Controls on the greenhouse gas exchange of a high-arctic ecosystem

Thomas Friborg, Birger Ulf Hansen, Claus Nordstroem & Henrik Soegaard.

Abstract

The polar regions have during the last decade received increasing attention, due to the potential importance that these areas have on the global greenhouse gas budget. During the period from spring to early autumn of 1997 the exchange of two of the most important greenhouse gases namely carbon dioxide and methane were measured in a high-arctic valley in northeastern Greenland. The results show a significant temporal and spatial variation in the exchange of these gases, as well as a high dependency on the prevailing climatic conditions of this harsh location.

From measurements carried out over three dominating vegetation types we found that during the summer season of 1997, the valley was a sink of CO_2 in the order of 11.5 g C m^{-2}, with the most densely vegetated areas showing the highest uptake rates. Over the same period the measurements showed that the valley was a source of CH_4 with a magnitude of 0.85 g C m^{-2}. Emission rates were mainly related to the soil temperature and to the position of the water table. This paper presents a summary of the most important processes controlling the seasonal dynamics of CO_2 and CH_4 exchange in high-arctic Greenland.

Keywords

Carbon dioxide and methane exchange, climate change, high-arctic Greenland.

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The increasing concentration of greenhouse gases in the atmosphere has, during the last decade, been a scientific topic which has gradually received more attention among researchers, politicians and the general public. There is a general agreement that the temperature of the earth is rising. Most researchers are convinced that at least part of this temperature increase can be explained by an increase in the concentration of carbon dioxide in the atmosphere as a result of the burning of fossil fuel. However, natural sources and sinks of CO_2 and CH_4 still have the highest regulative importance on the greenhouse gas budget. The organic content of the worlds soil is estimated to be in the order of 1580 Gt carbon (Reeburgh, 1997) of which, the boreal and arctic regions contain approximately 30% (Post et al. 1982). Most Global Circulation Models (GCMs) predict that future global climate change will have the highest impact in the near-polar regions (IPCC, 1996; Kattenberg et al., 1996). The dependency of CH_4 production/consumption and CO_2 production especially on temperature and precipitation, could turn the large pools of carbon found in the arctic, into a major source of greenhouse gas. This emphasizes the need for an in-depth understanding of the processes controlling the greenhouse gas exchange in the arctic areas and of what effects future climate change may have on this exchange.

For comparison, world fossil fuel combustion results in an emission of approximately 5.4 Gt C plus 1.4 Gt per year, due to deforestation. This is a relative small amount compared to a yearly uptake of 50 Gt through photosynthesis in the terrestrial biomass production (Reeburgh, 1997).

Though the basic processes of gas production in the soil are fairly well documented (e.g.Raich and Schlesinger, 1992; Schimel et al., 1993), large uncertainties exist in the response of natural ecosystems to general changes in the climate.

In this paper we will present the results of CH_4 and CO_2 flux measurements carried out over the summer of 1997 in high-arctic Greenland. During the campaign, measurements of the CO_2 net exchange were conducted over three different surface types in the Zackenberg valley, whereas CH_4 measurements covering all parts of the season were carried out over a minerotrophic fen. Also included in this paper, will be a description of the processes controlling uptake and emission of these two important greenhouse gases and an attempt to evaluate how climate conditions, on two different days, affected the exchange of CH_4 and CO_2.

Site description

The newly established Zackenberg research station served as a base for the flux measurements carried out during the summer of 1997. The station is located at the southeast end of the 6 km wide and 8 km long Zackenberg valley (74° 28'E, 20° 34'W) in northeastern Greenland. As the nearest permanent settlement is located 500 km to the south, the valley can be regarded as unaffected by direct human activities . The area is high-arctic (Maxwell, 1992), with an annual mean temperature of -10° C, which in 1997 ranged from a mean temperature of 5° C in August to -22° C in January. The annual precipitation is approximately 220 mm, most of which is received as snow during the winter (Meltofte and Rasch, 1998). The area is within the zone of continuous permafrost with an active soil layer which started developing from 21 June and reached a depth of 0.5 m under most vegetation types during early August, and remaining at this depth throughout the measuring campaign.

