliga kolbudgeten i Arktis.

Nyckelord: geografi, naturgeografi, NEE, eddy covariance, Arktis, CO_2, vinterflöden, Zackenberg

Contents

1. Introduction

Global warming is predicted to have a major impact on the ecosystems over the polar latitudes including the Arctic region with Greenland. Greenhouse gases, like carbon dioxide (CO_2) and methane (CH_4) produced by burning of fossil fuels as well as land use change, are thought to be the most important factors contributing to global warming and climate change. The Earth's surface has been warmer the last three decades than any previous decade since 1850 (IPCC 2013). The ocean and land surface temperatures show an increased temperature by 0.85 ºC for the period 1880- 2012. The Arctic is thought to be especially sensitive to predicted changes in temperature as well as precipitation and for the past 100 years the average Arctic temperatures have increased at almost twice the global average rate (IPCC 2013).

The soil organic carbon stock in the northern high latitude ecosystem is huge and is mainly stored in the permafrost. It is thought that the carbon has accumulated due to a long time period with cold and wet conditions that inhibited decomposition rates. However, the estimation of carbon stocks varies depending on the measurement depth and for example in peatlands the depth of peat in different areas is highly uncertain. An estimate of organic carbon stocks in the upper 1 meter of soil in the northern high latitude ecosystem is between 1400 and 1600 Pg C (McGuire et al. 2009).

To investigate the impact of climate change on carbon in the northern latitudes several research stations with gas flux measurements and meteorological stations have been set up. One of the research stations is set up in Zackenberg, north-east Greenland, with for example measurements of the active layer depth, an important indicator of climate change (Elberling et al. 2008). Increased temperatures lead to thawing permafrost and measurements of the active layer depth in Zackenberg show a large inter-annual variation between the measured years 1996-2005. Between the years 1997-2010 a significant increase in maximum thaw depth in Zackenberg was found (Lund et al. 2014). However, long term measurements are needed to be able to predict the effect climate change will have on permafrost and other environmental variables, and more monitoring is needed in the coast of Greenland (Christiansen et al. 2008).

So far, the research studying greenhouse gases have primarily focused on the short and intense growing season when carbon flux is mostly driven by plants and soil microorganisms. Regarding winter time, when there is no ongoing photosynthesis, little is known about what factors that influence the carbon flux between the land and the atmosphere and how big impact it has on the annual carbon budget (Lüers et al. 2014).

Several studies have suggested that the winter time respiration in a snow covered ecosystem will have a significant influence on the annual carbon budget (Fahnestock et al. 1999; Oechel et al. 1997; Zimov et al. 1996; Brooks et al. 1996; Lüers et al. 2014). Years where the snow cover melt away early will give an early growing start while a late end of snow melt will give a late growing season start (Rennermalm et al. 2005). During the winter time CO_2 flux only consists of heterotrophic respiration and it is seen that changes in temperature have an impacts on this respiration (Lloyd and Taylor 1994). During the growing season in summer time there is also photosynthesis and autotrophic respiration (Ruimy et al. 1995).

Even though some studies have modeled wintertime fluxes, more detailed information regarding the long period of wintertime outside of the growing season is needed. Also, since most of the annual budgets are modeled based on measurements from the amount of respiration during the growing season the actual flux during wintertime remains uncertainties (Soegaard and Nordstroem 1999).

1.1 Aim

This master thesis will focus on the land-atmosphere exchange of CO_2, one of the most important greenhouse gases. Data from a fen in Zackenberg, Greenland will be studied before and after the growing season using numbers from the last two years (August 2012- October 2014) collected by GeoBasis as a part of the program of Zackenberg Ecological Research Operations (ZERO). The Net Ecosystem Exchange (NEE) of CO_2 flux from an eddy covariance tower will be analyzed together with data from a meteorological station at Zackenberg. The main research question will be:

- How important are wintertime CO_2 fluxes on a net annual exchange basis?

Some sub- questions will be examined:

- What is the land-atmosphere exchange (NEE) of CO_2 during wintertime? (g C m^{-2})
- What is the land-atmosphere exchange (NEE) of CO_2 over the year? (g C m^{-2})
- What factors affect CO_2 flux during wintertime?
- Does seasonality (i.e. early winter, dark winter, late winter) affect relationships between carbon flux and the driving variables?

2. Background

2.1 Land- atmospheric exchange of CO_2

Net ecosystem exchange (NEE) is a direct measure of the net land- atmospheric exchange of CO_2. This carbon flux can be measured by the eddy covariance technique (explained later). NEE is the balance between GPP (Gross Primary Production; the net photosynthesis) and ecosystem respiration. Ecosystem respiration includes both respiration from plants (autotrophic) and heterotrophic respiration (see equation 1) (Ruimy et al. 1995). The sum of autotrophic and heterotrophic respiration is the total ecosystem respiration (Chapin et al. 2002).

$$NEE = (R_{plant+}R_{heterotrophic}) - GPP = R_{ecosyetem} - GPP \qquad (1)$$

Photosynthesis is not possible when there is no solar radiation and then NEE will only consists of respiration (Chapin et al. 2002). This is the circumstances during night time (except during the polar day when the sun never sets) and during the arctic polar night when the sun never rise over the horizon.

The sign convention stands for that CO_2 flux is positive when there is an emission to the atmosphere (respiration is dominating) and negative when CO_2 is taken up by the biosphere (photosynthesis is dominating).

2.2 Seasonal CO_2 flux in the Arctic

During winter time in the Arctic no photosynthesis is possible and Nordstroem et al, 2001 assumed photosynthesis to end completely by 1 of September. Instead there are small CO_2 emissions caused by respiration and trapped CO_2 in the snow that gives a low and steady gas flux. Nordstroem et al, 2001 also measured a high emission pulse of CO_2 just after the snow melt and before the onset of the growing season explained by respiration processes in the soil. (Nordstroem et al. 2001).

Photosynthesis was going on at the fen in Zackenberg during summer time and then decreased with the senescence and the shorter days in the autumn and NEE was also lowered. In June when there still was a snow cover there was a low CO_2 NEE flux (Nordstroem et al. 2001).

Oechel et al, 1997 found that respiration continued at soil temperatures down to -7°C and assumed it to stop thereafter (Oechel et al. 1997) . However the CO_2 emissions during winter time in the Arctic suggests that respiration continues down to much lower temperatures (Nordstroem et al. 2001). Significant CO_2 loss from an arctic tundra ecosystem in Alaska during the cold season was observed indicating the importance of winter time fluxes. It was found that average daily CO_2 emissions (due to respiration) increased significantly with temperature especially in October and May. In late June, which was the end of the cold season, CO_2 flux followed variations in PAR on a daily basis. This was however not the case in October (Oechel et al. 1997). Zimov et al 1996 observed substantial CO_2 release during wintertime in Siberia

(Zimov et al. 1996) and concluded that winter time CO_2 flux has an important impact on the annual NEE budget.

However, the thawing period may contribute more to CO_2 release than the low and steady emissions over the whole winter season. This release of carbon in the thawing period happen when the snow cover traps the gas over the season and with the heating of the surface in spring the trapped gas will be released for just a short period of time (Soegaard and Nordstroem 1999). For the fen in Zackenberg a budget of NEE was estimated for the year 1996 and was an uptake of 64.4 g C m^{-2} and for the summer season the same year (end of June to mid-August) that constituted an uptake of 96.3 g C m^{-2} (Soegaard and Nordstroem 1999). NEE was measured for the same site in 1997 where the summer time uptake was 130 g CO_2 m^{-2} and the budget for the whole year was a sink of 20 g C m^{-2} (Nordstroem et al. 2001).

Regarding the summer time CO_2 flux a time series from a heath in Zackenberg of seven years, 1997 and 2000-2007, shows that there has been a net sink of CO_2 during the summer period. The date of snowmelt correlated with the rate of uptake during the summer, where a high uptake followed a year of early snowmelt (Groendahl et al. 2007). Rennermalm et al. 2005 modeled NEE for a fen in Zackenberg where that summertime NEE varied between -50 g C m^{-2} to -123 g C m^{-2} for four years (1996-1999) (Rennermalm et al. 2005).

Hobbie et al, 2000 found that wintertime respiration represented around 20 % of the total annual respiration in an Arctic tundra ecosystem (Hobbie et al. 2000). Oechel et al, 1997 found that the cold season stood for 81 % of the flux in a wet sedge and 61 % for a tussock tundra ecosystem in Alaska 1993/1994 (Oechel et al. 1997). For a forest tundra the wintertime flux stood for 41 % of the total CO_2 exchange (Zimov et al. 1996). Fahnestock et al, 1999 found that the inclusion of wintertime CO_2 emissions increased the annual carbon flux by 17 % in a tundra ecosystem in Alaska (Fahnestock et al. 1999).

When making a CO_2 NEE budget the result is very dependent on where the measurement period start and end since emission and uptake varies over the seasons. It is important to examine the whole year and make an annual balance to avoid missing large fluxes (Nordstroem et al. 2001). For example Soegaard and Nordstroem 1999 did not catch the large early season CO_2 emissions that were later seen in the 1997 year data by Nordstroem et al 2001.

2.3 Environmental controls

There are different environmental controls that may affect CO_2 flux over the Arctic. Common studied environmental variables are temperature, snow (Elberling et al. 2008), water table depth, NDVI (Normalized Difference Vegetation Index), weather conditions, leaf area index (LAI) and PAR (photosynthetic active radiation). Consequently also the type of ecosystem will influence NEE between the land and the atmosphere.

CO_2 flux has been showed to be temperature dependent both in summer time (Soegaard and Nordstroem 1999) and in early and late winter (Oechel et al. 1997) (Fahnestock et al. 1999). In the summer time it was the photosynthesis that dominated and in early and late winter respiration was the process affected by temperature.

Based on modeling it was found that a change in temperature will reduce the CO_2 accumulation and that an increase by 5°C might turn the ecosystem into a CO_2 source instead of a sink (Soegaard and Nordstroem 1999). The response of the ecosystem to temperature change is important since temperatures are predicted to increase over Arctic in the near future (IPCC 2013). With higher temperatures the upper permafrost level in the Arctic might be lowered and a bigger active layer might lead to increased release of carbon that has been stored in the ecosystem for a long time (ACIA 2005).

More than a decade of eddy covariance measurements from a tundra heath at Zackenberg (2000-2011) was summarized. A linear increase in ecosystem respiration was seen with temperature in contrast to GPP where an observed increase in the beginning appeared to slowly level off. Based on this it was suggested that an increased warming will weaken the ecosystem CO_2 sink and may even turn the ecosystems into a CO_2 source depending on the changing climate (Lund et al. 2012).

A thick snow cover will isolate the soil and lead to higher soil temperatures (Oechel et al. 1997). Measurements from the tundra heath at Zackenberg (2000-2011) also found that years with a deep and long lasting snowpack correlated with increased CO_2 emission rates the following springs. Also, the mean daily net CO_2 uptake correlated with the day of snowmelt (Lund et al. 2012).

Furthermore, a thick snow cover in Zackenberg correlated with warmer soil temperatures for the time period 1997-2012 (ZERO 2013). Brooks et al. 1996 found that the differences in CO_2 flux likely was a function of snow depth, snow accumulation and dispersion rate (Brooks et al. 1996) where topography, vegetation and wind pattern influenced the snow distribution (Elberling et al. 2008). Another factor is the amount of precipitation during winter time that controls the snow thickness and therefore influence the time of snow melt in the spring (Rennermalm et al. 2005).

An environmental control that also was found to influence NEE rates was water table depth that has been found to affect CO_2 efflux over tundra sites (Christensen et al, 1998). Water table depth affects the relation between CO_2 and CH_4 emissions, where a much waterlogged anaerobic soil favors CH_4 emission and a drier soil favors CH_4 and vice versa. The study showed that the higher the water table position (closer to the surface), the lower the CO_2 flux was and a very low water table depth had higher CO_2 emissions.

NDVI was also associated with variation in ecosystem respiration (Lund et al, 2010). In this study also air temperature, growing season period, growing degree days, and vapour pressure deficit affected respiration. As mentioned in the previous section, PAR was found to follow CO_2 flux variations on a daily basis in late June, but not in October (Oechel et al. 1997).

In summer time assimilation was dependent of the weather and Nordstroem et al 2001 saw a huge decrease in CO_2 flux in August (1997) for a fen site in Zackenberg following windy, foggy and cold weather. Here photosynthesis was so low that respiration dominated and there was a low emission of CO_2. The same year the fen switched from being a net source to a net sink of CO_2 the 15th of July (Nordstroem et al. 2001). An average daily sum in this period was 0.41g CO_2 m^{-2} day^{-1} which can be compared with a wet sedge ecosystem in Northern Alaska for the period October to May with an emission of 0.29 CO_2 m^{-2} day^{-1} (Oechel et al. 1997).

The study by Rennermalm et al, 2005 showed that leaf area index (LAI) was the major control of the summertime NEE uptake of carbon and not environmental variables. LAI in turn was dependent of the date of snow melt and the start of the growing season. This meant that NEE in summer time was controlled by the climate during winter time (Rennermalm et al. 2005). A study in Zackenberg also found that carbon flux correlated with LAI in the summer (Soegaard et al. 2000).

Different types of ecosystems caused by their different environmental conditions and abiotic factors reveal large variances in CO_2 flux (Soegaard et al. 2000) for example if it is a wet sedge or a tussock tundra ecosystem (Fahnestock et al. 1999). Differences may be due to nutrient content (Elberling et al. 2008) or carbon stocks (Soegaard et al. 2000). For example a fen contains larger carbon stocks compared to a heath due to the wet and cold conditions that have inhibited decomposition rate over a long time (Billings 1987). Finally, the length of the growing season has been shown to affect soil processes and in turn affect NEE rates (Elberling et al. 2008).

It seems that temperature is an important factor influencing CO_2 flux both in the summer and early and late winter, where both air- and soil temperature are important. Snow is an important factor during winter time, both the snow depth and snow cover and LAI is important in summer time. The type of ecosystem and weather has an impact of different influencing environmental variables.

2.4 Eddy Covariance: general principles

Eddy covariance is a micro-meteorological technique for measuring fluxes such as CO_2, CH_4 and H_2O on an ecosystem level (Burda and Anderson 2005). The flux is defined as the amount of material transported through space per unit area and time with units of μ mol m^{-2} s^{-1}. The eddy covariance tower measures the net ecosystem exchange between the terrestrial ecosystem and the atmosphere. CO_2 level are affected by the global CO_2 concentration but on a much longer time scale than the flux from the ecosystem.

The principle is based on the air flow imagined as a horizontal flow of rotating eddies where each eddy has a 3D component. The covariance between fluctuations in vertical wind velocity and the CO_2 mixing ratio is measured. An ultra-sonic anemometer (in this study a Gill HS) sends pulses of sound between the sensors and measures the time it takes for the sound to travel between the transducer. The time it takes depends on wind, temperature and humidity (Baldocchi 2003). The system also consists of an enclosed path infrared gas analyzer (in this study LICOR 7200) that measures $CO_2$and H_2O in the free atmosphere (LI-7200 2009) adjusted to the sonic head where wind speed is measured.

The flux from the eddy covariance tower can be expressed as equation 2:

$$Fc= \rho\overline{c'w'} \qquad (2)$$

where ρ is the air density, c is the CO_2 concentration from the gas analyzer and w is the vertical wind speed obtained from the anemometer. The primes represent the deviation from the mean over a representative time period, typically 30 min (Baldocchi 2003).

