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Temperature and snow-melt controls on interannual variability in carbon exchange in the high Arctic

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With 6 Figures

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Summary

Net Ecosystem CO_2 Exchange (NEE) was studied during the summer season (June–August) at a high Arctic heath ecosystem for 5 years in Zackenberg, NE Greenland. Integrated over the 80 day summer season, the heath is presently a sink ranging from $-1.4\,\mathrm{g\,C\,m^{-2}}$ in 1997 to $-23.3\,\mathrm{g\,C\,m^{-2}}$ in 2003. The results indicate that photosynthesis might be more variable than ecosystem respiration on the seasonal timescale. The years focused on in this paper differ climatically, which is reflected in the measured fluxes. The environmental conditions during the five years strongly indicated that time of snow-melt and air temperature during the growing season are closely related to the interannual variation in the measured fluxes of CO_2 at the heath. Our estimates suggest that net ecosystem CO_2 uptake is enhanced by $0.16\,\mathrm{g\,C\,m^{-2}}$ per increase in growing degree-days during the period of growth. This study emphasises that increased summer time air temperatures are favourable for this particular ecosystem in terms of carbon accumulation.

1. Introduction

According to Maxwell (1992) climate change is expected to be most pronounced in the Arctic areas. The recent focus from ACIA (Arctic Climate Impact Assessment) and IPCC (Intergovernmental Panel on Climate Change) has added to the awareness of the effects of the increasing global temperature on the Arctic ecosystems. During the last century the land surface temperature (north of 60° N) has increased by approximately 0.9 °C (McBean et al., 2004) and the scenarios from IPCC expect the Arctic ecosystems to experience changes due to increasing temperature and precipitation in the future (IPCC, 2001). Moreover model studies reveal large geographical variations in the Arctic region in annual temperature response to predicted global warming and in NE Greenland, projected annual surface temperature, is expected to increase between +2 to +4 °C during the period 1990 to 2090 (Huntington et al., 2004).

How the terrestrial ecosystems in the high Arctic regions respond to change in temperature is not well known, and the scarcity of data, especially from the High Arctic, causes difficulties in predicting whether these areas are sources or sinks of CO_2. However, some predictions on how the Arctic region will be affected by climate change have been proposed. If increased temperatures cause earlier snow-melt, the onset of vegetation growth will occur earlier in spring. This might extend the length of the growing season and probably increase carbon sequestration, as in temperate forests, where an average increase in CO_2 uptake of $5.7\,\mathrm{g\,C\,m^{-2}}$ per day in growing season was found by Baldocchi et al.

(2001). Conversely, if precipitation increases in the form of snow, timing of snow free conditions might decrease the growing season, hence carbon sequestration might decrease (Petersen et al., 2001). Areas underlain by permafrost are, in particular, sensitive to increased warming, as increased active layer depth is likely to increase respiratory release of carbon dioxide from the soil (Maxwell, 1992). An understanding of the responses to the predicted temperature rise and increased active layer depth in the region is needed in order to predict the future status of the carbon balance in the Arctic region. According to Jonasson et al. (2001) differences of 1–2 weeks in time of snow-melt or growing season mean temperature differences of less than 1 °C are very significant for carbon sequestration in the Arctic ecosystems. Similarly, Shaver and Kummerow (1992) argued that the major factor controlling the onset of growth interannually in the arctic ecosystems is the timing of snow-melt and above-freezing temperatures.

During the past years, there has been a focus on whether the circumpolar tundra ecosystems, constitutes a source or a sink for CO_2. While the majority of these studies have been carried out in wet and moist ecosystems in the low Arctic region, such as Alaska and Siberia (Oechel et al., 1993, 1995; Oechel and Vourlitis, 1994; Vourlitis and Oechel, 1997, 1999; Harazono et al., 1998, 2003; Heikkinen et al., 2002), while dry ecosystems in the Arctic have been less investigated (Jones et al., 1998). The High Arctic is an important part of the Arctic region, according to data from Bliss and Matveyeva (1992), the ice-free part of the High Arctic covers an area of approximately $2.4{*}10^6\,km^2$, which constitutes 42% of dry ecosystems (semi-desert and polar desert). During the last decade the high Arctic region in Greenland has been subjected to studies on the carbon balance during the growing season, in Zackenberg, NE Greenland (Christensen et al., 2000; Illeris et al., 2003; Nordstroem et al., 2001; Soegaard and Nordstroem, 1999; Soegaard et al., 2000). In addition, carbon dioxide fluxes from a High Arctic dry ecosystem in Svalbard have been presented (Lloyd, 2001a, b).

Reported measurements of carbon dioxide flux in Arctic ecosystems during the last three decades have given a diverse picture of the C-balance in the region (Stieglitz et al., 2000). Oechel et al. (1995) showed that a wet sedge ecosystem in Alaska changed from a sink to a source during the period 1971 to 1992. Results from the entire Kuparuk River Basin in 1995–1996 showed that the area was a net CO_2 source of 218.1 GgC (Oechel et al., 2000).

However, in the recent decade, measurements from a moist tussock tundra ecosystem in Alaska indicates that the ecosystem is now a net sink (Vourlitis and Oechel, 1997, 1999). These results imply large differences between ecosystem types and sensitivity even to small changes in climate. Hence, it seems that the impact of climatic change might vary between ecosystems and the interannual responses of the ecosystem to the variation is diverse, resulting in the ecosystem being a net source of CO_2 one year and a net sink of CO_2 the next year (Oechel et al., 1993; Zimov et al., 1996; Vourlitis and Oechel, 1997, 1999; Stieglitz et al., 2000). Hence, an understanding of the factors controlling the flux of carbon from arctic areas is essential for predicting how these regions will respond to global change (Hobbie et al., 2000).

In order to achieve broader knowledge on carbon exchange in the High Arctic, micrometeorological measurements were initiated in Zackenberg in 1997 (Soegaard et al., 2000). Carbon fluxes have been monitored every summer since 2000, contributing to the evaluation on the climatic response of a high Arctic dry heath ecosystem by providing a time series of CO_2 flux data.

This paper presents the Net Ecosystem Exchange (NEE) from the high Arctic dry heath ecosystem in Zackenberg, measured using the eddy covariance technique, during the period from early June until late August. We investigated the temperature impact on the carbon balance of a dry heath ecosystem, expecting temperature to constrain the carbon exchange.