With the intention to cover the dominating vegetation types of the area, three sites were selected for CO_2 flux measurements within the valley. A fen site, where simultaneous CH_4 flux measurements were also carried out was dominated by sedges and arctic cotton grass (*Eriophorum scheuchzeri*) in the wettest parts and mosses and arctic willow *(Salix arctica)* on hummocks. The other two sites, where CO_2 measurements were conducted, were an arctic heath site dominated by *Dryas* spp., *Cassiope tetragone* and *Vaccinium uliginosum,* and a willow snowbed site which was dominated by *Salix arctica*, but contained a significant proportion of other vegetation types mainly grasses and sedges (Bay, 1998).

Over the summer, CO_2 measurements were carried out almost continuously from 1 June to 26 August at both the fen and heath sites. At the fen site, CH_4 measurements were obtained for 43 days during this period, the equivalent to 1000 hours of measurements. Continuous CO_2 measurements were obtained at the willow site during the period from 14 July to 1 August.

Methods

Identical instrumentation was used at the three sites. For eddy correlation measurements of CO_2 water vapour fluxes, the following instruments were used: 3D sonic anemometer (Gill Solent, UK) for wind speed and direction, and closed path CO_2 /H_2O infra red gas analyser (LiCOR 6262, USA), with the inlet tube mounted 0.2 m from the anemometer, at a height of approximately 3 m at the fen and heath sites and at 16 m at the willow site. At the fen site, a tunable diode laser (Aerodyne Research Inc., USA) was applied to obtain high frequency fluctuations in the CH_4 concentration. Raw data was stored using laptop computers at the rate of 20 Hz and fluxes of H_2O, CO_2 , CH_4 and sensible heat were calculated and corrected, applying the routines described in Moncrieff et al. (1997).

In addition to the gas flux measurements, a number of standard meteorological variables were recorded during the 1997 campaign, comprising: Air temperature/humidity at 2 m (MP100A, Rotronic AG, Campbell Sci.,UK), soil temperatures at -0.03, -0.1 and -0.38 m (thermocouples), radiative surface temperature (KT-17 Heimann, Germany), water table level (PDCR 1830, Campbell Sci., UK), incoming and reflected short wave radiation (Kipp & Zonen, CM7, Netherlands), PAR (LI-COR Inc., USA) and net all wave radiation (Q*6, REBS Inc., USA). Besides these automatic measurements some manual measurements of Leaf area index, LAI, (LAI-2000, LI-COR Inc., USA and Sunscan, DELTA-T-DEVICES, UK) and active layer thickness were carried out weekly.

Processes controlling the exchange of CO_2 and CH_4 in the arctic

Carbon dioxide

Figure 1 presents a schematic diagram of the sources and pathways of CO_2 and CH_4 in terrestrial ecosystems. The

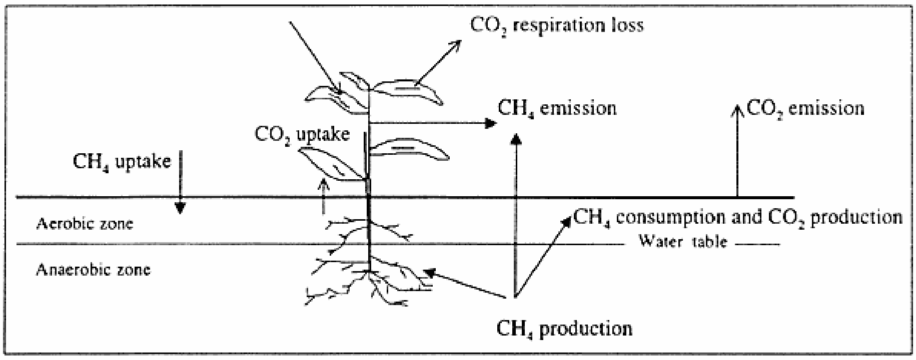

Figure 1: Schematic drawing of the processes and pathways of carbon dioxide (open arrow heads) and methane in natural wetlands.

figure applies to wetlands in general, where an anaerobic zone exists within the organic rich layers of the soil profile.