The area where fluxes are registered by the eddy tower is named the footprint which represents the area upwind of the tower (Burda and Anderson 2005). The flux footprint can vary from tens of meters to several hundred meters depending on the measurement height of the tower. It is also affected by the surface roughness and thermal stability (Burda and Anderson 2005).

There are some major assumptions to the technique, for example that measurements at one point represent an upwind area, the flux is fully turbulent and the terrain is horizontal and uniform. The method works best under steady environmental conditions and flat terrain, otherwise there may be systematic errors (Baldocchi 2003) which is why the eddy covariance technique has received some criticism. To minimize errors, data need to be quality checked (LI-7200 2009). However, the eddy covariance method is still very valuable for measuring fluxes on the ecosystem level. As an alternative, the chamber and cuvette techniques have been used for measuring CO_2 exchange but this method represent a very small area at a process based level (Baldocchi 2003) making it more suitable for studying different plant functional types than the whole ecosystem. Furthermore, measurements using the chamber and cuvette technique are often disturbed by the physical placement of the instrument as the environment in the chamber is modified (Baldocchi 2003).

3. Methods

3.1 Study site

Zackenberg research station is situated in north east Greenland (74º28’ N, 20º34’ W) and has the objective to make ecosystem research possible as part of the program of Zackenberg Ecological Research Operations (ZERO). The long-term geographical monitoring program, Zackenberg Basic has been collecting geographical data since 1995/1996 with the objective to gather environmental data and make it available (ZERO 2013). One of the sub-programs is GeoBasis that collect data of hydrological and terrestrial variables where measurements of gas fluxes such as carbon dioxide and methane are performed using both the chamber and eddy covariance technique (GeoBasis 2014).

Figure 1 shows Zackenberg valley with the different measurement stations and the position of the eddy covariance tower (from which data is used in this report) marked as MM2. The river Zackenberg flows through the valley and the Zackenberg mountain is shown to the left.

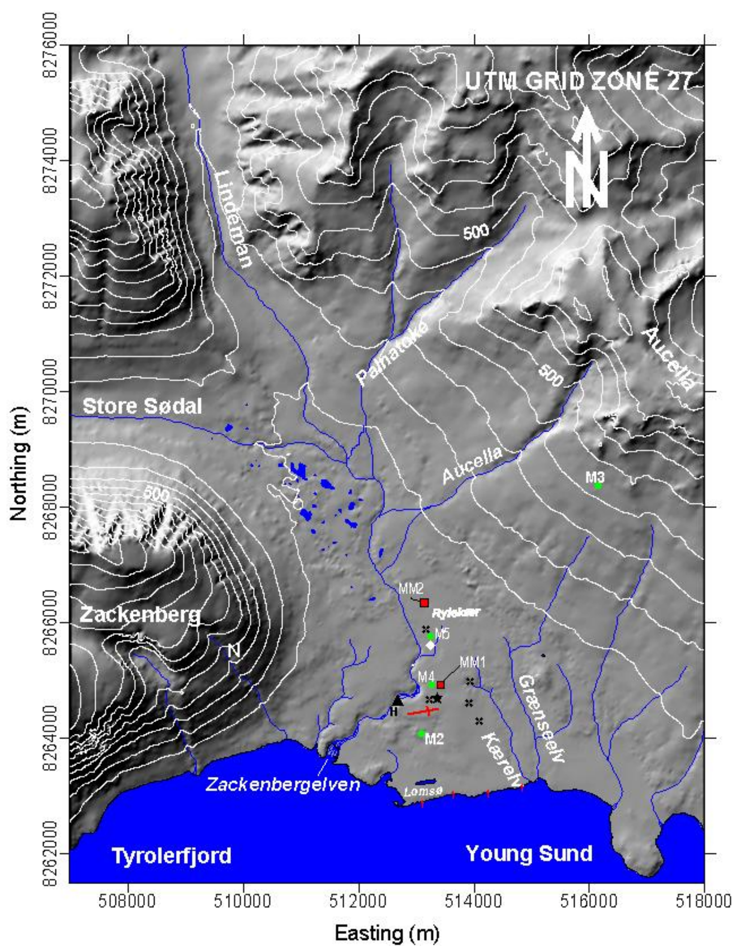

Figure 1. Zackenberg valley with the eddy covariance tower marked as MM2. The mountain Zackenberg to the left in the figure. Map from ZERO, 2012.

The position above the Polar Circle, gives Zackenberg a high Arctic climate where little energy is received from the sun (Hansen et al. 2008) driving the winds. Here the polar night lasts 89 days from 7th of November to 3th of February, when there is no incoming solar radiation. The polar day lasts 106 days from 30th of April to 13th of August where the sun never sets below the horizon. July is the warmest month of the year with a mean monthly air temperature of 5.8°C measured for the period 1996-2005. The period of the polar night and shortly afterwards has the coldest temperatures with a mean monthly air temperature of -20°C (measured from December to March 1996-2005). February is the coldest month with temperatures usually below -30°C (Hansen et al. 2008). Mainly due to the low temperatures the mean annual precipitation in Zackenberg is very low with a mean of 261 mm for the years 1997-2005. This dry condition is the reason that glaciers only form on the mountains and not in the valleys. Most of the precipitation falls during the autumn and winter and the least during the warmer summer period. In winter the precipitation is caused by cyclonic activity. Most of the year, the wind direction is from north or north-west due to air pressure and friction in the fjord. However in summer-time winds are mainly from south to south-east (Hansen et al. 2008). The topography as well as the wind direction governs the distribution of snow and in winter-time the wind direction causes snow accumulation on the south-facing slopes. The exposed ridge tops are windblown and accumulates little snow (Elberling et al. 2008).

The Zackenberg area is underlain by continuous permafrost and the landscape is controlled by periglacial processes (Christiansen et al. 2008). The active layer depth in the valley varies between 40-80 cm depending on the soil type (Soegaard and Nordstroem 1999). The active layer depth starts to develop when the snow has melted away for the winter season and the air temperature is positive. The permafrost thickness was modeled to be 200-400 m in Zackenberg where the temperatures closest to the surface, above 130 m was -10º C to -14º C in middle of the winter and reached maximum 2º C in the late summer (Christiansen et al. 2008). The snow cover and the snow depth have varied largely over the years (Christiansen et al. 2008;ZERO 2013). For example the maximum snow depth was1.3 m in the winter season of 2011/2012 compared to 0.45 m the season of 2010/2011 at the meteorological station at Zackenberg (ZERO 2013).

The waterlogged fen area where the eddy covariance tower is situated covers around 600 x 1200 m and the most abundant plant species are sedges and grasses that grows on the peat soil. Arctic cotton grass (Eriphorum scheuchzeri), Arctic red grasses (Arctagrostis latifolia) and Eriphorum triste, Dupontia psilosantha, and Carex Saxatilis are the most common species (Nordstroem et al. 2001).

One major study field, for the GeoBasis program is gas-flux monitoring. In this report already collected eddy-covariance CO_2 data and meteorological CO_2 data from the last two years (since autumn 2012 ending with data from October 2014) in Zackenberg will be analyzed.

3.2 Measurement methods

The Eddy Covariance tower is situated at lat: 74°28'44,760" N and long: 20°33'20,520" W at an altitude of 38 meter at a wet fen area in the Zackenberg valley. The system consists of an enclosed path infrared gas analyzer (LICOR7200) and a 3D ultra sonic anemometer (Gill HS) and measure CO_2 and wind speed as continuous high frequency data of 20 Hz giving values every 30 minutes. The anemometer is at 3 meter height on the tower and air is drawn in by 10 liter/min (changed to 15 liter/min 19th of April 2014) through a tubing of 1 meter with the inner diameter of 9 mm. Also a meteorological mast close to the eddy tower measure radiation (PAR), soil temperature, snow temperature, soil moisture, soil heat flux and snow depth collected on a CR1000 data logger.

3.3 Flux calculations

EddyPro (Licor, Inc., Nebraska, USA) is software for handling data and performing flux calculations from the Eddy Covariance tower. Data was downloaded from the tower and the files were used in EddyPro. The Basic Settings were used but values concerning the specific instruments and snow depth were changed manually.

Since there was a lot of snow the winter 2013/2014 the height from the sensor to the ground in EddyPro (the anemometer height) had to be corrected. When the snow depth passed 0.1 m the mast height was set to 2.9 m and when the snow depth past 0.2 m the mast height was set to 2.8 m and so on. However to limit the runs in EddyPro it was not run for less than one week at a time. If there was just one outlier in a long range of the same value this was ignored. However during snow melt when the values changed rapidly EddyPro was run for every day. For the season 2012/2013 when there was very little snow, the snow depth was never over 0.149 m (maximum snow depth was 0.13 m) so the Gill height here was set to 3 meter for all runs.

Canopy height was set to 0.1 m when there was no snow and 0.02 m when there was snow. There was no canopy in winter time, but if this parameter is set to zero the "footprint" of the Eddy tower will be infinitive because the canopy height decides the displacement height and roughness length in EddyPro.

3.4 Quality check

The run in EddyPro provided flux quality flags which is a quality check with values of 0,1 and 2 for every flux value, where 0 is best quality, 1 is flux good enough to use for general analyses such as annual budgets and 2 is bad quality and should be discarded. These quality flags are used to remove data that do not fulfill the eddy covariance assumptions such as stationarity and turbulent conditions (Foken et al. 2004). The three flags obtained in this analysis are based on nine quality flags from Foken et al 2004. The quality classes are based on the deviations of the 30 minute covariance from the mean covariance/ deviations of the measurements from the ideal conditions. For example in the system with nine quality classes a deviation lower than 15% were represented by quality flag 1, which is the best class (Foken et al. 2004). Quality flags with number 2 were removed in the quality check for the analysis in this report.

Friction velocity should be over 0.1 m/s (u*> 0.1) and values below were removed. When values are below 0.1 m/s the flux is affected by the friction velocity, which means that there is not sufficient atmospheric mixing. High atmospheric mixing is necessary for the eddy tower to give correct results. The value normally used is 0.1. Lund et al 2007 tested the dependence of low friction velocity with night time NEE for a bog in southern Sweden and found a positive relationship below u*=0.1 m/s which means that those values were influenced by u*(Lund et al. 2007). This value has been commonly used by researchers (Lafleur et al. 2001).

Reasonable values for the CO_2 concentration measured in the free air is 375< CO_2 <420 ppm and corresponding flux values outside the range were removed. The unrotated vertical velocity (w) which is the wind component along the w anemometer axis, the wind that is not rotated for tilt corrections, should be close to zero on a half-hourly basis. Reasonable values are -0.2<w<0.2 m/s and values outside that range were removed.

After the quality check for these four parameters extreme outliers of the CO_2 flux data were removed. For the period of dark winter ±3 standard deviations from the mean were removed. For the rest of the year when incoming solar radiation have an effect on NEE, PAR was used as a measure for removing outliers. For each of the rest of the periods (see table 1) the standard deviation for CO_2 flux where corresponding PAR<100 and PAR>1000 were calculated. Then plus three standard deviations from CO_2 where PAR<100 and minus three standard deviations from PAR>1000 were used to set the limits for the CO_2 flux.

3.5 Gap filling

Gap filling were done to be able to make an annual budget. Gaps in data were due to removed values from the quality check as well as missing data from errors etc. The gap filling here were based on (Reichstein et al. 2005) and modified by Magnus Lund 2014. The filling was based on temperature and PAR (incoming solar radiation).Vapor pressure deficite (vpd) used in Reichstein et al 2005 were not used since this factor has a low impact on the NEE in Zackenberg.

If there was no NEE data present the program checked the temperature and PAR for days before and days after the missing data and related this to flux values. For the dark winter a larger window size was used, since the fluxes were expected to have a low fluctuation. For the summer period a shorter window size should be used. Small gaps left after the gap filling were filled with the already gap filled data.

For data in 2012 the window size was 7-16 which means that the program first looks at values 7 days before and after the missing value and if not enough data is found the window is expanded to 16 days. Late winter 2013 had the window size 7-10 but a few values were still missing which were filled with the gap filled data. The summer of 2013 had a window size of 7-10. The 9th of September 2013 to 22th of June 2014 had the window size 7-14 and were gap filled once more with the already gap filled data. The summer 2014 and autumn 2014 had the window size 5-10.

Between the period 23th of December 2012 and 15th of February 2013 there were no data at all and the program could not run. Here a mean flux of the week before was calculated as well as a mean after the gap. Thereafter the mean of those were set for all values in the missing data period.

3.6 Data analysis

3.6.1 Environmental data

The relationship between CO_2 flux vs. air temperature, PAR, soil temperature at -10 cm, snow depth and snow temperature 10 cm above ground were visualized with scatterplots. NEE was tested for correlations for different time periods where one year was divided in four periods (see table 1). The first period was set to early winter, that started when the first mean daily temperature was zero or below and ended when the polar night started. The second period was represented by the dark winter which was the polar night (7th of November to 3rd of February) when there was no incoming radiation. Late winter started when the polar night ended and stopped when the snow was gone for the season.

For the correlations daily means of the environmental variables data were used. The data was quality checked and outliers were removed but the gap filled data was not used (would have meant pseudo correlation with PAR and air temperature).

Table 1. The time periods were divided in early winter, dark winter and summer. The table also shows the dates for the whole winter and the whole year.

Year	Early winter	Dark winter	Late winter	Summer	Whole winter	Whole year
2012				29 Aug-4 Sept 2012		
2012/2013	5 Sept-6 Nov 2012	7 Nov-3 Feb 2012/2013	4 Feb-25 May 2013	26 May-8 Sept 2013	5 Sept-25 May 2012/2013	5 Sept-4 Sept 2012/2013
2013/2014	9 Sept-6 Nov 2013	7 Nov-3 Feb 2013/2014	4 Feb-22 June 2014	23 June-5 Sept 2014	9 Sept-22 Jun 2013/2014	5 Sept-4 Sept 2013/2014
2014	6 Sept-21 Oct 2014				6 Sept-21 Oct 2014	

An annual budget of NEE and budgets for the different time periods was calculated using the gap filled NEE data. The annual budget was calculated in g C m^{-2} per season by multiplying the flux with the molar weight of carbon (12 g mol^{-1}) and converting half hourly measurements to the desired time periods.

3.6.2 Statistics

Significant correlations were tested between NEE and environmental variables (air temperature, soil temperature -10 cm, snow depth, snow temperature -10 cm and PAR) using SPSS, version

20.0 . It was assumed that data was normally distributed by visually looking at histograms over the data. Pearson's correlation was used and the data was set to be statistically significant at three levels: $p<0.05$, $p<0.01$ and $p<0.001$

Paired t-test was used to test if there was any statistical significance in NEE (gap filled) between the different seasons for the two years ($p<0.001$).

4. Results

4.1 Meteorological data

The meteorological station provided data of half hourly values. There were missing data between 23th of December 2012 and 15th of February 2013 for all meteorological variables caused by power failure.

Air temperature and PAR (for the period 29th of August 2012 – 21th of October 2014) are shown in figure 2. Air temperatures were well below zero in the winter and almost never reached over 10 ºC in summer time. PAR (µmol m^{-2} s^{-1}) was the incoming solar radiation measured from the sensor pointing upwards. PAR was high during summer and zero during the polar night when there was no incoming solar radiation. Figure 2 shows the daily averages for air temperature and PAR for the different seasons and are very synchronized. The temperature was higher in the summer, when PAR was high, with a maximum of 17.4 ºC in the summer of 2013 and a maximum of 14.7 ºC in the summer of 2014.