2. Methods and materials

2.1 Site description

The Zackenberg research area (74°28′N, 20°34′W) is located in the north-eastern part of Greenland. According to Bliss and Matveyeva (1992) the area is within the High Arctic zone characterised by a mean temperature below 5 °C in July and annual precipitation varying from 148–236 mm water equivalent (Rasch and Caning, 2003).

The area of the low-lying part of Zackenberg valley (below 200 m.) is approximately 17 km^2. The valley consists of three dominating ecosystem types: fen, willow snowbed and heath. The heath ecosystem covers approximately 5.5 km^2 corresponding to 31% of the valley (Soegaard et al., 2000). The plant coverage on the heath is sparse, *Cassiope tetragona* (White Arctic Bell-heather), *Dryas integrifolia* (Mountain Avens) and *Vaccinium uliginosum* (Arctic blueberry) dominate the heath ecosystem, accompanied by patches of mosses, *Salix artica* (Arctic willow) and *Eriophorum scheuchzeri* (Cotton grass). This vegetation composition is floristically representative for large parts of NE Greenland. Maximum single-sided Leaf Area Index (LAI) reached 0.2–0.3 at the heath during the peak of the growing season, whereas in the moist ecosystems in the valley it may reach 1–2 (Soegaard et al., 2000).

The valley has a northern border at a narrow pass and a fjord to the south. The eastern and western parts of the valley are bound by mountain ridges with altitudes of approximately 1500 m. The topographic impact on the local wind is seen from the dominating wind direction. NNW winds are dominant most of the year. In summer, from June to August, the wind direction is SSE. Land sea breeze occurs throughout the summer. Summer wind velocities ranges from 3–4 ms^{-1}.

The area is underlain by permafrost, which disintegrates during the summer season, and the activelayer at the heath increases to approximately 70 cm. Soil temperatures above zero are found from mid June until late August.

2.2 Measurements

In the five years 1997, 2000–2003, micrometeorological measurements of CO_2 exchange were conducted from the first week in June, while snow still covered the surface until the last week in August. Thus, the measurements included the entire growing season at this site. The study site at the heath was established in 1997 (Soegaard et al., 2000). In the period from 2000 onwards measurements were conducted every summer within the ZERO (Zackenberg Ecological Research Operations) programme.

2.3 Instrumentation

As described by Soegaard et al. (2000) CO_2 exchange was monitored by the eddy covariance technique. A mast is equipped with a 3D sonic anemometer, Solent 1012R2 (Gill Instruments, Lymington, United Kingdom) placed 3 m above the surface and a closed-path infrared gasanalyser (Licor 6262, LI-COR, Nebraska, USA). Raw data from the system was logged at 21 Hz on a portable computer equipped with the EdiSol software (Moncrieff et al., 1997). For post-processing of the fluxes a 200 s running mean of wind and scalar components were used and windspeeds were axis rotated in order to prevent flow distortion/effects on the vertical wind speed from landscape obstacles and misalignment of the anemometer according to Mcmillen (1988). Fluxes were calculated as 30-min averages. Corrections in the fluxes were applied for frequency loss (Moore, 1986), attenuation of the CO_2 signal in the tube and effects of water vapour on the CO_2 signal (Webb et al., 1980). A detailed description of the instrumental setup, flux calculation and correction routines can be found in Moncrieff et al. (1997). Typical errors for this instrumental setup under the climatic conditions in Zackenberg were according to Soegaard et al. (2000) found to be ±7% of NEE or ±7 mg CO_2 m^{-2} h^{-1} during mid-season in the present study.

A total of 80 days are reported here from each season. Gaps originating from instrumental malfunctioning, equipment maintenance and calibration resulted in 8.9% of the data was missing in 1997, 0.8% in 2000, 1.4% in 2001, 0.9% in 2002, and 2.4% in 2003. Gap-filling was performed in accordance with Falge et al. (2001); gaps <2 h were filled by linear interpolation between earlier and later measurements. Longer time periods were filled by binned half-hourly values computed from a 6-days period surrounding the gap.

The energy balance components during the time of snow-free conditions (July to August) for the heath site is composed of the sensible, latent and ground heat fluxes. During this period, the energy balance closure resulted in a negative residual that, on average, during the five years constituted 9% of the net radiation.

The eddy covariance mast was located at the *Cassiope t.* dominated heath with a fetch of approximately 1000 m in all directions. The permanent climate station, approximately 200 m SSW of the eddy covariance mast, supplied the additional meteorological data such as air temperature at 2 m height, precipitation, net and global radiation. In addition, snow depth and depletion was monitored (SR50 Ultrasonic Sensors, Campbell Scientific, USA) and ortho-photos of the central part of the study area provided snowcover images. Detailed information on the measured variables are found in the ZERO annual report (Rasch and Caning, 2004).

2.4 Flux components

The measured CO_2 flux between an ecosystem and the atmosphere referred to as NEE, is the balance between plant uptake of CO_2 through photosynthesis and respiratory loss of CO_2 from plant and soil (Ruimy et al., 1995)

$$\mathrm{NEE} = (\mathrm{R_a} + \mathrm{R_h} - \mathrm{GEP}) = \mathrm{R_{eco}} - \mathrm{GEP} \qquad (1)$$

where GEP is the gross ecosystem photosynthesis, R_a is the autotrophic respiration consisting of contributions from leaf respiration, respiration from the stem and woody parts of the plants and root respiration. The heterotrophic respiration flux, R_h, derives from the decomposition of organic material by micro-organisms in the soil, also referred to as soil respiration. The sum of the heterotrophic respiration and autotrophic respiration constitutes the total ecosystem respiration, R_{eco}.

2.5 Respiration

In order to determine ecosystem respiration, R_{eco}, we used an empirical exponential relationship between measured CO_2 flux at night-time and the soil temperature. Assuming that the ecosystem respiration response to soil temperature applied at day-time, we used the derived regression models to extrapolate ecosystem respiration to the entire season. The regression models are year specific, i.e. they cannot be applied to other years.

3. Results

3.1 Meteorological conditions during the five years

A summary of air temperature, global radiation and precipitation is presented in Table 1. Large differences were seen between thaw, pre-green, green and the post-green period mean daily air temperatures. The air temperatures in the thaw period 2002 was notably high, 2.2 °C, which was approximately 1 degree higher than the other years. Differences between air temperatures are also seen in the green period, where the mean daily air temperature in 2003 provided a strong contrast to the other years.