In vegetated areas the Net Ecosystem Exchange (NEE) is controlled by i) the photosyntetic process, which transforms CO_2 and water by means of light into plant tissue during hours of daylight and ii) the respiration from soil and plants. NEE, as measured by the eddy correlation technique, therefore expresses the balance between CO_2 assimilated by the vegetation and CO_2 emitted by plants and soil due to respiration.

During daytime the net CO_2 flux is controlled by these two oppositely directed contributions. However, variation in the net CO_2 flux can often be closely related to the incoming radiation, thus the photosynthesis measurements have larger diurnal variations than the respiration measurements. The vegetation density is expressed by the Leaf Area Index (LAI) which is the areal coverage of green vegetation per unit surface. Only a few arctic vegetation types reach a LAI of 1, while agricultural fields in the mid-latitudes can have a LAI of 5 or higher during peak season. The denser the vegetation, the greater the fraction of the incoming radiation that will be absorbed by the leafs and used for photosynthesis.

Outside the growth season it is soil respiration that controls the CO_2 balance, especially in areas where the organic content of the soil is high, like the arctic wetlands and tundra. During spring and autumn the soil respiration controls the CO_2 budget, with emission rates that are closely related to the amount of organic matter in the soil and the soil temperature in the upper soil layers (Christensen et al., 1998; Lloyd and Taylor, 1994). It is only in mid-winter when the biological activity in decomposition becomes so slow that the soil respiration for modelling purposes can be set to null. During the summer, soil respiration is of relatively minor importance to photosynthesis, but can together with the plant respiration, even during the peak growing season, have a magnitude which is 30-40 % of the atmospheric flux (Soegaard and Nordstroem, 1999), but in an opposite direction.

Methane

As shown in figure 1, methane is produced in the anaerobic zone of the soil, which under most conditions is below the water table. Root exudates and other dead vegetation matter provides the substrate of labile carbon for methanogenesis, which is the bacterial production of CH_4 (Schimel et al., 1993). As microbiological activity in the soil depends on temperature, it has been shown in several studies (eg. Daulat and Clymo, 1998) that the CH_4 production is closely related to soil temperatures.

Provided that the soil is not water logged, an aerobic zone will be found above the anaerobic layer of the soil, where methanotrophic bacteria will consume CH_4 and produce CO_2. This implies that the amount of CH_4 emitted to the atmosphere is only a proportion of the CH_4 produced in the anaerobic zone. It has been shown that vascular plants play an important role, by transporting CH_4 through plant roots and tissue to the atmosphere, thus bypassing the aerobic zone and the methanotropic process (Torn and Chapin, 1993). This implies that when living plants are present, methane emissions to the atmosphere are higher, than if there are no plants present (Whiting and Chanton, 1992), however, this process seems to be passive and not linked to the stomatal control of the vegetation.

The consumption of CH_4 in the aerobic zone, especially in dry soils, can lead to a net uptake of methane from the atmosphere. Although in much smaller rates than normally found for emission, the uptake can be important because of the huge areas of dry tundra and forest soils in the North (Whalen and Reeburgh, 1990).