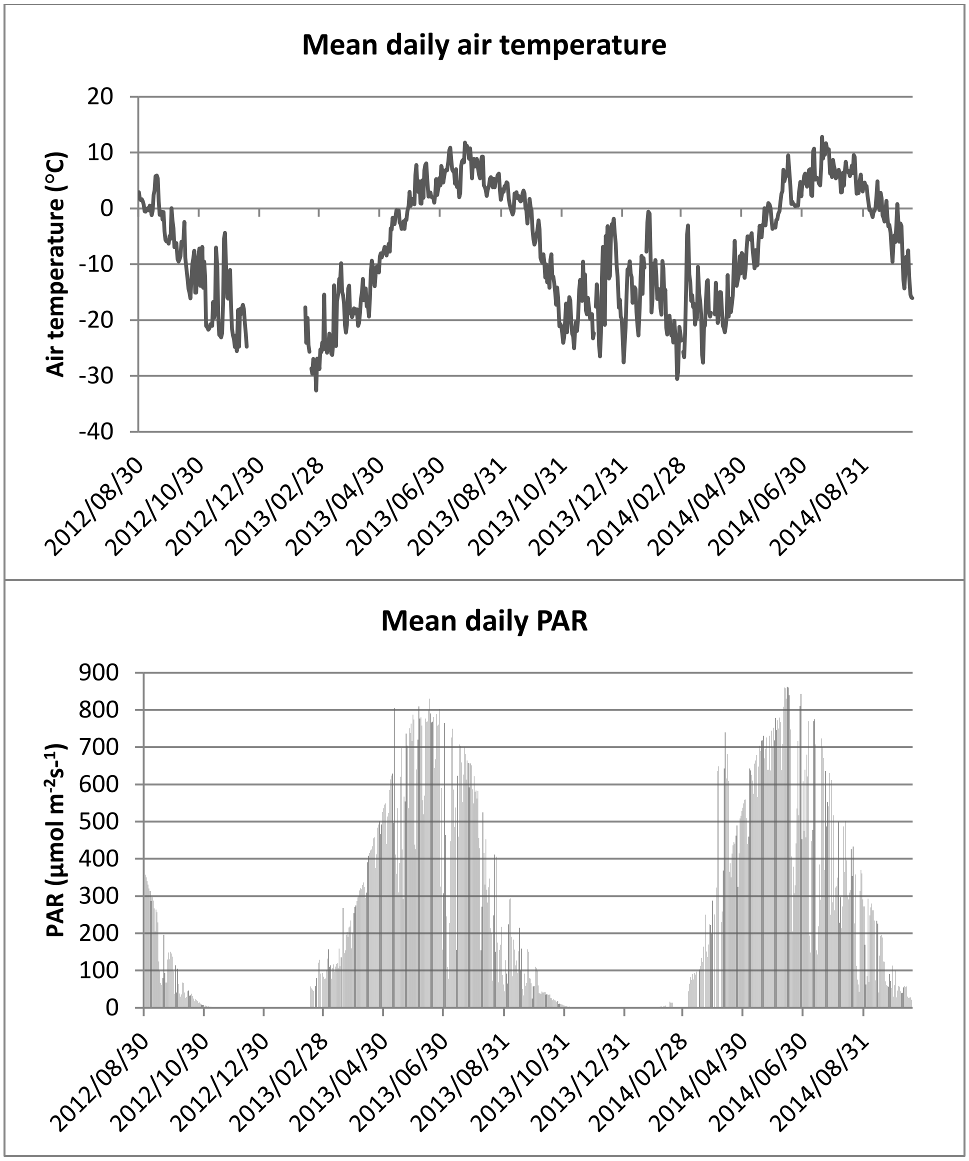

Figure 2. Mean daily values of incoming PAR (µmol $m^{-2}s^{-1}$) and air temperature (ºC) for the period 29th of August 2012 – 21th of October 2014. There was missing data between 23th of December 2012 and 15th of February 2013.

The mean monthly air temperatures are shown in figure 3. The season 2012/2013 had the coldest mean monthly air temperatures in December, February and Mars compared with the season 2013/2014 (missing data in January). In the time periods outside of winter the values were almost the same for the two seasons. The three months in 2014 were also similar to the other years.

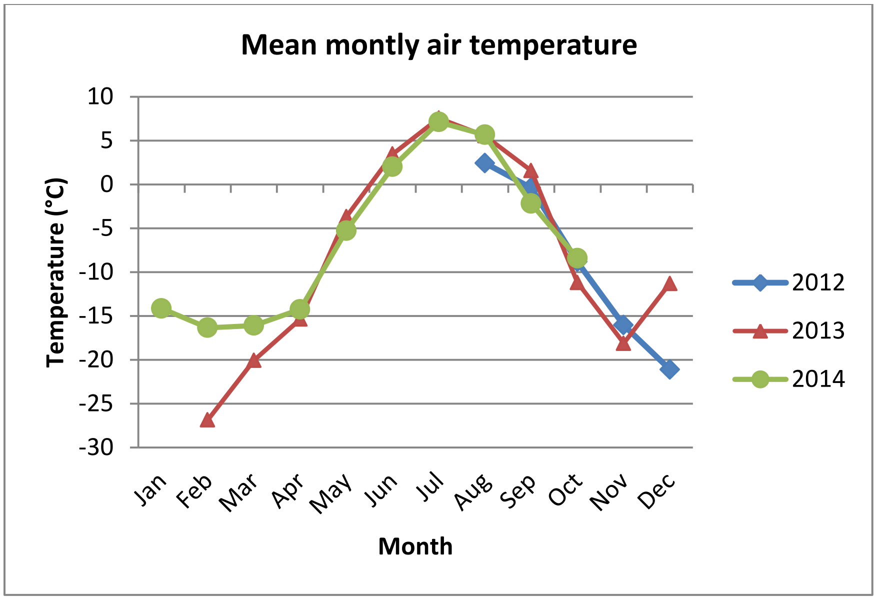

Figure 3. The mean monthly air temperatures (°C) for the different years. Blue line with squares display August 2012 to December 2012 and red line with triangles display 2013. The year 2014 are displayed with green lines with circles. Data are from 29th of August 2012 to 21th of October 2014.

The mean air temperatures (ºC), PAR, soil temperatures at -10 cm, snow depth, snow temperature at 10 cm and NEE for each time period are shown in table 2. Over the whole yearly season the mean air temperatures are the same at one decimal phase (-6.1 ºC). Seen over the whole winter period, the 2012/2013 season was coldest and had the coldest temperature in the dark and late winter compared to 2013/2014. The symbol "–"stands for no data.

Table 2. The mean environmental parameters for each time period with the NEE budget in the last column. The symbol "–"stands for no data.

		Air temp (°C)	PAR (µmol m^{-2} s^{-1})	Soil temp (-10 cm) (°C)	Snow depth (m)	Snow temp (10 cm)(°C)	NEE (gC m^{-2})
2012	Summer	1.8	314.5	1.5	-	-	2.5
2012/2013	*Early winter*	-5.8	84.3	-1.6	0.03	-	34.8
	Dark winter	-18.6	-	-14.7	0.07	-17.2	23.6
	Late winter	-14.1	345.4	-17.0	0.09	-24.0	9.2
	Summer	5.0	489.7	3.6	-	-	-103.5
	Whole winter	-12.3	182.6	-11.3	0.08	-22.5	67.7
	Whole year	-6.1	294.6	-6.0	-	-	-39.2
2013/2014	*Early winter*	-7.5	57.5	-1.3	0.10	-16.0	21.5
	Dark winter	-13.5	-	-12.0	0.39	-13.5	0.1
	Late winter	-9.2	429.5	-9.8	0.81	-9.5	9.8
	Summer	5.7	404.8	5.0	-	-	-154.8
	Whole winter	-9.9	218.9	-8.2	0.55	-16.7	31.4
	Whole year	-6.1	263.9	-5.1	-	-	-120.0
2014	*Early winter*	-4.5	104.3	-0.50	0.18	-6.92	24.3

The mean daily snow depths (m) for the two winter seasons are shown in figure 4. The season of 2013/2014 had substantial more snow, over 1 meter compared to 2012/2013 that never reached over 20 cm.

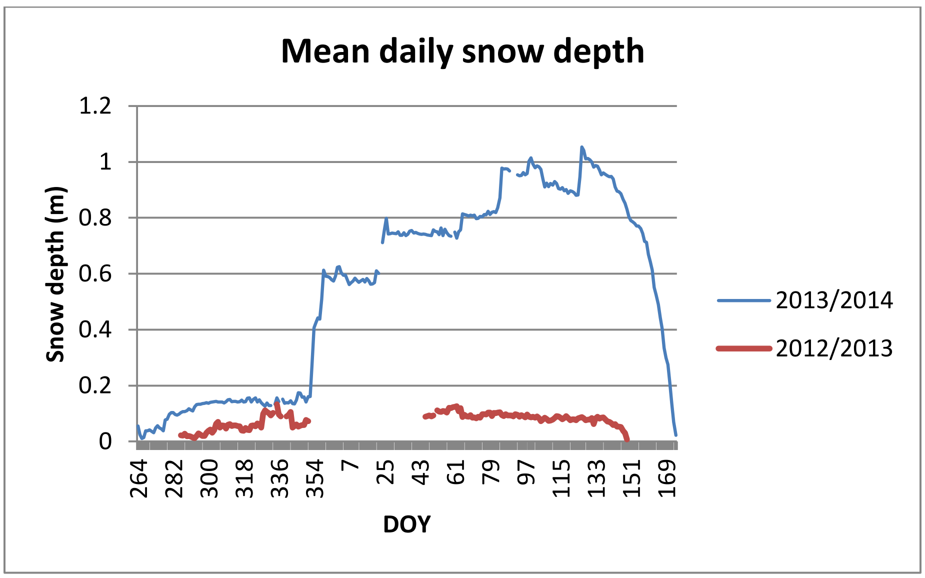

Figure 4. Mean daily snow depth (m) for the two winter seasons. Thin blue line shows the season 2013/2014 and the thick red line the season 2012/2013. The start value of DOY 264 (Day Of Year) is the 21th of September and DOY 169 is the 8th of June.

The length of the snow seasons with the first and the last day of snow and the maximum snow depth are displayed in table 3. Also here the big difference between the winter seasons can be seen.

Table 3. The day of first and last snow and the maximum mean daily snow depth for the different years are summarized. Measurements of snow depth ended 19th October 2014. The symbol "–"stands for no data.

Year	**2012/2013**	**2013/2014**	**2014**
Day of first snow	13 Oct	15 Sep	1 Oct
Day of last snow	29 May	22 Jun	-
Max snow depth	0.13 m	1.11 m	0.88 m

NDVI (Normalized Difference Vegetation Index), snow temperature (at 10 cm) and soil temperature (at -2 cm, -10 cm and -50 cm) for the period 29th of August 2012 to 2th of September 2014 are shown in figure 5. Values of NDVI are only shown for the growing season. Maximum NDVI for the summer of 2013 was 0.68 and the mean value was 0.43. For the summer of 2014 the maximum value was 0.70 and mean value 0.48.

Measurements of snow temperature were done at several levels, but only 10 cm depth (values measured 10 cm above the surface) is displayed in the graph since the temperatures didn't differ that much. This was expected since snow works as an insulator, but the closer to the snow surface the more impact will air temperatures have. For example if there is a deep snow depth, snow temperature closer to the ground is less variable than the snow temperature closer to the snow surface.

The minimum soil temperature was at 2 cm depth of -24 ºC in the winter season 2012/2013 while the coldest temperature in the winter season 2013/2014 was -19.9 ºC. The maximum temperature was in 2014 with 17.5 ºC and in the summer of 2013 the maximum temperature was 16.3 ºC.

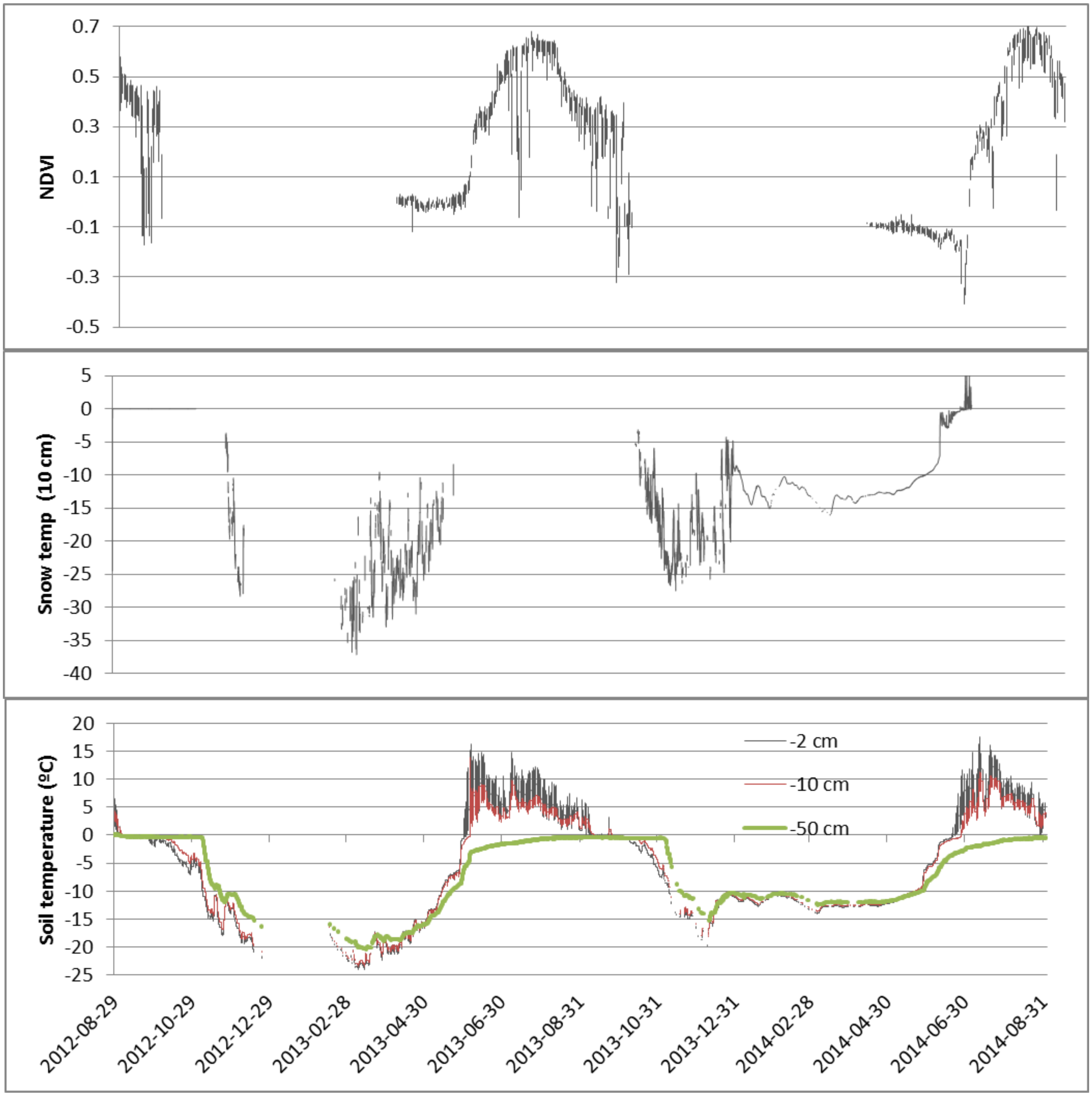

Figure 5. NDVI, snow temperature at 10 cm above ground and soil temperature for 2, 10 and 50 cm depth for the period 29th of August 2012 to 2th of September 2014. Soil temperatures at 2 cm depth (black line) show the highest variability, followed by 10 cm depth (red line) and 50 cm depth (green thick line).