Table 1. Monthly average values of global radiation ($\mathrm{W\,m^{-2}}$), air temperature (°C) and precipitation (mm) in 1997, 2000–2003

	1997	2000	2001	2002	2003
	by phenological period and year				
Mean daily air temperature (°C)					
Thaw	1.14	1.3	0.77	2.18	1.22
Pre-green	3.75	3.97	3.5	3.35	3.04
Green	5.47	4.97	5.71	5.93	7.39
Post-green	3.34	5.06	5.9	4.15	5.15
Mean daily global radiation ($\mathrm{W\,m^{-2}}$)					
Thaw	165	303	255	409	284
Pre-green	219	307	293	295	320
Green	207	213	226	181	192
Post-green	180	142	122	117	131
Total precipitation (mm)					
Thaw	22.9	3.2	25.4	73.9	85.2
Pre-green	25.2	0.3	0.2	0	0.3
Green	10.8	13.2	3.8	25.6	9.2
Post-green	0.1	0	11.4	0.5	0.3

In 2002, global radiation levels during the thaw period were high compared to the other years. However, due to periods of poor weather during the green period the average global radiation was below the levels received during the other years in this period.

Precipitation in this high arctic area is characterised by a few very intensive events each summer: on average, 32 mm falls every year from the time when snow has melted in June/July to the end of August. In 1997, the pre-green period was characterised by rain events originating from storms passing the area during July and the green period received precipitation on most days. During the post-green period in 2001 the area received 11.4 mm precipitation, which was a strong contrast to the other years. A wet green period characterised 2002 and the heath received 25.6 mm rain.

Snow depth and day of snow-melt varied between the five years. Snow-melt rates were calculated from the monitored snow depths at DOY 140 (20 May), when global radiation albedo was at a maximum (0.80), indicating that snow had not begun melting. Therefore, we assumed that the densities of the snow packs were identical during the five years. In 1997, snow persisted until DOY 179 which was 10 days longer than 2003. This was attributed primarily to lower air temperatures during the period of melt. We defined the melting potential of the snow from a degree-day model, using the summed hourly air temperatures above −2 °C $((\Sigma T_{a,\,hour} \geq -2\,°C)/24)$. As seen from Fig. 1, the snow depth at DOY 140 correlated strongly with cumulative degree-days, confirming temperature as a significant snow-melt factor. The considerable variation in snowdepth, from 0.48 m to approximately 1 m, resulted in an average melt-rate of 7.4 mm/degree-day amongst the years, which explained 93% of the variation.

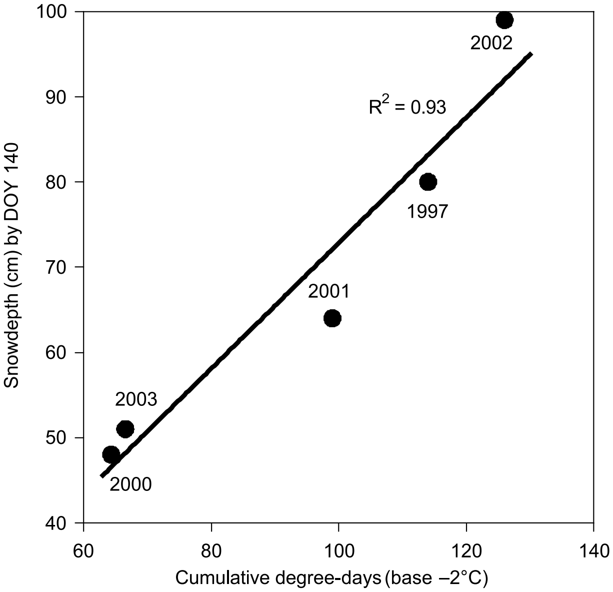

Fig. 1. Snowdepth (cm) at DOY 140 versus the cumulative degree-days with base −2 °C, from DOY 140 until the snow had melted

3.2 Study periods and definition of phenological periods

In this study, data from the years 1997 and 2000–2003 were analysed. Each year, CO_2 fluxes at the heath were measured in the interval from the first week in June until the last week in August, covering the thaw and the growing periods. For comparative purposes, data are presented for all years covering an 80 day season (DOY 159–238) in this study referred to as summer season. The season was divided into 4 periods (Table 2), following the seasonal changes in daily integrated NEE as well as variations in global radiation albedo, temperature and phenological development.

The thaw period was characterised by melting snow cover and during this period the global radiation albedo decreased as the snow progressively melted and soil temperatures increased as a result. This period always showed positive daily NEE values, indicating a respiratory loss of CO_2. The pre-green period was a period of transition, defined from the time when the global radiation albedo was below 0.1 and from visual inspection of photos to determine when the snow had melted in the micrometeorological mast fetch area. During this period air temperatures increased and the daily integrated NEE was positive. However, the vegetation progressively started photosynthesising during the latter part

Table 2. Phenological period for each year in the study

	1997	2000	2001	2002	2003
Day of Year for each phenological period					
Thaw	159–179 (8 June –28 June)	159–169 (7 June–17 June)	159–176 (8 June–25 June)	159–173 (8 June–22 June)	159–168 (8 June–17 June)
Pre-green	180–193 (29 June–12 July)	170–176 (18 June–24 June)	177–187 (26 June–6 July)	174–182 (23 June–1 July)	169–177 (18 June–26 June)
Green	194–233 (13 July–21 August)	177–226 (25 June–13 August)	188–230 (7 July–18 August)	183–227 (2 July–15 August)	178–232 (27 June–20 August)
Post-green	234–238 (22 August–26 August)	227–238 (14 August–25 August)	231–238 (19 August–26 August)	228–238 (16 August–26 August)	233–238 (21 August–26 August)