Results

Flux measurements of CO_2 and CH_4 were carried out from 1 June to 26 August 1997, which covered the period from spring to early autumn in northeast Greenland. When the campaign was initiated, the valley bottom had a 0.5 to 2 m snow cover, which lasted during the first two weeks of measurements. In autumn, the first snow was recorded just two days after the termination of the campaign. In figure 2a, the seasonal fluctuation in air temperature is shown together with incoming PAR. It should be noted that in the beginning of the campaign the weather was characterized by clear sky conditions, with relatively high air temperatures which accelerated the melting of the snow pack (1 to 21 June), immediately followed by a rapid development of the active layer (21 June and onwards). Over the summer, weather conditions varied between periods with dense cloud cover and rainfall (periods 4 to 14 July and 1 to 8 August), and drier periods, with higher temperatures and radiation loads. By the end of the campaign, air temperature during night time dropped below freezing point, leading to ice formation in the wettest parts of the fen. The limited amount of precipitation during the second half of the campaign is reflected in a 8 cm decrease in the water table level of the fen by the end of the campaign, see figure 2b.

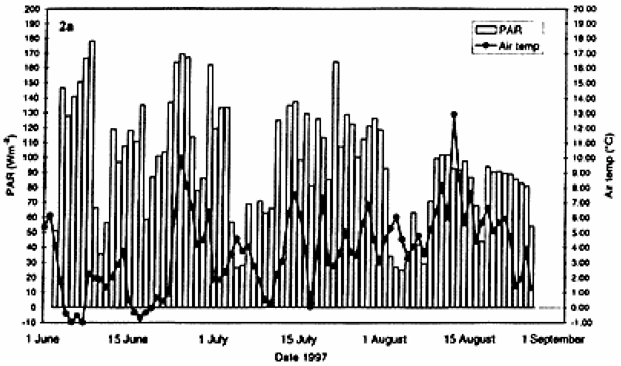

Figure 2a: Diurnal means of Photosynthetic active radiation, PAR (bars) and air temperature at the fen site during the measuring campaign from 1 June to 26 August 1997.

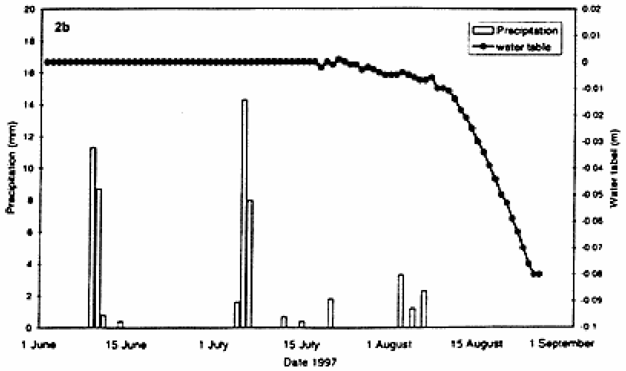

Figure 2b: Precipitation per day (bars) and diurnal mean of water table level (0 indicates a water table level at or above surface).

In the following section, two days representing characteristic parts of the campaign, have been selected to obtain a more detailed insight on how environmental conditions affect the exchange of CO_2 and CH_4 in the Zackenberg valley. The first chosen day is 24 June which is typical for the transition period between the snow melt and the vegetative period. As only very little vegetation had germinated before this day, it provides the opportunity to investigate the decomposition in the soil leading to CO_2 respiration in relation to the soil temperature. At the fen site, the water table level was at the soil surface, and the CO_2 release at this site must therefore, be attributed to respiration in the hummocks. The second day selected, 29 July, represents the warmest part of the summer, where both methane and carbon dioxide fluxes reached their highest levels during the summer of 1997.

Figure 3 displays the CO_2 flux from the fen and heath sites and figure 4 shows the air and surface temperature and PAR over the fen, as measured on 24 June 1997. At this early stage of the season, the flux at both sites is entirely controlled by soil respiration with a possible release of CO_2 trapped in the soil, due to the gradual melting of the soil layers. It is not possible to distinguish between these two contributing components, which are both closely linked to the soil temperature. However, the thickness of the active layer at the fen site was approximately 5 cm, and since most respiration takes place in the upper 2 cm of the soil, it can be assumed that the larger part of the flux is related to respiration (Oberbauer et al., 1991). It is clear from figure 3 that the flux from the fen site (3.4 g CO_2 m^{-2} d^{-1}) is substantially larger than the flux measured at the heath site (0.9 g CO_2 m^{-2} d^{-1}). The difference in the fluxes corresponds well to the difference in thickness of the organic layer found in the two soils (Nadelhoffer et al., 1992). The fen has a peat layer of 25 cm (Christensen et al., 1998) while the heath site has less than 10 cm of peat above the mineral soil (Jakobsen, 1992). At this early stage of the season, no soil temperature was recorded, but the