4.2 NEE budget

Figure 6 shows the gap filled NEE (µmol m^{-2} s^{-1}) for the two years 2012/2013 and 2013/2014 with start and end dates. During summer time, with a maximum around late July/ early August, fluxes were mostly negative, meaning an uptake of CO_2.

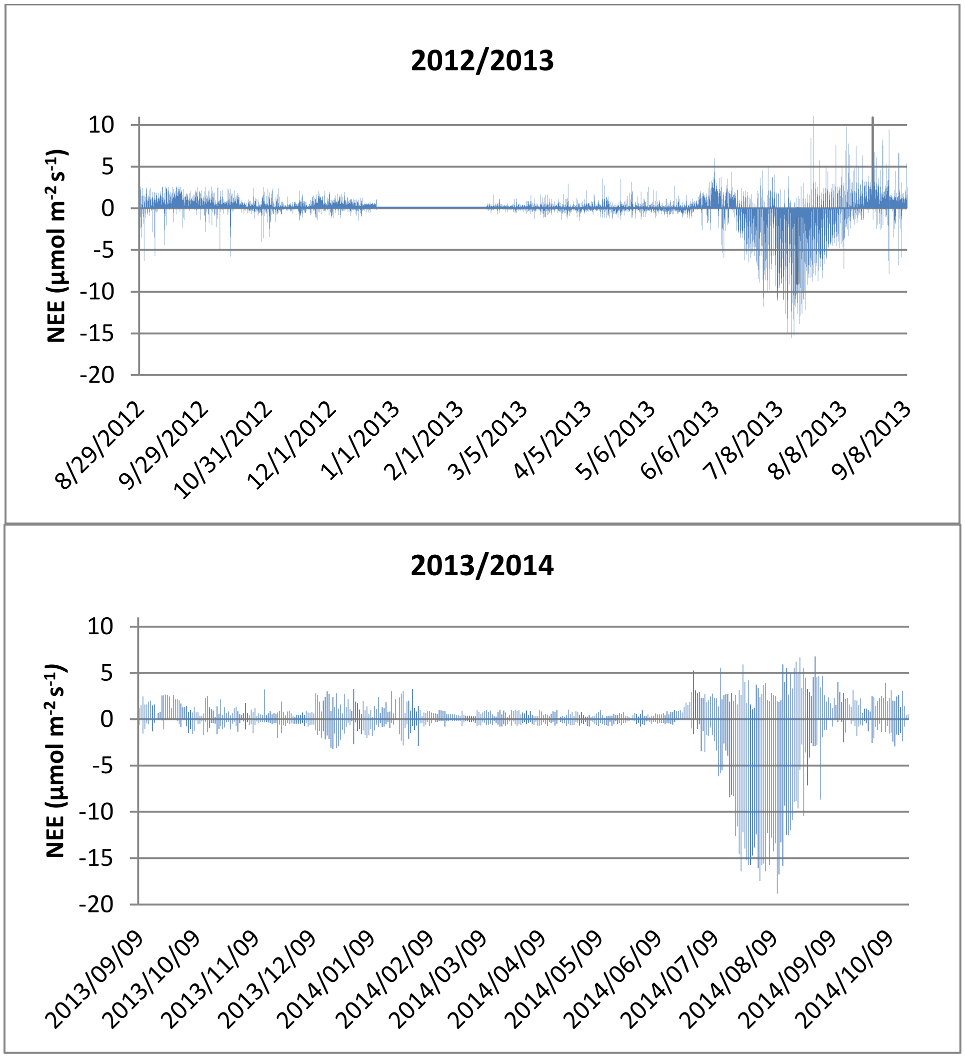

Figure 6. NEE (µmol m^{-2} s^{-1}) for the two years 2012/2013 and 2013/2014 with start 29th of August 2012 and end 19th October 2014.

Table 4 shows the CO_2 flux (NEE) in sums (g C m^{-2}) for the different time periods (same as in table 2). It can be seen that there was a big difference between the years, especially for the dark winter with NEE almost zero for 2013/2014. The uptake in summer was around 50 g C m^{-2} more in 2014 than in 2013. These two differences reflected the variance between the seasons over the whole year. However, for both seasons there was a net release of carbon in winter time and an uptake of carbon in summertime. For the missing data period from 23th of December 2012- to

15th of February 2013 the flux (gap filled) was 11.6 g C m^{-2} and for the corresponding period in the year 2013/2014 there was a positive flux of 2.6 g C m^{-2}. The whole winter 2012/2013 stood for 39.5% of the total annual NEE budget and the whole winter 2013/2014 stood for 16.9% of that year's total NEE budget.

Table 4. The carbon flux (NEE) in numbers (g C m^{-2}) for the different time periods.

	Early winter	*Dark winter*	*Late winter*	*Summer*	*Whole winter*	*Whole year*
2012				2.5		
2012/2013	34.8	23.6	9.2	-103.5	67.7	-39.2
2013/2014	21.5	0.1	9.8	-154.8	31.4	-120.0
2014	24.3					

Figure 7 shows an example of how the NEE data (g C m^{-2}) was gap filled based on the quality checked data for four days in the winter 2013 and in the summer 2014. The example is a good representation of all gap filled data. For the winter time the gap filling values were mostly low and positive. For the summer there was a clear uptake of CO_2 during the day and a low positive value during the night. More data was missing in the winter time example than in the summer time example.

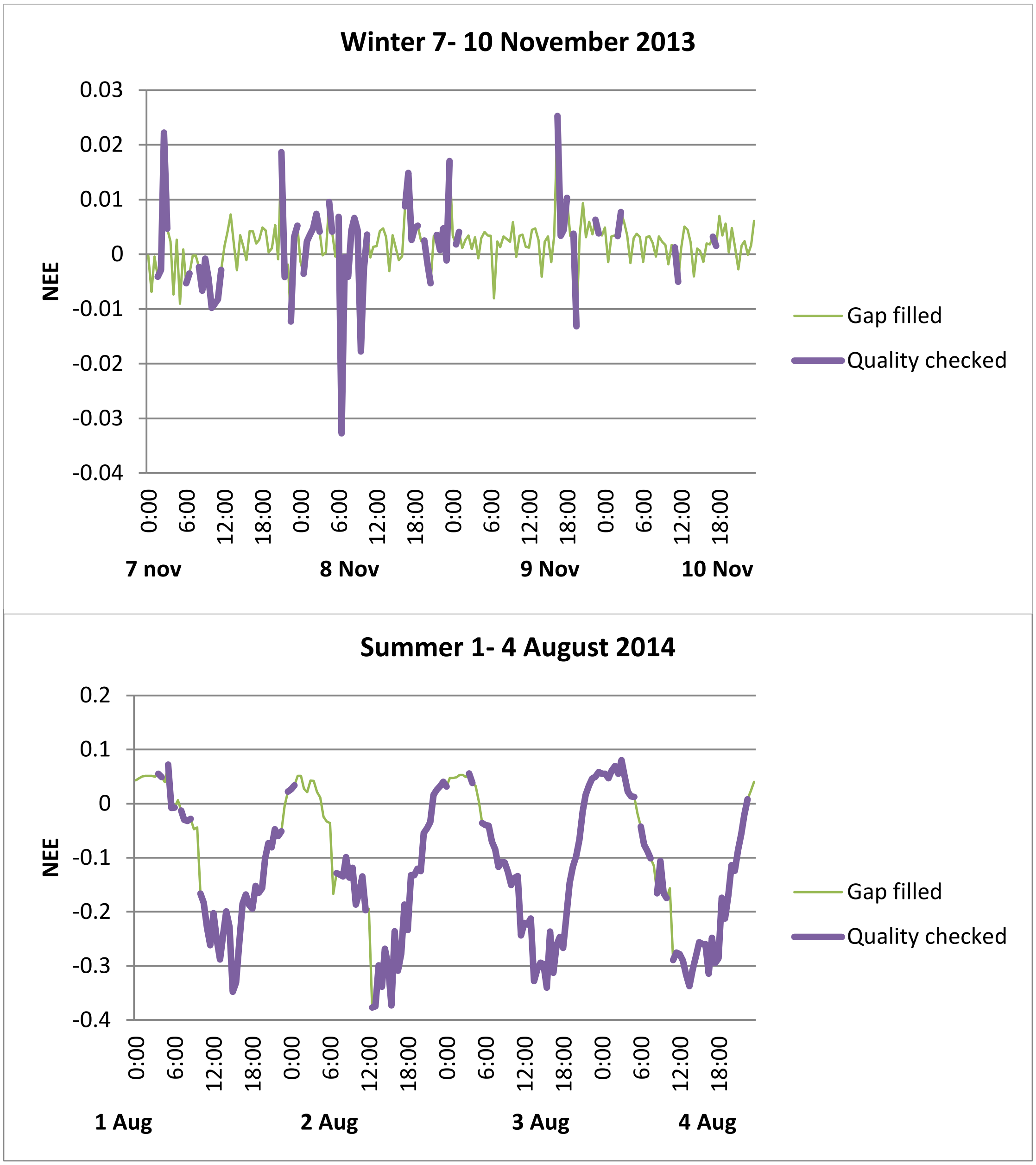

Figure 7. Four days of NEE (g C m^{-2}) for winter (7th -10th of November 2013) and summer (1th-4th of August 2014) with gap filled (thin green line) and quality checked data that is not gap filled (thick lilac line). The data is form every half-hour.

4.3 Environmental controls

In this chapter correlations between NEE and different environmental variables are shown. Correlations where done with daily means of non-gap filled NEE data (to avoid pseudo correlation for air temperature and PAR). The data of the daily means were quality checked and all available half-hourly values were included in the calculations. Even if there were days with very few values they were also included.

4.3.1 Temperature

The dependence of air temperature on NEE (daily means) was tested fitting Van't Hoffs exponential function (see equation 4). This function is mostly used for the temperature-respiration dependence and this should be kept in mind for summer time when there was photosynthesis.

$$NEE=a*exp\ (b*T) \qquad (4)$$

where a and b are parameters and T is the air temperature. Table 5 shows the coefficients of determination (R^2) for the different seasons for air temperature and soil temperature. The best fit was for the early winter for both years which is shown in the scatterplot in figure 8. The next best fit after the early winter was with the whole winter of 2012/2013 (R^2= 0.30) (shown in figure 8) and the summer of 2014 (R^2=0.28).

Table 5. R^2 (based on equation 4) for NEE as a function of the environmental variables air temperature and soil temperature.

		R^2	
Year	**Season**	Air temp	Soil temp
2012/2013	Early winter	0.67	0.46
	Dark winter	0.00	0.02
	Late winter	0.07	0.08
	Whole winter	0.30	0.43
	Summer	0.12	0.20
2013/2014	Early winter	0.61	0.39
	Dark winter	0.02	0.32
	Late winter	0.04	0.12
	Whole winter	0.08	0.32
	Summer	0.28	0.35

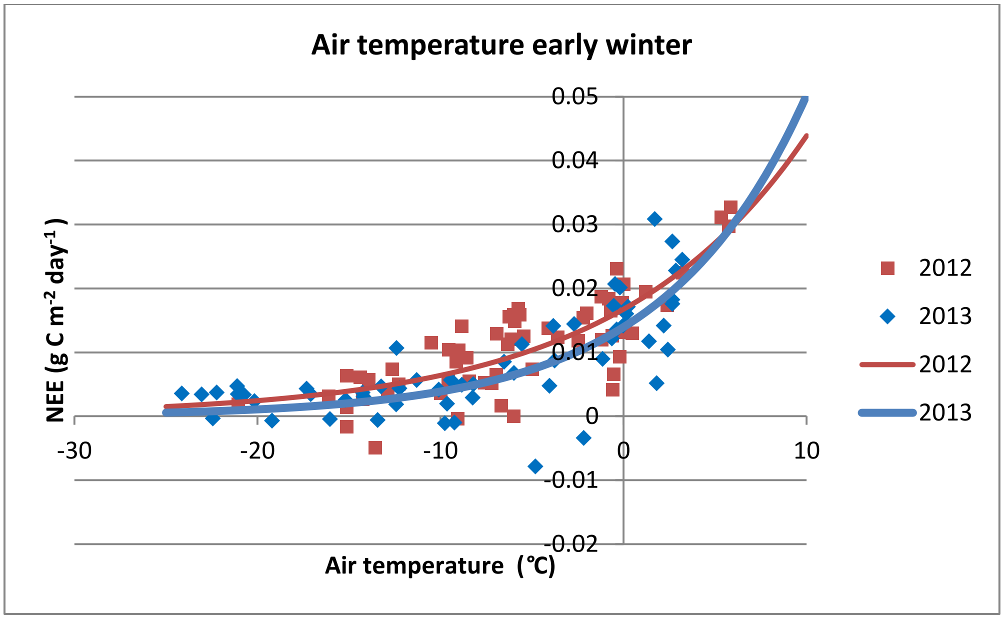

*Figure 8. Scatterplot of measured air temperature and NEE for the early winter for the two years. Curves show modeled NEE (equation 4) as a function of air temperature. For 2012/2013: NEE=0.0168*exp (0.0963*T). For 2013/2014 NEE=0.01396*exp (0.1281*T). For R^2 see table 5.*

Figure 9 shows relationship between the air temperature and NEE for the whole winter period. NEE was usually higher when air temperatures were higher which reflect the better fit from the early winter. For the dark and late winter (figure 10) no clear trend could be seen with air temperature and NEE. Actually NEE was higher with colder temperatures for dark winter 2012/2013 and for dark winter 2013/2014 there were some negative NEE values. NEE in late winter 2013 was very low and in late winter 2014 NEE was slightly higher.