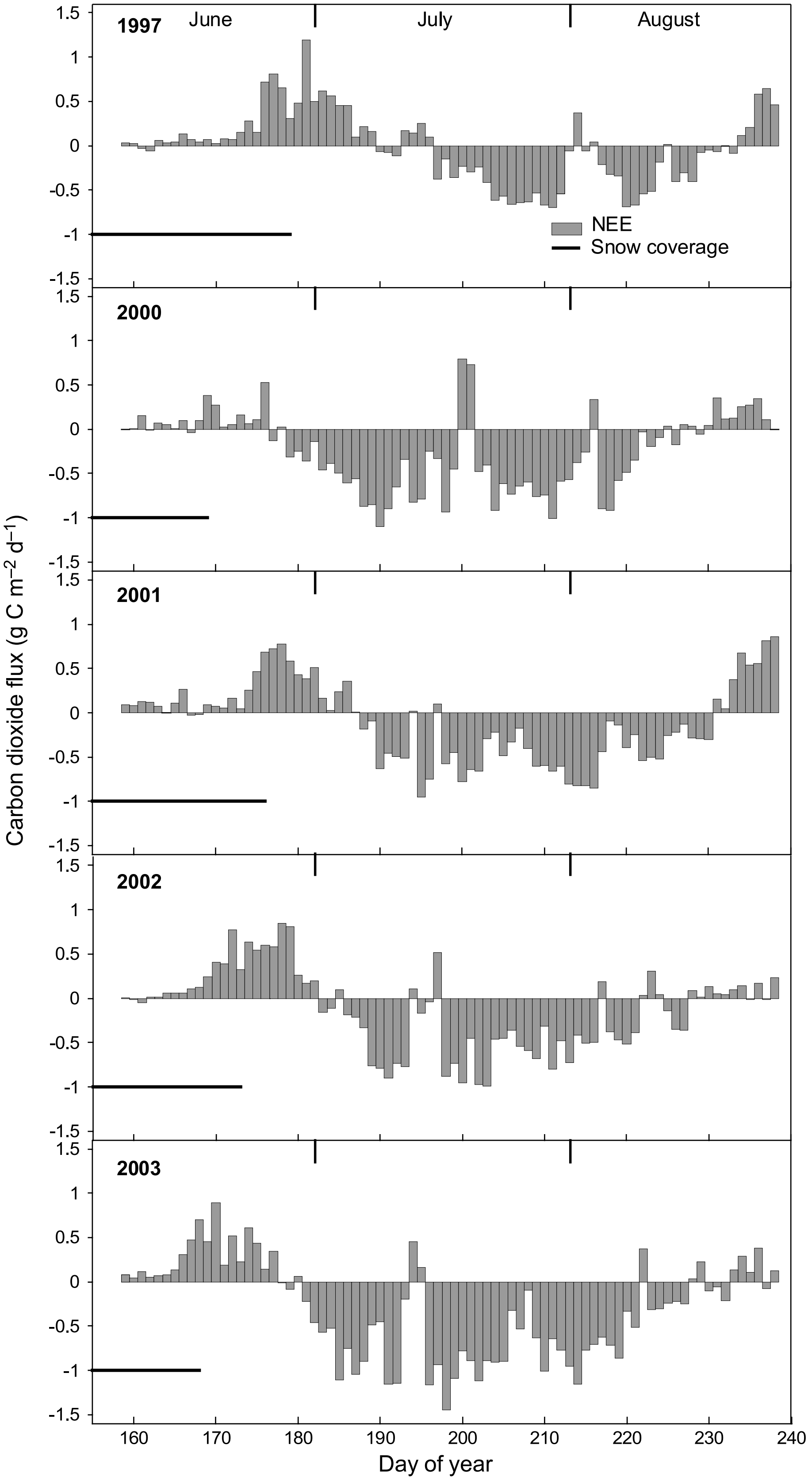

Fig. 2. Daily integrated NEE of carbon dioxide ($g\,C\,m^{-2}\,d^{-1}$) for the years 1997 and 2000–2003

of the period. As daily integrated NEE turned from a net source to a net sink the green period began, this was the period of net growth. During this period the vegetation turned green and the LAI progressively increased to a maximum of approximately 0.3 (Soegaard et al., 2000). The length of the green period varied from five weeks in 1997 to eight weeks in 2003 (Table 1). During the post-green period, the ecosystem respiration exceeded the photosynthesis and daily integrated NEE showed a net loss. This period was characterised by decreasing soil and air temperatures as well as decreasing global radiation levels.

3.3 Net ecosystem exchange

The daily integrated sums of NEE ($\mathrm{g\,C\,m^{-2}\,d^{-1}}$) during the five years of measurements at the heath is seen in Fig. 2. Using the micrometeorological sign convention, downward directed flux of CO_2 from the atmosphere to the surface is negative, denoting an ecosystem sink and thus positive values denote a source of CO_2. Respiratory losses increased as soil temperatures progressively increased.

The seasonal amplitude during the period from June to August is clearly seen in Fig. 2. Respiratory losses of CO_2 during the pre-green and post-green periods delimit the net CO_2 gain during the green period. In 1997 and 2002 the daily average NEE in the pre-green period was $0.5\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$, whereas the pre-green period in 2000 only had a small respiratory loss of $0.2\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$.

In the green period with the strongest sink strength, the average daily integrated NEE ranged between $-0.3\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$ in 1997 and approximately $-0.6\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$ in 2003. Onset of and uptake of CO_2 from the atmosphere varied by three weeks during the five years, whereas the end of the green period varied by only a few days. In 1997 the first day of net uptake was DOY 194 (13 July) and in comparison the uptake of CO_2 began on DOY 177 (25 June) in 2000. The end of the green period varied from DOY 226 (13 August) in 2000 to DOY 232 (20 August) in 2003, which caused a distinct difference in