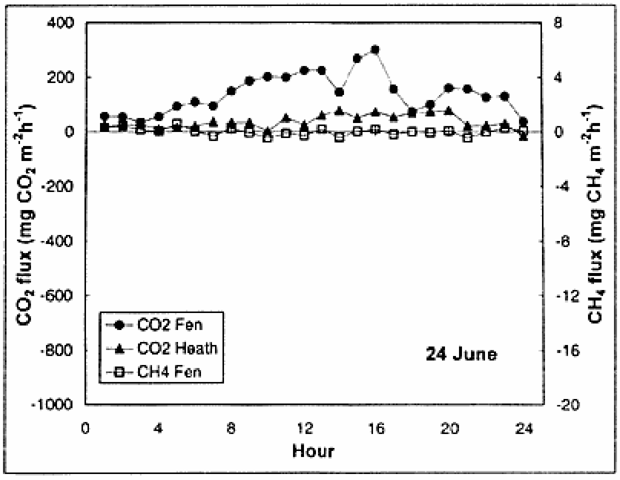

Figure 3: Fluxes of CO_2 at the fen and heath sites and CH_4 flux at the fen site 24 June 1997.

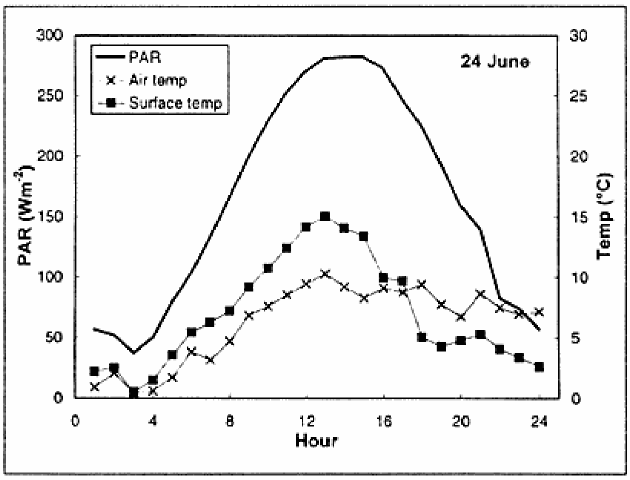

Figure 4: Air and surface temperature and PAR at the fen site 24 June 1997.

flux at the fen site shows a clear response to the surface temperature measured at the site, see figure 4. Both sites exhibit a diurnal variation in fluxes with the highest fluxes during the daytime, reaching maximum in late afternoon and early hours of the evening.

For the same day, the methane flux (figure 3) shows virtually no fluctuation and, therefore, diurnal variations must be assigned to instrumental noise rather than to natural variations in the CH_4 flux. A reason for the low CH_4 emission may be found in the fact that methanogeneses generally takes places in the lower layers of the soil, deeper than respiration, which produces CO_2. Studies have shown that most CH_4 is produced at about 10 cm depth in the soil (Thomas et al., 1995), if the water table is at the soil surface. Since the active layer had not reached this depth on 24 June, the most active layer for methanogeneses was still frozen. No live vegetation, which could transport methane to the surface, was present in the fen at this early stage of the summer, therefore, any CH_4 produced was likely to be oxidised in the aerobic layer (e.g. in hummocks).