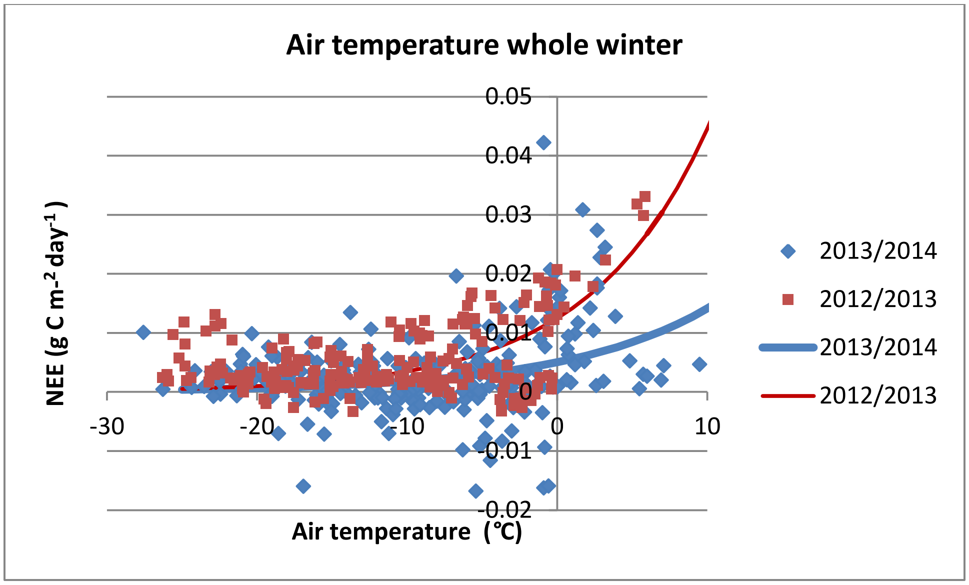

*Figure 9. Scatterplot of measured air temperature and NEE for the whole winter for the two years. The curve shows modeled NEE (equation 4) as a function of air temperature for the year 2012/2013. For 2012/2013: NEE=0.0125*exp (0.1271*T). For 2013/2014 NEE=0.0050*exp (0.1030*T). For* R^2 *see table 5.*

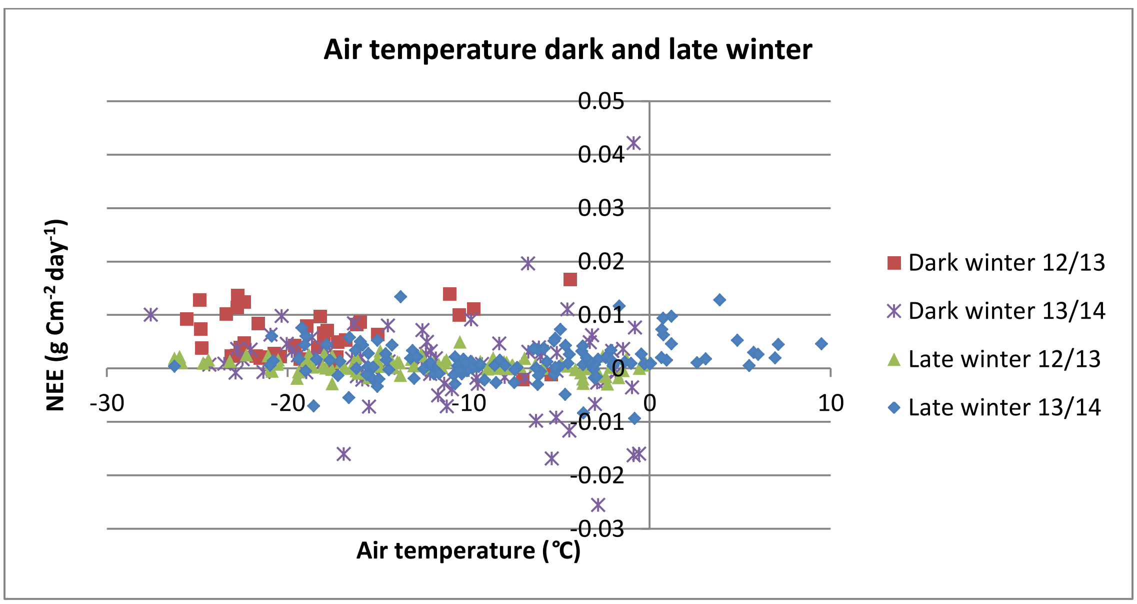

Figure 10. Scatterplot of measured air temperature and NEE for the late and dark winter for the two years. In this graph trendlines and equations are not shown due to very low R^2 *and no correlation could be seen. For* R^2 *see table 5.*

For the early winter, NEE was lower when the soil temperature was lower for both years (figure 11). The values are fitted to Van't Hoffs exponential equation (see equation 4) and R^2 for NEE as functions of soil temperature are shown in table 5. R^2 was higher for early winter in 2012 (R^2=0.46) compared to early winter in 2013 (R^2=0.39)

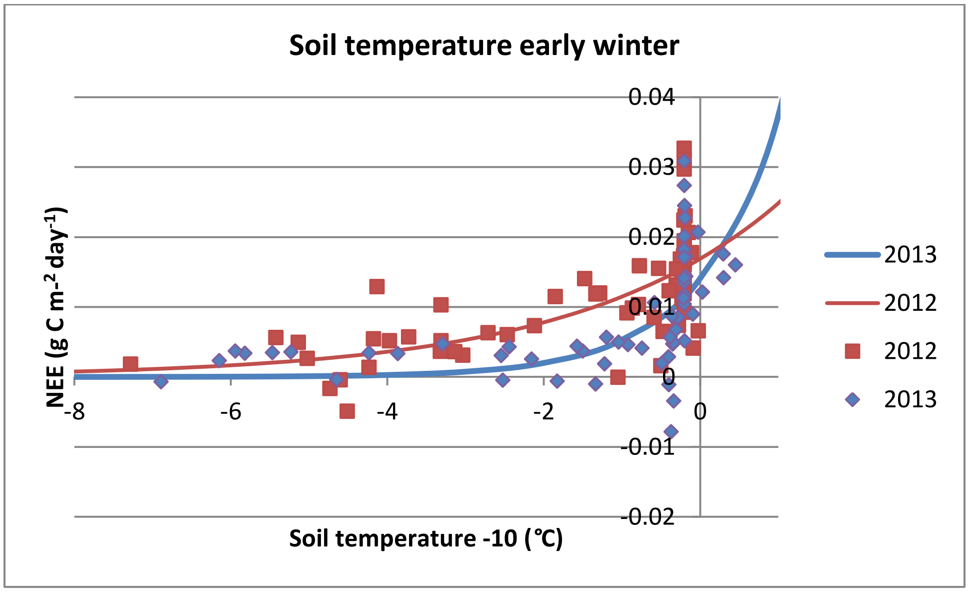

*Figure 11. Scatterplot of measured soil temperature (-10 cm) and NEE for the early winter with modeled exponential curves for the two years. For 2012/2013: NEE=0.0169*exp (0.38610*T). For 2013/2014 NEE=0.0141*exp (0.9758*T). For R^2 see table 5.*

For the whole winter 2012/2013 respective 2013/2014 soil temperatures versus NEE are shown in figure 12. Temperatures around zero had a higher flux than the rest of the soil temperatures for both years. For the period dark winter and late winter (figure 13) there was a bad fit with the exponential equation (no line showed).

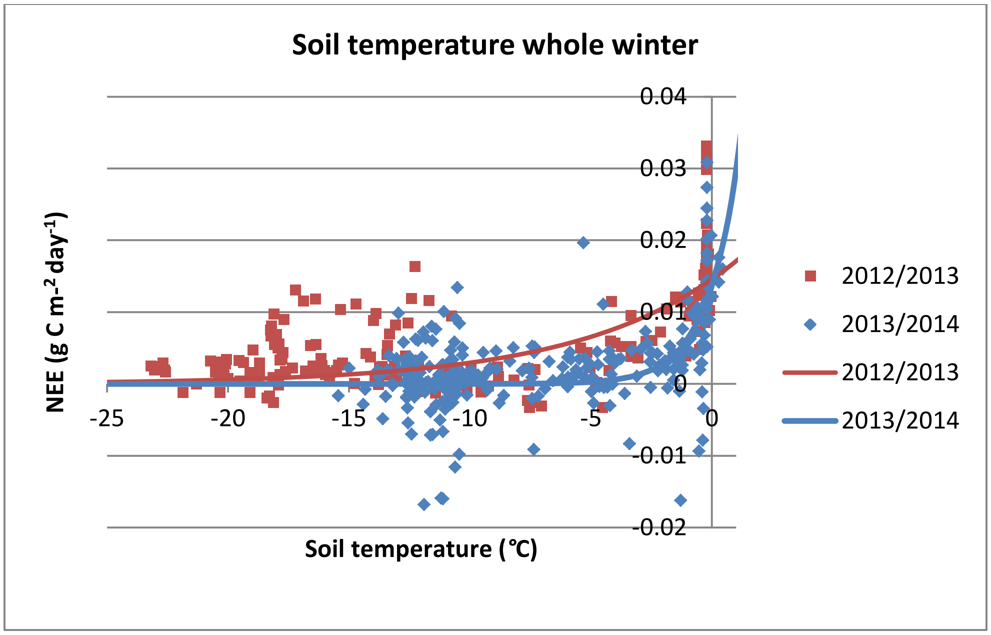

*Figure 12. Scatterplot of measured soil temperature (-10 cm) and NEE for the whole winter the different years with modeled exponential curves showing NEE as a function of soil temperature. For 2012/2013: NEE=0.01458*exp (0.15970*T). For 2013/2014 NEE=0.01372*exp (0.7763*T). For R^2 see table 5.*

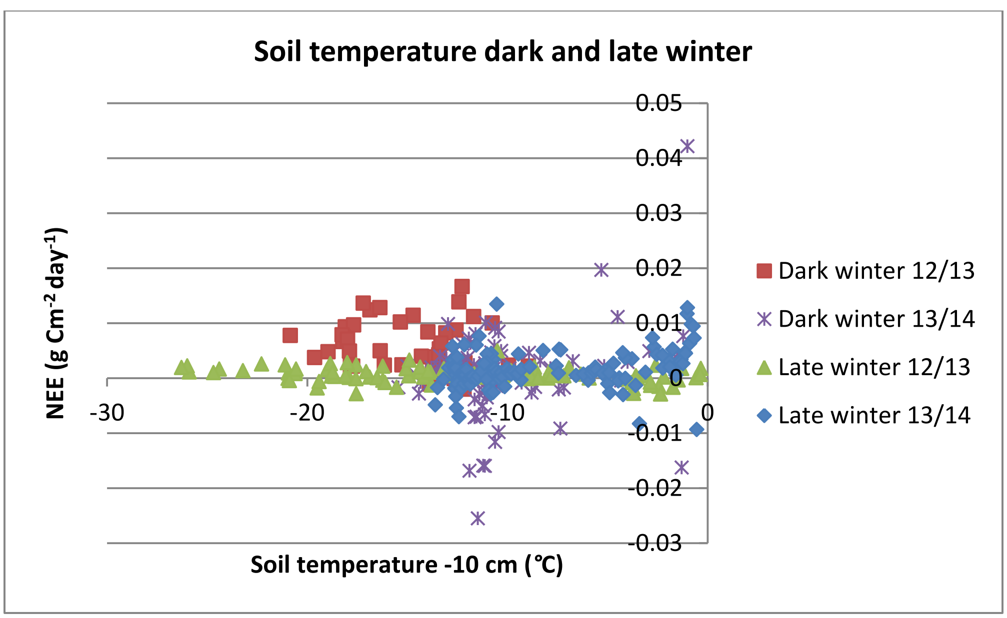

Figure 13. Scatterplot of measured soil temperature (-10 cm) and NEE for the dark winter and late winter for the two years. In this graph trendlines and equations are not shown due to very low R^2 and no correlation could be seen. For R^2 see table 5.

4.3.2 PAR

Late winter and early winter relationships with PAR and NEE are shown in figure 14. For the early winter PAR was low and so was NEE, almost no flux and no incoming radiation. Instead, for the late winter PAR was higher and NEE was also higher both the positive and negative flux. For the summer time (figure 15), NEE was negative (an uptake of CO_2) and there was a trend with increasing NEE with increasing PAR, however R^2 was not very strong with the best in the summer of 2013 ($R^2 = 0.1$).

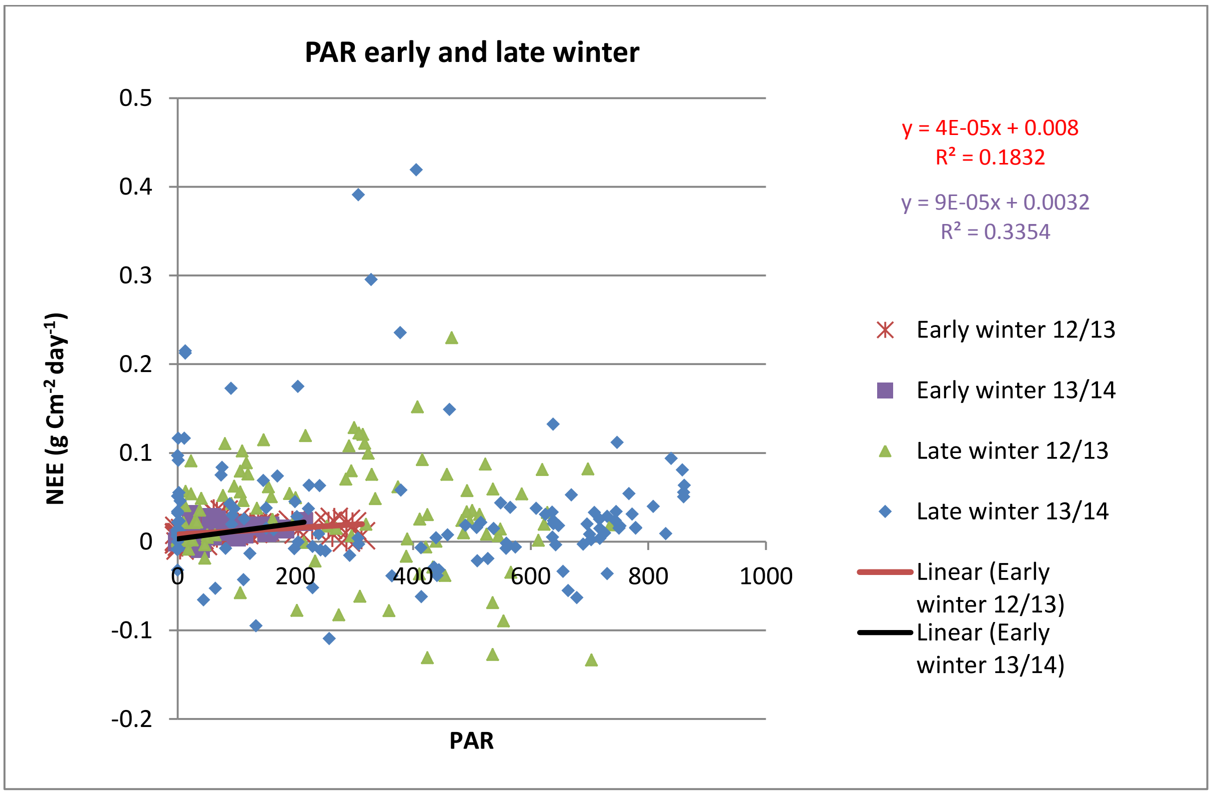

Figure 14. Scatterplot of measured PAR and NEE for the late and early winter for the two years. In this graph trendlines and equations are only shown for early winter and not for late winter since late winter had a very low R^2 and no correlation could be seen.