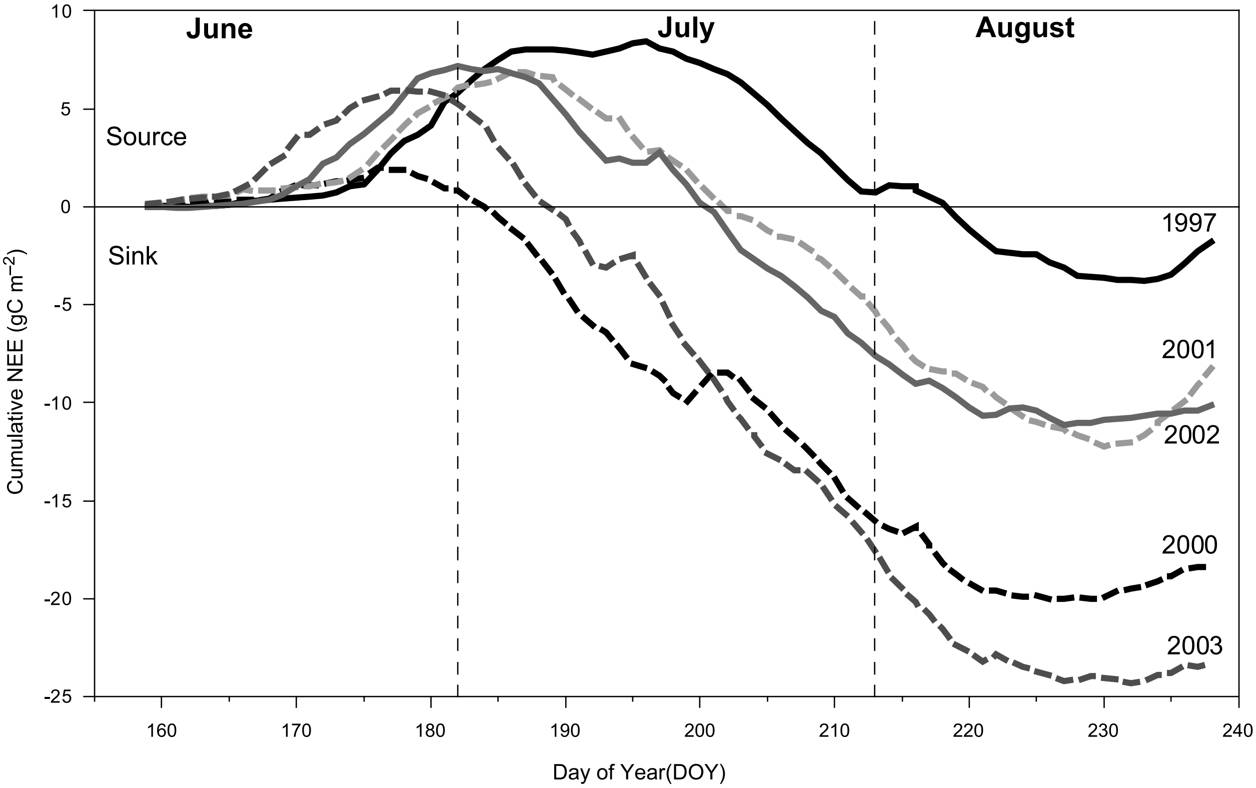

Fig. 3. Growing season cumulative net ecosystem CO_2 exchange ($\mathrm{g\,C\,m^{-2}}$) during 5 seasons of measurements at a high Arctic heath in Zackenberg NE Greenland

the length of the green period of 39 days in 1997 and 54 days in 2003.

Each year, periods of poor weather (usually periods of rain) reversed the fluxes and the ecosystem became a source of CO_2 for a short period.

Maximum daily integrated NEE was seen in the period from DOY 190 to DOY 199, except in 1997, which had a maximum daily integrated uptake at DOY 220 and coincided with the highest daily average air temperatures.

The vegetation senesced during late August and the respiratory losses exceeded the plant uptake of CO_2. NEE during the post-green period varied from daily average losses of 0.06 g C m^{-2} d^{-1} in 2002 up to 0.5 g C m^{-2} d^{-1} in 2001.

3.4 Variation in cumulative NEE

Cumulative net ecosystem CO_2 exchange during the five years of measurements is shown in Fig. 3. During 1997 monitoring period, cumulative NEE showed a net gain of carbon by DOY 238 of −1.4 g C m^{-2}. The large effluxes of CO_2 seen in the pre-green period (Table 3) originated from the high heterotrophic respiration, associated with increasing soil temperatures and release of CO_2 from the thawing soil. Losses increased from DOY 159 until the end of the pre-green period by DOY 196. In the green period, the photosynthesis exceeded R_{eco} and the heath gained −11.4 g C m^{-2} (Table 3). Throughout the post-green period, from DOY 234 until the end of the measurements by DOY 238, the heath lost 2 g C m^{-2}.

Table 3. Cumulative net ecosystem CO_2 exchange (g C m^{-2}) for each phenological period and year

	1997	2000	2001	2002	2003
Thaw	0.7	0.4	1.2	0.4	0.7
Pre-green	7.3	1.6	5.6	6.8	5.3
Green	−11.4	−22.5	−19.1	−18.1	−30.3
Post-green	2.0	1.6	4.0	1.0	1.0
Summer season	−1.4	−18.9	−8.3	−9.9	−23.3

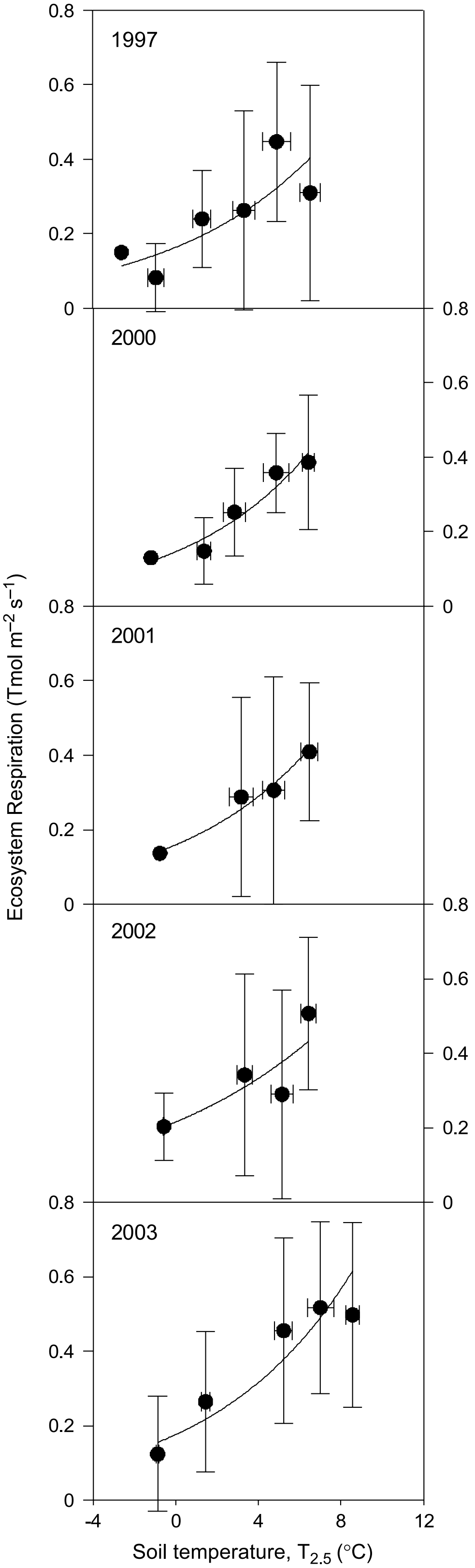

Fig. 4. Estimated ecosystem respiration versus soil temperatures at 0.025 m depth ($T_{2.5}$), during the five years. Exponential regression in 1997 ($0.1637\,e^{0.1388x}$; $R^2 = 0.66$, $p = 0.050$), 2000 ($0.1463\,e^{0.1611x}$; $R^2 = 0.93$, $p = 0.009$), 2001 ($0.1549\,e^{0.149x}$; $R^2 = 0.97$, $p = 0.015$), 2002 ($0.2155\,e^{0.1085x}$; $R^2 = 0.76$, $p = 0.128$), 2003 ($0.1762\,e^{0.1462x}$; $R^2 = 0.88$, $p = 0.017$)

In 2000 the heath gained $-18.9\,\mathrm{g\,C\,m^{-2}}$ in the 80 day measuring period. Photosynthesis exceeded R_{eco} by DOY 177 and photosynthesis remained larger than R_{eco} until DOY 226, except for a few days in July, where poor weather resulted in a small reduction in cumulative NEE. However, the heath remained a net sink of carbon throughout this period.

During the summer season 2001 the heath gained $-8.3\,\mathrm{g\,C\,m^{-2}}$. During the thaw when the microbial activity was low there was a small respiratory release of CO_2 and also in the pre-green seasons the cumulative NEE was positive. The heath had a gain of carbon from DOY 188 until DOY 230, of $-19.1\,\mathrm{g\,C\,m^{-2}}$.

Cumulative net exchange of carbon during 2002 showed a strong similarity to the 2001 season. During the summer season, the heath gained $-9.9\,\mathrm{g\,C\,m^{-2}}$ in total. Following the same pattern as the 2001-season, the heath lost 88% of the total seasonal loss during the thaw and pre-green seasons. By DOY 183 the photosynthesis exceeded R_{eco} and the heath started gaining carbon.

The 2003 season showed some similarity to the 2000 season. However, the loss of $5.3\,\mathrm{g\,C\,m^{-2}}$ through the pre-green period is larger than in the 2000 season. This is accomplished by the gain during the green period, where cumulative gain was $-30.3\,\mathrm{g\,C\,m^{-2}}$. The variation in NEE during this period was closely related to canopy development (Soegaard and Nordstroem, 1999), NEE increased as LAI increased. By the end of the summer season at DOY 239, the net cumulative gain was $-23.3\,\mathrm{g\,C\,m^{-2}}$.

3.5 Ecosystem respiration, R_{eco}

Using the eddy covariance technique, direct measures of ecosystem respiration and photosynthesis are not available. However ecosystem respiration can be estimated from the night time fluxes (Lavigne et al., 1997). Hence, to reveal the ecosystem response to the climatic differences during the five years, the ecosystem respiration and the residual GEP were analysed using parameterisations with a simple empirical regression model.

Figure 4 shows the relationship between ecosystem dark respiration, obtained from night-time eddy covariance measurements during periods of low levels of incident radiation, and soil temperatures at 2.5 cm depth, $T_{2.5}$. Estimating ecosystem respiration from eddy covariance data at a high Arctic site is complicated by the incoming radiation, received 24 hours a day from 1 May until 8 August. Hence we defined night-time as incident short-wave radiation $<20\,\mathrm{W\,m^{-2}}$, assuming photosynthesis to be inactive at this level.

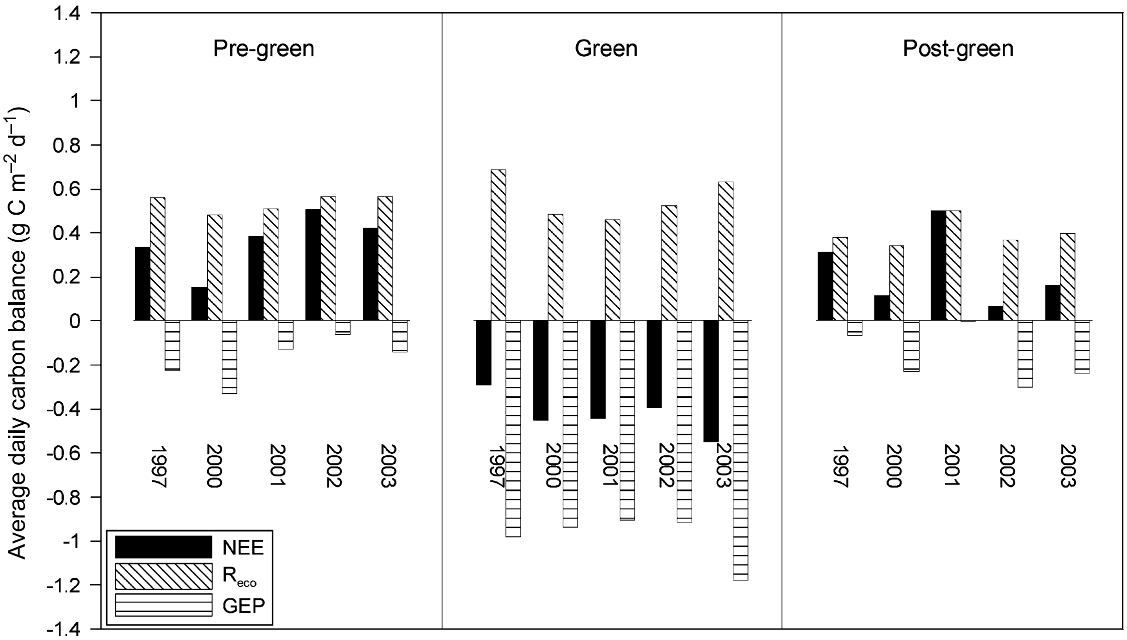

Fig. 5. Average daily NEE, R_{eco} and GEP ($\mathrm{g\,C\,m^{-2}\,d^{-1}}$) for each phenological period and year