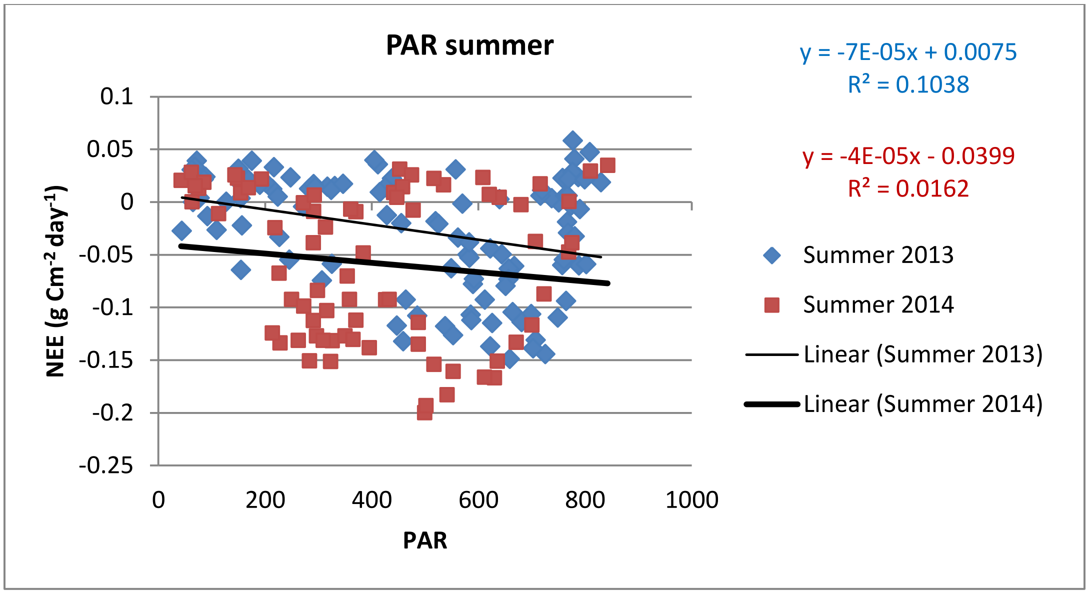

Figure 15. Scatterplot of measured PAR and NEE for the summer for the two years.

4.3.3 Snow depth

Figure 16 and 17 shows scatterplots of the mean daily snow depth and NEE for the two snow covered seasons. For both 2012/2013 and 2013/2014 snow season a very low snow depth tended to have higher fluxes than a deeper snow depth. However when there was a substantial amount of snow no clear trend could be seen in NEE.

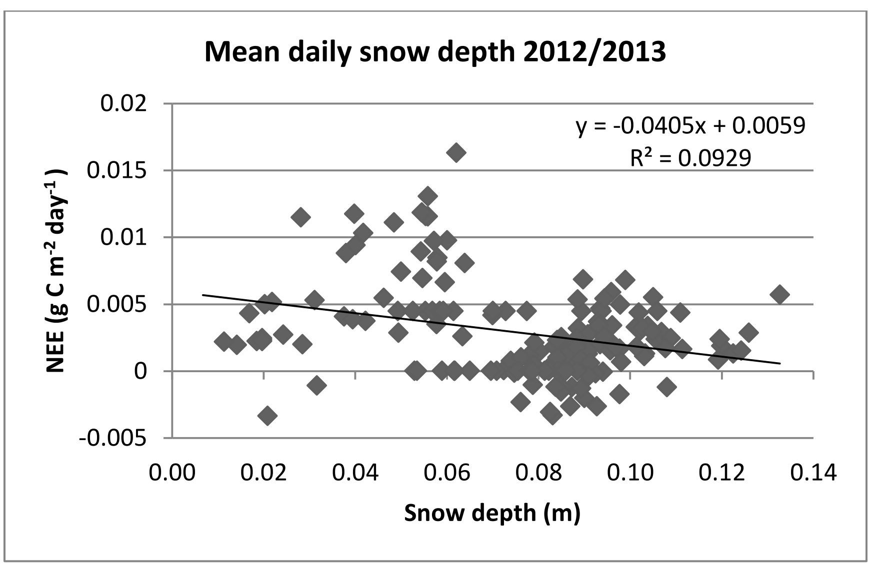

Figure 16. Mean daily snow depth and NEE for the snow season 2012/2013.

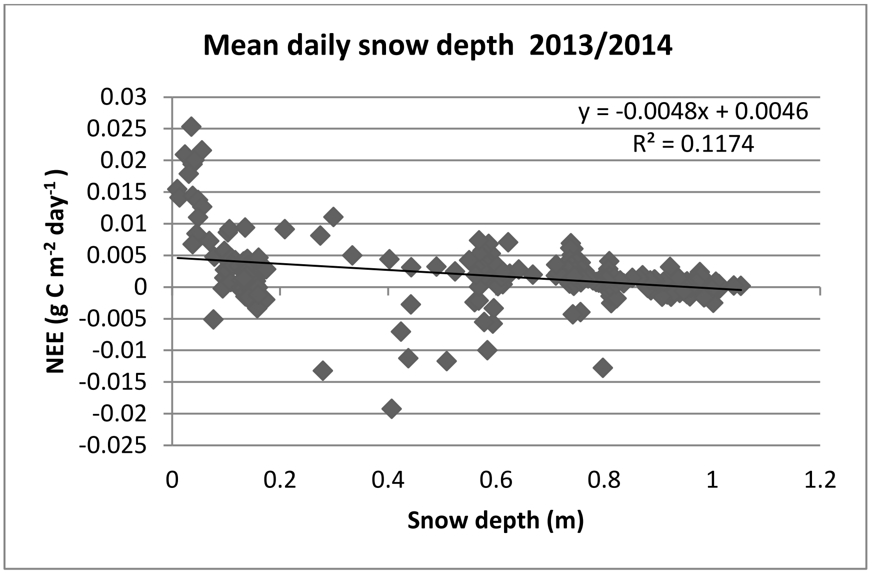

Figure 17. Mean daily snow depth and NEE for the two snow seasons 2013/2014.

The dark winter 2012/2013 was the time period where the best linear trend between NEE and snow depth could be seen (figure 18). Here NEE was a little bit higher with higher snow depth. For the dark winter 2013/2014 the same trend could not be seen since NEE was very low for this dark winter period.

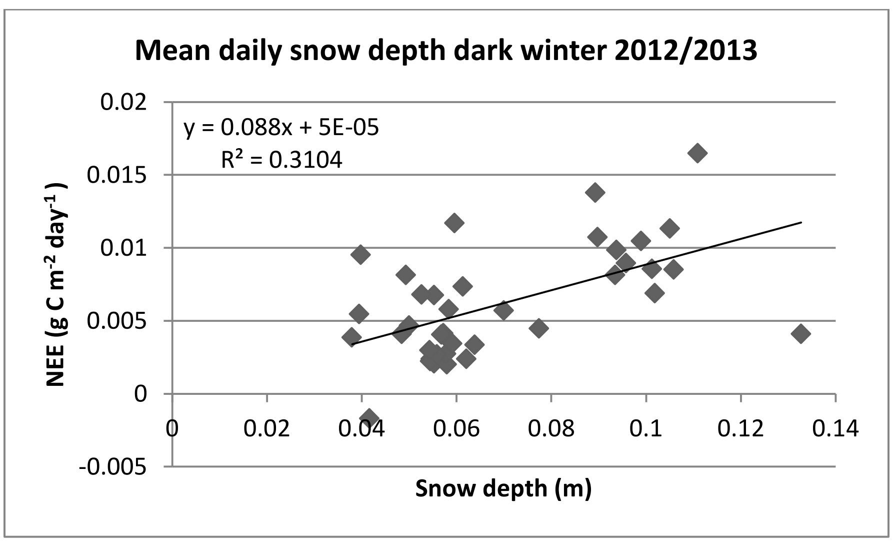

Figure 18. Mean daily snow depth and NEE for dark winter 2012/2013.

4.3.4 Snow temperature

Van't Hoffs exponential function does not fit the snow temperature data very well (figure 19) and there seem to be no relationship between snow temperature and NEE. The highest R^2 was for dark winter (R^2= 0.32) and was only caused by one single point far away from the others. Only the year 2013/2014 are shown since the year before very often had a snow depth below 10 cm.

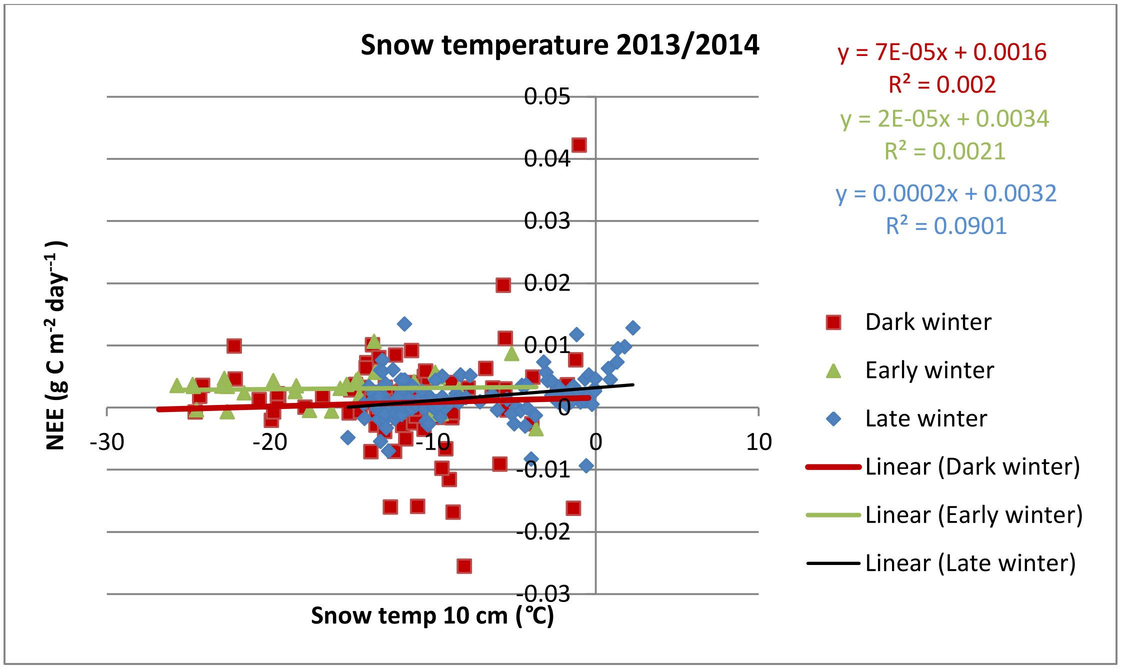

Figure 19. Mean daily snow temperature and NEE for the dark-, early- and late winter season of the year 2013/2014.

4.4 Statistical analysis

Table 6 shows correlations and statistical significance for CO_2 flux versus different environmental parameters. Daily means was used and non-gap filled data to avoid autocorrelation. Pearson's correlation coefficient is shown in numbers and three stars represents a statistical significance $p<0.001$, two stars shows a statistical significance $p<0.01$ and one star shows a statistical significance $p<0.05$. For values without stars there was no statistical significance.

The strongest correlations are values closest to -1 and +1 since they are the highest possible for the linear dependence between the two variables (total dependence).

For the year 2012/2013 the early winter had high positive correlation coefficients with all variables. When there was lower air temperature, PAR and soil temperature there was also a lower flux (emission of CO_2), but as the snow depth increased NEE decreased (negative correlation). In contrast in the dark winter snow depth had a positive correlation coefficient which means that there was a higher flux with higher snow depth.

PAR was zero in the dark winter and no statistics were done here. The coefficients for late winter were only significant for air temperature and soil temperature in 2012/2013 with negative relationships. Soil temperatures had the highest dependence seen over the whole winter. For the summer time 2012/2013 there was a negative relationship meaning that with higher temperatures and PAR there was a negative flux (uptake of CO_2 by photosynthesis).

Pearson's correlation coefficients for the year 2013/2014 are also shown in table 6. In early winter snow depth had a strong negative correlation, meaning that a higher snow depth did not result in a higher flux (which was the case for 2012/2013) instead the flux decreased with increasing snow depth. Air temperature, PAR and soil temperatures had positive correlations with CO_2 in early winter for both years. For dark winter there was no statistical significance at all for both years. For the late winter snow depth had a negative dependence in 2013/2014 but a positive in 2012/2013. In summer time there was a negative relationship with temperature and PAR for both years.

*Table 6. Pearson's correlations coefficients for CO_2 flux versus different environmental variables for 2012/2013 and 2013/2014. The stars shows the statistical significance for *** p<0.001, ** p<0.01 and for * p<0.05, no stars is no statistical significance. The symbol "–"stands for no data.*

Year	**Season**	Air temp	Soil temp -10 cm	PAR	Snow depth	Snow temp 10 cm
2012/2013	Early winter	0.783***	0.647***	0.428***	-0.414*	-
	Dark winter	0.041	-0.160	-	0.470**	-
	Late winter	-0.285**	-0.291**	-0.139	0.139	-
	Whole winter	0.389***	0.566***	-0.308***	0.065	-
	Summer	-0.333**	-0.428***	-0.319**	-	-
2013/2014	Early winter	0.687***	0.475***	0.579***	-0.738***	0.048
	Dark winter	-0.138	0.256	-	-0.155	0.045
	Late winter	0.141	0.32	-0.113	-0.321	0.298
	Whole winter	0.218	0.46	-0.018	-0.302	0.092
	Summer	-0.602***	-0.677***	-0.127	-	-

Paired t-test was used to test if there was any statistical significance in NEE (gap filled) between the different seasons for the two years. The corresponding seasons over the two years were significantly different from each other for all cases at a value of p<0.001.

5. Discussion

5.1 Meteorological data

The air temperatures in Zackenberg for this measurement period was a bit higher compared to the time period 1996-2005 (Hansen et al. 2008). The coldest period occurred under and after the polar night both for the year 2012/2013, the year 2013/2014 and for the time period 1996-2005. This was expected since there is no incoming solar radiation under the polar night and strong radiative cooling that drop temperatures below 20 ºC and often down to daily minimum of -30 ºC. The coldest mean monthly temperature for the measurement period in this report was -26.8 ºC which was in February 2013. For the time period 1996-2005 the month December to March had mean monthly temperatures below -20 ºC with a minimum of -22.4 ºC in February.

July is normally the warmest month of the year with a mean of 5.8 ºC for the period 1996-2005 (Hansen et al. 2008). In this study the mean July temperature in 2013 was 7.5 ºC and in 2014 it was 7.1 ºC which showed a small increase in temperature compared to 1996-2005. In the time period 1996-2005, the year of 2003 had the warmest air temperature with 7.6 ºC (Hansen et al. 2008). The air temperature was highest in the summer, with a maximum of 17.4 ºC in the summer 2013 and 14.7 ºC in the summer 2014. This can be compared with the summer 2012 which was a normal year in meteorological conditions (except that April and May were colder than normal). The maximum temperature in 2012 was 19.4 ºC which was recorded 19th of August (ZERO 2013).

The snow depth varied greatly between the years where the season 2012/2013 almost had no snow depth at all and the ground was also covered for a shorter time period. Variability between years is normal and for example the season 2010/2011 had a low snow depth mostly under 0.45 m, while in 2011/2012 the maximum snow depth was almost 1.3 meter (ZERO 2013). The time period when the ground is snow covered affects NDVI that will be around zero when there is snow. The snow also reflects radiation from the sun and a snow cover has an albedo of around 80-90 % (Hansen et al. 2008). In 2012 the snow was completely gone the 26th of June (ZERO 2013) to be compared with 25th of May in 2013 and 22th of June 2014. The average day of free ground after snow is the 17th of June so 2013 was an earlier year and 2014 just five days over the average.