Reliable night-time measurements of fluxes require adequate mixing of air. Often low wind speed prevail at night and as such, there might be an inhibition of the mixing (Lavigne et al., 1997). Therefore, we used data from the night-time periods with a friction velocity threshold of $u^* > 0.1\,\mathrm{m\,s^{-1}}$. Due to the length of the day at this high latitude, the criteria used for selecting the appropriate data for the models limited the number of available data ($n = 58$ in 1997; 98 in 2000; 70 in 2001; 65 in 2002 and 145 in 2003). Data available to examine the relationship were scattered, probably due to seasonality in the fluxes, as seen from the standard deviation hence to obtain a clear relationship between soil temperature and nocturnal eddy covariance data, averages of 30-min fluxes were binned in 2 °C intervals (Fig. 4). Soil temperatures in 2.5 cm depth accounted for 66% of the variance of R_{eco} in 1997 and 99% in 2001, which is in accordance with findings from Alaska (Harazono et al., 2003). Models derived for all years were significant at the 0.05-level, except 2002 which was probably due to the limited number of points ($n = 4$). Pearson's correlation showed that the correlation between the obtained models for 2001 and 2003, and 2002 and 2003 were not statistically significant. The derived relations were used to calculate R_{eco} during the growing season for each of the five years. Assuming that the ecosystem respiration during day-time could be estimated by the derived exponential relationships, GEP was estimated as the residual.

Average daily NEE, R_{eco} and GEP for the pre-green, green and post-green period are seen from Fig. 5.

4. Discussion

4.1 Interannual variability in NEE

The results presented here show that there are large interannual differences in net ecosystem CO_2 exchange during the five years of study, which are caused by the variability in climatic conditions. The largest interannual variability in cumulative NEE is found during the post-green period (Table 3). However, the total seasonal cumulative NEE varied approximately 2.5 fold between the seasons 2001 and 2002 compared to 2003, whereas 1997 varied by 12.9 fold (Fig. 3). The interannual variability in NEE is driven by change in the photosynthetic uptake of the dwarf shrubs and respiratory loss by the ecosystem. The residual GEP rates were generally more variable than the estimated R_{eco} rates through all three periods (Fig. 5). We, therefore, assume that the variation in NEE is largely driven by changes in rate of photosynthesis rather than respiration. This is supported by another study in Zackenberg in 1997 (Christensen et al., 2000).

The uptake of CO_2 is controlled overall by radiation for the photosynthetic process. We, however, did not find any correlation between global radiation levels and cumulative NEE during the study period. However, Semikhatova et al. (1992) reported that arctic plant species are adapted to their environment, enabling photosynthetic capacity at low light levels. Moreover, Semikhatova et al. (1992) argued that photosynthesis proceeds at near-maximum rates over a broad range of temperatures, reporting optimum temperatures ranging from 10°–25 °C in the Russian Arctic. Further, Shaver and Kummerow (1992) and Oechel and Billings (1992) supported this, arguing that the temperature at which arctic plants grow are rarely optimal even for these

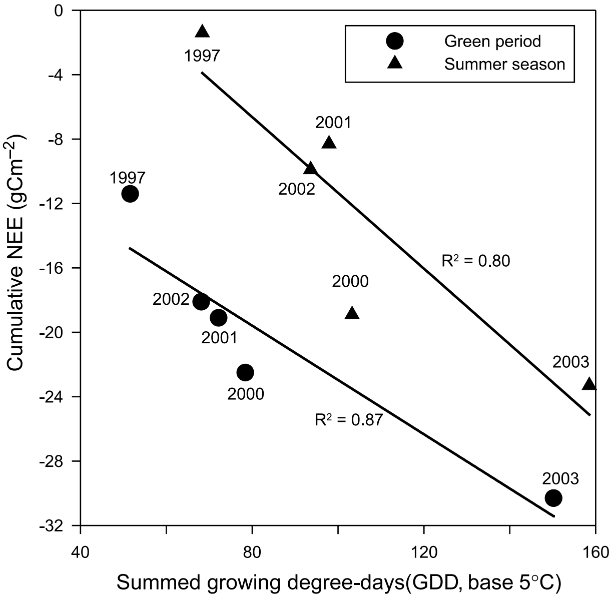

Fig. 6. Cumulative NEE during the green period and the summer season (June–August) versus summed degree-days (base 5 °C). Regression lines are shown as solid lines (green period, −0.169 × −6.105, $R^2 = 0.87$; summer season −0.235 × +12.192, $R^2 = 0.80$)

highly adapted species. Hence, when examining summed growing degree-days (GDD) and cumulative NEE, a clear ecosystem response to increased temperatures is seen (Fig. 6). We defined GDD according to Maxwell (1992), who found the growing season for plants to be climatically defined by the total number of degree-days above 5 °C. This definition was also used in the study performed by Aurela et al. (2001a, b) in Finland. We modified GDD slightly and calculated summed degree-days from hourly temperatures exceeding 5 °C divided by 24, to a daily basis. The predictive power of this correlation is very robust, as variation in GDD accounts for 87% of the variance in observed cumulative NEE during the green period (Fig. 6). Timing of snow-melt constrained the length of the green period and hence had a strong impact on cumulative NEE during this period. The smallest cumulative NEE of $-11.4\,\mathrm{g\,C\,m^{-2}}$ was seen in 1997 when snow had melted by DOY 179. This was contrasted by the largest uptake of $-30.3\,\mathrm{g\,C\,m^{-2}}$ in 2003 when snow had melted by DOY 168.

This is further supported by findings from a subarctic fen in Finland (Aurela et al., 2004), where snow-melt timing was concluded to be the most important factor controlling the annual carbon balance. Similarly, a strong correlation ($R^2=0.8$) is found between summer season (June–August) cumulative NEE and summed GDD (Fig. 6). Hence, we hypothesise that this particular high arctic ecosystem has a strong temperature control on NEE. This is consistent with the findings of Havstrom et al. (1993), who found positive growth response in *Cassiope t.* to increased temperature, this effect was increased with latitude.

The temperature based ecosystem respiration models are presented in Fig. 4. The respiratory rates are in accordance with results from chamber measurements at a heath site in the Zackenberg research area (Elberling et al., 2004), suggesting that the empirical relationship is representative for this ecosystem. The variation in respiratory rates is satisfactory, R^2 values ranged between 0.66 and 0.99, which justifies the use for this specific site. The estimated R_{eco} during the green and post-green periods varied between $0.4\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$ and $0.7\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$, which are comparable to findings from the few other studies in the high Arctic (Christensen et al., 2000; Elberling et al., 2004; Illeris et al., 2003; Jones et al., 2000). Chamber measurements from a *Cassiope t.* dominated heath site in Zackenberg showed respiration rates ranging between 1 and $2.1\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$ (Christensen et al., 2000). However, the respiratory fluxes reported by Christensen et al. (2000) were measured between 10:00 and 15:00 hours, where top-soil temperatures are expected to be highest, which might explain the large differences from the daily averaged R_{eco} values in this study. An experiment in Zackenberg found respiration rates at a dry *Cassiope* heath ranging between 0.3 and $1.07\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$ (Illeris et al., 2003). From a polar desert in NW Greenland Jones et al. (2000) found respiratory rates ranging from 0.1 to $0.9\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$. Whiting et al. (1992) found, from chamber measurements in Alaska, values of total ecosystem respiration of approximately $1\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$.

We found that precipitation had an impact on NEE. During days with rain in the green period the flux reversed and the ecosystem acted as a source of CO_2 (Fig. 2). Similarly, Illeris et al. (2003) found respiratory losses of CO_2 from the dry heath surface in Zackenberg, fast and significantly after rain events, and related the response to the increased microbial activity. Hence, the respiration at the heath might be constrained by the sparse precipitation events during the summer season.

4.2 Growing season budget

The length of the green period varied from 36 days in 1997, with a cumulative NEE of $-11.4\,\mathrm{g\,C\,m^{-2}}$ up to 54 days in 2003, resulting in a cumulative NEE of $-30.3\,\mathrm{g\,C\,m^{-2}}$. Hence, NEE is expected to enhance on average by $1\,\mathrm{g\,C\,m^{-2}}$ per increased day in green period. Green period length was controlled by the day of snow-melt. Thus, earlier snow-melt is expected to increase the length of the green period and increase carbon accumulation. The length of the analysed summer season was 80 days during the five years, with a 12.7-fold increase in cumulative NEE from 1997 to 2003 (Fig. 6).

The variability in sink strength within ecosystems is however an issue which needs further attention to be able to predict the precise impact of future climate warming. Timing of snow-melt and air temperature in addition with frequency of rain events are the major parameters that control the carbon balance of this ecosystem. Lloyd (2001b) showed that a high arctic semi-dessert ecosystem shifted from being a summer sink to a source the next year due to variability in environmental parameters. Many of the performed studies in the Arctic have been conducted during the summer seasons. Therefore, many annual budgets are based on summer fluxes. However, carbon losses from the Arctic ecosystems have been shown to be significant during winter (Fahnestock et al., 1999; Oechel et al., 1997; Zimov et al., 1996). Hence, measurements during winter and autumn are critical in our understanding of the carbon balances in the Arctic ecosystems. Results from a study on wet and moist tundra in Alaska showed that the winter time respiratory loss accounted for 70% of the annual respiration (Oechel et al., 1997), while in other ecosystems inclusion of winter time losses of CO_2 into the annual budgets increased the annual respiratory loss by 17% (Fahnestock et al., 1999).

The respiratory loss during winter from the 1997 season at the heath in Zackenberg, was modelled by Soegaard et al. (2000), resulting in an area integrated loss of $6.5\,\mathrm{g\,C\,m^{-2}}$ $\mathrm{season^{-1}}$, assuming respiration as a function of temperature. Assuming that the respiratory loss does not change interannually, this result, coupled with our present study, indicates that NEE at the heath is in balanced on an annual basis. However, understanding and quantifying the annual carbon budgets of high arctic ecosystems, more studies on wintertime fluxes are needed in order to conclude on the ecosystem source/sink strength. Modelling of annual carbon balance for the heath by Soegaard et al. (2000) indicated an area integrated loss of $5.2\,\mathrm{g\,C\,m^{-2}\,y^{-1}}$ in 1997. The carbon balance was constituted by an area-integrated sink of $-7.1\,\mathrm{g\,C\,m^{-2}}$ $\mathrm{season^{-1}}$ during the green period and a loss during the rest of the year of $12.3\,\mathrm{g\,C\,m^{-2}}$ $\mathrm{season^{-1}}$. The 1997 summer season was dominated by poor weather. Although mean daily air temperatures and global radiation levels seem comparable to the other years, the resulting cumulative growing degree-days were low. In addition, the frequently occurring rain events during the 1997 green period might have increased the respiratory losses. Hence, the sink strength was expected to be smaller as seen from Fig. 3.

5. Conclusion

The response of the high Arctic ecosystems to climate change is uncertain. The sporadic study of carbon dioxide exchange from different Arctic and high Arctic ecosystems in addition to the short period of research from these sites makes it difficult to observe long-term changes in these ecosystems. A diverse pattern of carbon dioxide exchange is seen throughout the Arctic region, this study however indicates that the heath in Zackenberg during the observed summer season has a net uptake of carbon dioxide. From the presented results, we conclude that in this particular ecosystem the photosynthesis responded stronger to increased temperatures than ecosystem respiration. Hence, uptake of CO_2 increased as growing degree-days increased. However, this relation only applies if soil moisture does not increase. Our results confirm that the air temperature expressed as growing degree-days are critical to the sink/source strength of this particular ecosystem. From the results it can be observed that the ecosystem sink strength increases by $-0.16\,\mathrm{g\,C\,m^{-2}}$ per increase in growing degree-days (base 5 °C) during the green period. Similarly, van Wijk et al. (2003) found a reduction in annual gross primary production of $4\,\mathrm{g\,C\,m^{-2}\,y^{-1}}$ per day at the start of growing as the season was delayed in a tussock tundra ecosystem. However, the sink strength on an annual basis is debatable, given the lack of measurements during especially autumn but also winter. Hence, we can conclude that temperature has a strong impact on the dry heath ecosystem in Zackenberg, increasing the summer season sink strength. The interannual variation in summer season NEE originated mainly from the variations in date of snow-melt and the air temperatures during the green period. Summed melting degree-days explain 93% of the variation in snow-melt (Fig. 1). In a climate change perspective this is important, since this area, according to the climate model, is subject to increased annual temperatures. Increased temperatures might lead to increased accumulated

NEE and probably also increase the length of the growing season.

In contrast to the studies performed in wetlands in the arctic region, where ecosystems respond quite variably to increased temperatures (Oechel et al., 1993; Zimov et al., 1996; Vourlitis and Oechel, 1997, 1999; Stieglitz et al., 2000), we have demonstrated that this particular ecosystem seems to benefit from increased summer temperatures.

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