The negative NDVI values may have been caused by clouds and/ -or snow. In the winter time when the ground was snow covered no vegetation was visible and consequently the NDVI values was not reflecting the vegetation. NDVI values were up to 0.6 which reflected the relatively dense vegetation in the fen measurement area, for example compared to the heath in the Zackenberg valley which is around 0.4-0.5 (Ellebjerg et al. 2008). For the summer of 2014 the NDVI values were a little bit higher than for the summer of 2013. Comparing with the NEE budget for the summer, this may be part of the explanation for the higher uptake of CO_2 in 2014 that had more biomass compared with the lower uptake in summer 2013.

The season 2012/2013 had the lowest soil temperature at 2 cm depth of -24.0 ºC compared with -19.9 ºC in the winter season 2013/2014. This difference may be caused by the lower snow cover in 2012/2013 that had a lower insulation effect on the soil. The maximum summer temperatures were more similar with only 1.2 ºC in difference. The soil temperature had a lower variability deeper down in the soil due to less influence of meteorological conditions in the atmosphere.

The snow temperature at 10 cm depth for 2012/2013 was not correct because there was not enough snow. For the season 2013/2014 the temperature was more stable and around 10 °C which indicate that the snow worked as an insulator. For the season 2012/2013 the snow had a lower insulating effect on the ground due to the little amount of snow.

5.2 NEE budget

As seen from other areas in the Arctic the yearly and seasonal budget varies greatly, from very low fluxes to remarkably high emissions and uptake of CO_2. This may be caused by differences in ecosystems for example due to carbon and nutrient content.

In this study the winter season 2013/2014 had snow cover almost a month longer than the 2012/2013 season until snowmelt. This should lower the possible uptake of CO_2 by plants in the summer of 2013 since photosynthesis is not possible under snow and consequently the day of snowmelt will have an impact on annual NEE. However from the results in this study the uptake of carbon in the summer was higher in 2014 than in 2013 which mean that there must have been other factors than day of snow melt that made the uptake in 2014 higher. As an example, in a study in 1997 the CO_2 uptake in summer correlated with leaf area index (LAI) (Soegaard et al. 2000) .

The much lower value in dark winter for 2013/2014 was due to low flux that was both positive and negative. For the period 2012/2013 there was a huge gap in data for the dark winter and this was filled with mean values for the weeks before and after. These values were low but positive and for the missing data period (23th of December- 15th of February) the flux was 11.59 g C m^{-2} which explains some of the difference between the years. For the same period 2013/2014 there was a positive flux of 2.64 g C m^{-2}. The winter 2012/2013 had colder air temperature, and colder snow temperature than the winter 2013/2014. Also the soil temperature, which should have the strongest influence on respiration under snow conditions, was colder 2012/2013. This would mean that less soil respiration would be possible for the winter 2012/2013. Instead the winter emission were higher in 2012/2013 compared to the very low emission in the winter 2013/2014. The mean CO_2 (ppm) concentration for the dark winter 2012/2013 was 393 ppm and for the dark winter 2013/2014 398 ppm reflecting the global concentrations.

In early winter the emission were higher for 2012/2013 than for 2013/2014. This could have been caused by an earlier end of photosynthesis in 2012/2013 that stopped CO_2 uptake or more respiration could be going on that emitted CO_2 to the atmosphere. For the late winter the emissions were almost similar for the two years. The whole winter and whole year reflected the much lower emission in dark winter and the higher uptake in summer. For the whole year and summer there was still an uptake of CO_2 and in the winter there was an emission, that agree with earlier studies in Zackenberg (Soegaard et al. 2000). The high variability is normal between years and these two years had a big difference in snow depth and snow cover and the summer 2014 was also a wetter than the summer 2013. However the very low negative fluxes in dark winter 2013/2014 can be discussed. It may have been possible that CO_2 was trapped in the very deep snow and could not escape through the snow pack until it melted away in spring time. The fluxes in late winter 2014 were around 6 g C m^{-2} more than in 2013, but there are many possible explanations to this, for example the late winter was much longer for 2014.

The gap filling method appeared to be satisfactory when looking at the two examples showing both gap filled and quality checked data, especially for the summer time, where a clear daily pattern was seen. In the summer example there were not so many missing values with the consequence of more correct gap filling values.

The carbon balance for the area of grassland, continuous fen and hummocky fen in Zackenberg valley was calculated for the year 1997 (Soegaard et al. 2000). For the whole year there was an uptake of -18.8 ±18.3 g C m^{-2} and for the growing season (July-August) an uptake of -48.7±1.7 g C m^{-2}. The values for the winter season were modeled based on soil temperatures and efflux was assumed to end at a temperature of -6.5°C. The carbon budget for the winter season was 13.8 ± 12.3 g C m^{-2}.

The eddy covariance method was used on a bog peatland (Mer Bleue) near Ottawa in Canada and NEE measured over a year (1998-1999) (Lafleur et al. 2001). Here NEE varied over the year with an increase in net daily uptake after the snowmelt, with the highest uptake in midsummer and then decreasing closer to the fall. During the late fall and the snow covered period NEE flux were low and continuous. On an annual basis NEE had a net uptake of 248 ±68 g CO_2 m^{-2} yr^{-1}. For the whole measurement period from 1th of June 1998 to 31th of May 1999 the uptake was 68 g C m^{-2} (Lafleur et al. 2001). For the same peatland (Mer Bleue) in Canada a 6 year mean of NEE was found to be -40.2±40.05 g C m^{-2}. The large variation between seasons and years were caused by variations in climate (Roulet et al. 2007). The authors also drew attention to the importance of measuring NEE, CH_4 flux and DOC (Dissolved Organic Carbon) when making a total carbon balance of a peatland. The high variability in NEE from Mer Bleue reflects the variability found between the two years 2012/2013 and 2013/2014 in this study that differed in 80.8 g C m^{-2} for the whole years. These two years also had differences in climatic conditions mainly regarding snow depth and air temperature. There were also differences in NEE between seasons in accordance with Mer Bleue. Furthermore, NEE in Zackenberg followed the same pattern as Mer Bleue over the year, increasing after snow melt, being highest in summer, decreasing towards fall and being low and steady during winter time.

NEE was calculated for a high Arctic tundra with permafrost on the west coast of Svalbard, Spitsbergen, based on eddy covariance data (Lüers et al. 2014). The annual carbon budget was close to zero g C m^{-2} yr^{-1} but NEE showed a large variation over the year. During the snow melt period emissions to the atmosphere were around 0.25 g C m^{-2} day^{-1} and changed to an uptake by -0.4 g C m^{-2} day^{-1} at the time where the ground was snow free. When the ground was bare photosynthesis dominated the carbon flux with an uptake following the time of most insolation during the day. In August the photosynthetic activity decreased which correlated with lower insolation and in September there were positive CO_2 fluxes and respiration started to dominate. In winter time (October-May) when the ground was covered in snow the flux was very low of ± 0.1 g C m^{-2} day^{-1} but for the whole winter season (November-April) there was a net release of 6-7 g C m^{-2} (Lüers et al. 2014). The annual and the winter time carbon budget here were much lower compared with the results from this study. This can be due to the greater amount of biomass at the fen in Zackenberg compared with the studied ecosystem in Svalbard that consists of sparse vegetation and big areas of bare ground.

Carbon flux was measured for the period September 2007 to May 2011 for two ecosystems in Alaska (Euskirchen et al. 2012). During summertime (July-August) the uptake was around 51-95 g C m^{-2} yr^{-1} for all years. During wintertime (September-May) there was a big release of CO_2. For a wet sedge ecosystem the emission was different for the four winter seasons with 105 g C m^{-2}, 61 g C m^{-2}, 145 g C m^{-2} and 139 g C m^{-2} (seasons were 2007-2008, 2008-2009, 2009-2010 and 2010-2011). The annual budget was 2 g C m^{-2}, 82 g C m^{-2} and 44 g C m^{-2} for the three years seasons respectively at the wet sedge. NEE at the heath was 121 g C m^{-2}, 72 g C m^{-2},105 g C m^{-2} and 119 g C m^{-2} for the four winter seasons respectively. Annual budgets at the heath were 21 g C m^{-2} , 51 g C m^{-2} and 61 g C m^{-2}. Here it could be seen that there was a large variation between the years and the numbers here were higher than at the tundra in Svalbard (Lüers et al. 2014). The emissions and uptake here also fitted better with the numbers obtained in this study.

The wintertime CO_2 balance for a fen in northern Finland was also found to be important in the annual carbon budget with a higher total number of CO_2 flux in the winter than the total annual flux (Aurela et al. 2002). The study area was a wet mesotrophic fen with a moderate fertility and no permafrost that had a low but steady emission during the winter. For the same fen the winter time efflux was measured to be between 23-26 g C m^{-2} that also was an substantial part of the annual budget (Aurela et al. 2004). The mean total uptake of a year was -22 g C m^{-2} based on measurements from six years. These are lower values than for the two years in Zackenberg even if the fen in Finland was wet which usually have a high rate of NEE (Lund et al. 2012).

Comparing with the NEE budget from the heath in Zackenberg (Groendahl et al. 2007) the fen had higher flux values. For the heath over the 80 day summer period NEE in 1997 was -1.4 g C m^{-2} and in 2003 it was -23.3 g C m^{-2}. There was however a big difference between the years which are in line with the fen. The heath in Zackenberg has lower fluxes compared to the fen due to more biomass and wetter conditions in the fen area.

The importance of wintertime flux on an annual basis is greatest for ecosystems further north due to their longer winter period (Wang et al. 2011). This is why it is especially important to include winter time in the Arctic.

5.3 Environmental controls on NEE

5.3.1 Temperature

Both the air and the soil temperature fitted the Van't Hoffs exponential function well for the early winter seasons. This was in accordance with other studies that showed that CO_2 flux (respiration) was expected to respond exponentially to temperatures (Lund et al. 2007; Lindroth et al. 2007). However for the rest of the winter periods the fit was not as good. For the air temperature this could be explained by the much lower flux in the dark and late winter which made it hard to see any strong relations maybe caused by the noise here being bigger in proportion to the flux.

For the dark winter 2013/2014 there was some negative NEE values and it seemed that data from the dark winter 2013/2014 was more variable than the other data. Removing the negative values would have destroyed the balance between too negative and too positive values. The high variability may be due to measurement uncertainties.

For four north European mires air temperature was found to be the most important factor in explaining the variation in CO_2 flux when using mean half-monthly nighttime rates. The night time respiration was fitted to the exponential function by Lloyed 1994 and showed a very good fit. The fit was also tested using the measured half hourly values which gave a very bad fit with temperature (Lindroth et al. 2007). For the analysis in this report mean daily NEE and temperature values was used. However the analysis was also done with half hourly values which gave a much lower fit to the exponential equation (lower R^2). For the study of four northern European mires the uptake of CO_2 were expected to increase as a response to increased temperature (Lindroth et al. 2007).

The R_2 in the early winter for soil temperature was lower than for air temperature which means that air temperature fitted the exponential curve best. For the soil temperature the high emissions at temperatures around zero had a big part in the exponential function. The negative flux in the dark winter 2013/2014 was likely due to measurement errors and should be neglected since there should be no CO_2 uptake in the dark winter.

As Van't Hoffs exponential function mainly are used for respiration- temperature dependence this can be the reason why summer time R^2 values are low (photosynthesis is going on). In the early winter there may also be some photosynthesis still going on giving different results than if only respiration would have been used.

In this study for the fen in Zackenberg the best NEE soil temperature (-10 cm) dependence was found in early winter. This was also found for a fen in northern Finland (Aurela et al. 2002), however the correlation there was seen with the soil surface temperature (-3cm). The flux was thought to be produced in the very top soil and decreased further into the winter. Several environmental variables were tested for the same fen (from 1997-2002) and the best correlation was found with air temperature in spring time. There were also a good correlation with the day of snowmelt (a linear relationship) (Aurela et al. 2004). When the non-growing season started (September- December) the air temperature was also the controlling factor over CO_2 flux. In February to March the soil temperature started to dominate as there was a thick snow pack. Regarding the results from Zackenberg there were no correlation with soil temperature and NEE in the late and dark winter which could be expected since the soil is no longer in contact with the air but only the soil.

Chamber measurements were done on a fen in North Hampton, USA during winter time and a significant correlation between mean winter ground temperature (-5 cm) and mean NEE for all locations of the chambers were found (Bubier et al. 2002). This correlation what linear with an R^2 of 0.61; $p<0.01$.The ground was snow covered and soil temperatures varied less than with bare ground (+2 to -6 °C). The largest flux of CO_2 was around temperatures close to zero. This pattern can also be seen in the early winter for data in this report. During snow storms and low pressure there was also a high CO_2 flux from the fen in North Hampton. This was thought to be caused by a greater diffusion rate at the low pressure event that released stored CO_2 (Bubier et al. 2002).

Wang et al. 2011 also found that temperature had a great influence on winter time respiration over a big range of northern ecosystems (Wang et al. 2011). However the samples of Arctic ecosystems were limited.

During the thawing period of 1997 in Zackenberg, chamber measurements for one hummocky and one continuously fen showed a positive correlation between NEE and air temperature. There was also a correlation with thaw depth and in some areas with the water table depth (Christensen et al. 2000) showing that other factors than the ones analyzed in this report have an effect on NEE. In the summer time NEE correlated with photosynthesis which is a good example of autocorrelation.

CO_2 exchange was studied for 12 northern tundra and peat sites where ecosystems with a high photosynthesis were strong CO_2 sinks. The variation in ecosystem respiration was associated with air temperature, growing season period, growing degree days, NDVI and vapour pressure deficit (Lund et al, 2010). For the summertime in this study soil temperature had the highest significant correlation with NEE ($p<0.001$) followed by air temperature.

It was found that temperature at 5 cm depth explained the half-hourly nighttime NEE variability by 48 % during snow free conditions at a peatland in Canada. Regarding wintertime it was suggested for this ecosystem that respiration continued in the soil producing CO_2 and that this production was more important than already produced CO_2 that at some points were escaping from the snow (Lafleur et al. 2001).

From the heath in Zackenberg it was argued that the air temperature and the time of snow melt during the growing season strongly influenced the interannual variation in CO_2 flux. Furthermore cold and rainy weather events in the summer time influenced the flux by changing the usual uptake of CO_2 to a release instead in these periods (Groendahl et al. 2007). It was also found that photosynthesis was more important than respiration for the variation of fluxes between the years.

Regarding summertime flux a strong negative relationship with air and soil temperature was seen in summer 2013/2014 which agrees with a study in Svalbard (Lloyd 2001). In 2012/2013 there was also a negative correlation but not as strong. In Svalbard there was also a strong correlation with solar radiation but in this study no strong correlation with PAR could be seen.

5.3.2 PAR

From the data analysis in this report it could only be seen that in general when there was higher PAR there was a higher flux (in both directions) especially in the summer when there was a negative flux. In the early winter both flux and PAR were so low that no clear correlation could be seen. In the late winter (which in 2014 reached into June) PAR values were obviously higher and NEE started to be higher both in emission and uptake. However PAR must have some effect on NEE since photosynthesis needs solar radiation to function. In the autumn PAR decreased and respiration was starting to dominate. Less radiation meant lower temperatures that effected respiration meaning that PAR has an indirect effect on NEE.

In the springtime the snow cover inhibits incoming radiation to reach plants and no significant correlation with PAR was seen here. Under the thawing period of 1997 in Zackenberg, chamber measurements on one hummocky and one continuously fen showed a poor correlation with PAR and NEE (and photosynthesis) (Christensen et al. 2000).

In the dark winter during the polar night there is no PAR and in the absence of radiation other factors must govern CO_2 flux in this period. In summer time PAR should be a more dominating factor which also was shown from the results of this study (when there was higher PAR NEE was negative in summer). There was also a daily pattern in PAR with more incoming radiation in the middle of the day. For the end of the cold season NEE flux was found to follow PAR closely over the day in a tundra ecosystem in Alaska (Oechel et al. 1997).

In the summer time the daily flux was correlated to PAR for the peatland Mer Bleue in Canada. The statistical analysis showed one of the strongest correlations between PAR and flux in summer; however the correlation with air temperature was higher (Lafleur et al. 2001). PAR seems to be an important factor for NEE and have the highest impact in summer and early winter.

Vourlitis and Oechel 1999 also showed that daily variation of CO_2 flux was a function of PAR in an Alaskan tussock tundra ecosystem (Vourlitis and Oechel 1999).

5.3.3 Snow depth and snow temperature

Snow has an insulating effect on the ground and prevents heat losses from the soils which keeps temperatures higher and make soil respiration possible for a longer time. Snow also prevents CO_2 from being released from the soil and pockets in the snow can store high CO_2 concentrations until it is out blown by the wind. The soil thickness, porosity and the properties of the snow surface will have an impact on the pocket formation. In a tundra ecosystem in Alaska, winter NEE (November – April) was found to be negatively correlated with snow depth (Euskirchen et al. 2012).

In this study the only clear correlation could be seen in the dark winter 2012/2013 when there was a positive relationship between snow depth and NEE; the deeper snow depth, the higher CO_2 emission. On the other hand in general there seem to be a negative relationship where a little snow cover means higher CO_2 emissions. The two snow seasons in this study are very different regarding snow depth and snow period and the graphs reflects this difference. The snow season 2012/2013 had lower CO_2 flux over 5 cm snow depths which could have been due to the trapping of CO_2. This is also the case for 2013/2014 and it may be that as little snow as up to 5 cm had very little effect on the ongoing respiration in the soil. Also based on the assumption that snow traps CO_2 there was very little flux when there was the highest snow depth in 2013/2014.

The impact of increased snow depth on CO_2 flux has been modeled in the high Arctic where including the snowpack in the model caused a higher release of CO_2. For latitudes north of 30º during the time period November to March there was a higher release of CO_2 and a greater uptake of CO_2 in the period between June and August. This increase in CO_2 during the non-growing season was thought to be caused by the insulating effect of the snow pack (McGuire et al. 2000).

Snow fences were set up in a tundra site in Alaska and the impact of increased snow depth tested (Welker et al. 2000). The result showed that a deeper snow pack increased CO_2 efflux but in summer time there were decreased efflux as a consequence. An increase in both deeper snow pack and warmer summer temperatures will almost double the annual amount of CO_2 for this tundra site. How NEE will be affected of higher temperatures and increased snowpack at different sites in the Arctic were not exactly clear from this study. However, it was clear that snowpack depth and time of snow cover affected the winter and spring time respiration and as a consequence affected the CO_2 budget over the year (Lund et al. 2012; Welker et al. 2000).

Increased snow depth were also tested in North Western Greenland and showed no linear response to different heights of snow depth (Rogers et al. 2011). However a bigger snow pack in the winter increased CO_2 efflux. A change in snow depth will change NEE, but the carbon flux may be in both directions. An increase in snow depth of 0.25 meter increased Gross Ecosystem

Photosynthesis (GEP) but did not increase ecosystem respiration. An increase in snow cover with additionally 0.75 meter increased both GEP and ecosystem respiration. Increased snow accumulation in winter time will influence physical parameters like soil nutrient availability and leaf nitrogen concentrations both over the winter and in the growing season (Rogers et al. 2011).

Snowpack was found to have an important influence on wintertime fluxes as well as the annual NEE budget in a study in Spitsbergen, Svalbard. When there were rapid changes in meteorological conditions seen by pressure changes and/ or higher wind speeds a rapid release of CO_2 was seen from the snowpack in wintertime (Lüers et al. 2014). The study concluded that the snow cover was important for storing and releasing CO_2 that had been stored in the snow pack from soil respiration in the late season. This was in line with Bubier et al, 2002 that also found that snow depth and the time of snow cover was important for CO_2 flux (Bubier et al. 2002).

Snow is also coupled to the CO_2 outburst in spring and this was seen in a subarctic peatland, Abisko, Sweden, where almost no flux during the winter season rose to 1.8 C m^{-2} day^{-1}. This release was probably due to trapped CO_2 in the soil that was released when the snow started to melt (Friborg et al. 1997).

A study in Canada point at the complex variability in CO_2 exchange in the Arctic and could not find a significant relationship with snow melt date and the annual NEP as a result of snow melt date (Humphreys and Lafleur 2011).

The effect of the length of the snow season and snow depth seem to have different effects on NEE and so were also the results from this study where it was both a positive and negative correlation. It is clear that snow has an impact but uncertain exactly how.

5.3.4 Other environmental controls

Other factors than the ones analyzed in this report may influence NEE. Meteorological conditions were found to affected CO_2 flux over a shorter time scale (Vourlitis and Oechel 1999), but it was found that on a seasonal trend the uptake of CO_2 was governed by ecosystem phenology.

In a study in Spitsbergen, Svalbard the small but consistent CO_2 emissions over wintertime stopped around January (Lüers et al. 2014) . This was thought to be because respiration stopped due to the low organic content in the soil. This can be compared with a study in Alaska where the respiration continued during the whole winter season but has a much more organic rich soil (Euskirchen et al. 2012). The CO_2 emissions from the fen in Zackenberg continued over the whole season reflecting the high productivity in this ecosystem. In Spitsbergen, the wintertime NEE was found to be positively correlated with wind speed and atmospheric pressure that released CO_2 from within the snow (Euskirchen et al. 2012).

5.3.5 Carbon flux in the future

As the Arctic peatlands store huge amounts of carbon, the future climate change is of great importance due to the release/uptake of CO_2. Studies indicate that the system may switch from being a net sink to a net source of CO_2 (Oechel and Vourlitis 1994) caused by increased temperatures. A study conducted in Alaska showed that a tundra now has switched to a net source of CO_2 (Oechel et al. 1993). It was believed that this source of carbon will have a positive feedback on climate change where higher CO_2 concentrations will lead to higher temperatures and this will in turn cause a greater release of CO_2. The warmer temperatures will have an indirect effect caused by a decrease in the water table depth and greater drainage that increases CO_2 emissions.

Data from 1960-1998 suggest that the ecosystems can acclimate to observed warming in the arctic in the summer period (Oechel et al. 2000). These adaptations include changes in the nutrient cycling, physiological changes and changes in population and communities. This was concluded when the studied ecosystem went back from being a source to a sink after a warming period. Regarding winter time fluxes, most studies show a release which makes the ecosystem a source of CO_2 on a net annual exchange basis.

Climate change means rising temperatures including the Zackenberg area which may extend the growing period as a result of an earlier snowmelt. In a study at the heath in Zackenberg it was seen that the CO_2 uptake in summer will be 0.16 g C m^{-2} higher with an extra growing degree day (GDD) in a year (Groendahl et al. 2007). GDD was shown to regulate the time when the tundra ecosystem in Alaska changed from a net source to a net sink of CO_2 in the spring time (Euskirchen et al. 2012). A higher number of GDD over the year will favor an earlier uptake of carbon by photosynthesis but in the end of the growing season respiration will be favored to a greater extent, meaning release of CO_2 instead of a longer uptake (photosynthesis is lowered due to lower insolation).

The environmental controls on carbon flux in the Arctic tundra were modeled for different time scales under a simulated warming scenario (Stieglitz et al. 2000). Meteorological factors were found to affect CO_2 flux on a shorter time scale. On a medium time scale the controlling factor was the ecosystems ability to retain labile nitrogen. For a longer time period the adaptation of the ecosystem by changes in leaf nitrogen and leaf area index (LAI) was of the greatest importance. However, to be able to draw any certain conclusions of how NEE will be affected by climate change, longer time series simulation have to be modeled. In this study it can’t be said if the Arctic tundra will act as a source or a sink to warmer climate.

Other studies have shown different responses for photosynthesis and respiration to warmer temperatures (Oechel et al. 1997; Zimov et al. 1996). For example, for a tundra ecosystem in Alaska, an increase in carbon flux to the atmosphere in the early season was caused by increased soil temperatures, soil aeration and thaw depth (Oechel et al. 1993).

Not only CO_2 are important for studying carbon flux in the future but also methane (CH_4), which is a stronger greenhouse gas, for which the Arctic constitutes an important source. The emissions of CH_4 are complex but are affected by soil moisture, temperature, organic matter, and vegetation (Oechel and Vourlitis 1994). An increase in CO_2 may on the long term increase photosynthesis, but plants in the Arctic are restricted by the availability of nutrients and can therefore not benefit from higher concentrations under those circumstances (Oechel and Vourlitis 1994). Soil moisture is also thought to be an important factor for NEE in the Arctic.

5.4 Reliability of the results

There are uncertainties in the eddy covariance technique since it works best under steady environmental conditions (like wind, temperature, humidity and CO_2) and flat terrain (Baldocchi 2003). In the study area in Zackenberg the terrain is very flat and uniform but the environmental conditions can change rapidly, for example caused by Föhn winds during the winter time. Studies show that for a nearly ideal site the error of the net annual exchange is less than ±50 g C m^{-2} yr^{-1} (Baldocchi 2003). From a bog peatland in Canada the error in NEE for a year was ±68 g CO_2 m^{-2} $yr^{-1}$with a total integrated annual uptake of 248 g CO_2 m^{-2} yr^{-1}. However, the interannual variability for that study area was not well known (Lafleur et al. 2001). Having long time series of data and averaging over days to years will reduce errors to smaller values (Baldocchi 2003). Due to these uncertainties it is important with a robust quality check of eddy covariance data.

As an alternative to eddy covariance are the chamber and cuvette techniques but they do not catch CO_2 flux on an ecosystem scale and are therefore not suitable for the purpose of this study.

The settings in EddyPro will affect the flux values obtained after the run of the program. The Gill height depending on snow depth could have been adjusted more often; however the results were not affected that much by the different Gill heights. Different values could also have been used for the quality check, for example the range for acceptable CO_2 values in the air (ppm) which might have had some minor influence on the resulting fluxes.

Also the method for removing outliers from the data could have been more precise by calculating standard deviations for shorter time periods. To make it simple in this study the periods were chosen to be the same as the ones for calculating the flux (early-, dark-, late winter and summer).

Since the daily means was calculated with all available values even if there was just a few, the mean value may have differed a bit from the real. A way could have been to calculate the mean only for those days with a minimum of for a certain number of values.

Missing data had to be filled for making a budget and here the values could have been more precise. There are different methods for gap filling and they are usually based on statistical and empirical models (Baldocchi 2003). An empirical technique with different phenological models for day- respectively nighttime was used (Lafleur et al. 2001). For the program used in this study the larger the window size the more days away the program looks at the meteorological data. Furthermore in the data there was a big gap from December 2012 to February 2013 and here the fluxes were set to be the same for the whole period and are therefore not correct, probably the flux is overestimated. However the fluxes in this period were low since it was during the polar night with cold and dark climate. However, since the focus in this report was on winter time fluxes it would have been useful to have less missing data.

The seasonality was chosen regarding the time when temperature was below zero in the autumn and the day of snow melt in the spring, but could have been chosen differently, for example using PAR instead. Other studies have used different time periods for calculating budgets depending on data availability and question of issue.

The statistical analysis was done with Pearson's correlation that should be used for data that are normally distributed. Here the data was assumed to be normally distributed based on visual inspection of data histograms. In the analysis there were autocorrelation in time between the data sets that were ignored. There are always uncertainties with statistical analysis. There were also autocorrelation with the data, since a measured value are likely to be related to the next value 30 minutes later. This may lead to an overestimation of the significance.

The magnitude of flux in the winter 2013/2014 were higher than in the winter 2012/2013 meaning higher variability in data. However both negative and positive flux was higher in 2013/2014 and consequently cancelled out each other leading to a low flux when summed up.

5.5 Future perspectives

Long time series is needed to be able to draw reliable conclusions for the future. Two years of data that are used here is certainly not enough. Modeling fluxes based on measured data are a key tool for simulating future scenarios. Winter time fluxes as well as all fluxes over the year have to be included in the estimations since they are important for the annual budget.

This study gives the budget for these two years and examines the factors that affect CO_2 flux for this area. Correlations with more climatic factors could have been performed to extend the study for example with thaw depth, water table depth, humidity, wind, day of snow melt. Other researchers have tested for other controlling factors like LAI and GDD, other time periods and other places in the Arctic. It was for example shown that the largest emissions of CO_2 occurred from the snow cover when the air pressure declined (Bubier et al. 2002). Also an estimation of GPP and ecosystem respiration would have been interesting. All these data have to be used together with more research to be able to understand how the Arctic will react to climate change in the future.

6. Conclusion

Wintertime CO_2 flux was found to be important on a net annual exchange basis since there was a low but steady emission over a long time period. In this report winter time was defined as the beginning of September for both years to 25th of May in 2013 respectively 22th of June in 2014, which is around nine months, and summer time when there was a net uptake of CO_2 (photosynthesis) was only around three months. Winter time flux varied between the two years but the winter time flux for both years stood for a substantial amount of that whole year's total NEE budget. The part of the winter time flux was highest for the year 2012/2013 compared with the year 2013/2014.

The land-atmosphere exchange (NEE) of CO_2 during wintertime in 2012/2013 was 67.7 g C m^{-2} and for winter time in 2013/2014 it was 31.4 g C m^{-2}. For the early winter 2012 NEE was 34.8 g C m^{-2} and in 2013 NEE was 21.5 g C m^{-2}. For the dark winter 2012/2013 NEE was 23.1 g C m-2 and for 2013/2014 0.1 g C m^{-2}. For the late winter 2013 NEE was 9.2 g C m^{-2} and for late winter 2014 9.8 g C m^{-2}.

The land-atmosphere exchange of CO_2 for the whole year 2012/2013 was -39.2 g C m^{-2} and for the year 2013/2014 it was -120.0 g C m^{-2} which means an uptake for both years. Summer time NEE was -103.4 g C m^{-2} for 2013 and -154.9 g C m^{-2} for the summer 2014.

Air temperature, PAR, soil temperature and snow depth are factors that affected CO_2 flux during wintertime but no clear relationship could be seen with snow temperature. Seasonality (i.e. early winter, dark winter, late winter) clearly has an impact on the relationship between carbon flux and the driving variables.

The strongest relationships between NEE and environmental variables were in the early winter for both years. Here NEE increased exponentially with air temperature and soil temperature (-10 cm) but the relationship was strongest with air temperature. There was also a strong statistical significance ($p<0.001$) and a high Pearson's correlation coefficient for early winter in both years (air temperature 2012: R^2= 0.783 and 2013: R^2= 0.687) and soil temperature 2012: R^2= 0.428 and 2013: R^2= 0.475).

Also PAR had the highest Pearson's correlation coefficient in the early summer and a positive relationship with NEE (except for summer). Snow depth correlated negatively in the early winter, meaning a higher snow depth gave a lower flux. In dark winter 2012/2013 the relationship switched to positive. In 2013/2014 the relationship continued to be negative.

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