The period from late July to mid August can be regarded as peak season in terms of vegetational coverage, soil temperatures, active layer thickness and water table level. In accordance with what could be expected, the measured integrated net exchange rates of both CO_2 and CH_4 reached maximum values during this period. In the last week of July the measurements showed an integrated daily uptake of CO_2 in the order of 2.5 and 10 g m^{-2} day^{-1} for the heath and fen site respectively. The measured methane emissions also reached maximum rates, in the order of 100 to 120 mg m^{-2} day^{-1} during the last week of July. A typical day from this period was 29 July. Incoming PAR, soil and air temperatures are shown in figure 5. Despite clear sky throughout the day, air temperatures did not reach values above 8°C, which is due to the low elevation angel of the sun. Further a typical pattern of light south easternly winds, moving cold air from the sea into the valley during day time, was important for temperature regulation of the valley system. The measured CO_2 fluxes for the day are shown in Figure 6. All three sites show the same diurnal pattern. The magnitude of the flux is determined by the differences in LAI between the sites. On the 29 July, LAI at the three sites;

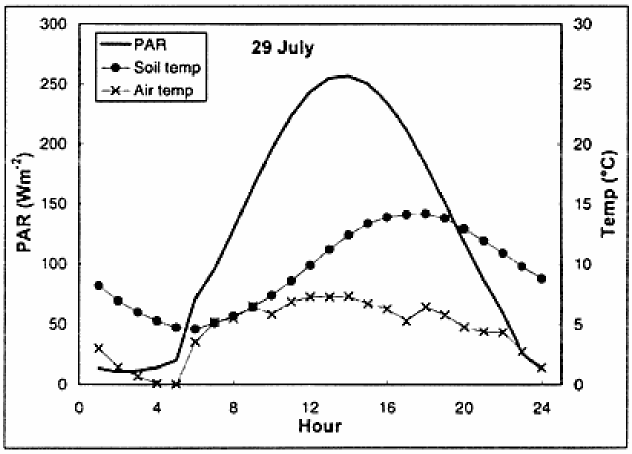

Figure 5: Air and soil (-0.03 m) temperature and PAR at the fen site 29 July 1997.

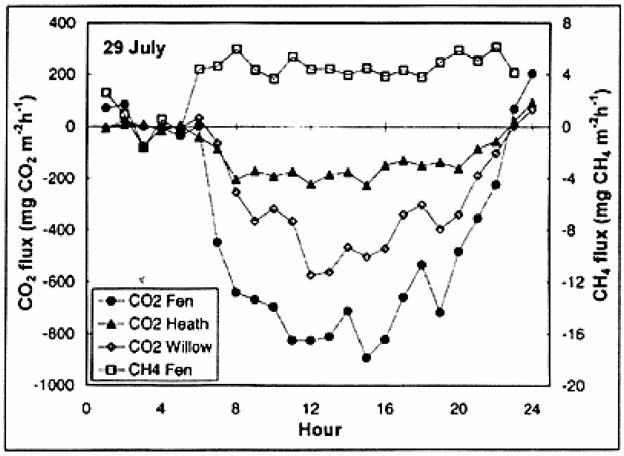

Figure 6: Fluxes of CO_2 at the fen, heath and willow sites and CH_4 flux at the fen site 29 June 1997.

heath, willow and fen was approximately 0.2, 0.55 and 0.7 respectively.

During night-time hours (0 to 4 am), the CO_2 fluxes at all three sites were very small due to the cold conditions on the night between 28 and 29 July, with air temperatures down to freezing point, and surface temperatures marginally below freezing point, which suppresses both plant and soil respiration rates. From sun rise to sun set (6 am to 10 pm) the flux at all three sites was dominated by photosynthesis reflected in an uptake of CO_2 during all times of the day. Maximum net uptake rates were found between 12 am and 3 pm at all sites, corresponding with the maximum in incoming radiation. It should be noticed that no distinct peak can be observed in CO_2 uptake at any of the three sites during midday hours, which was a general pattern for the CO_2 flux during this time of the campaign. This diurnal pattern was also observed for the fen site, previously studied by Soegaard and Nordstroem (1999), who by the use of a photosynthesis model were able to separate the limitations in carbon uptake due to light, and the limitation due to CO_2 availability within the leaves (controlled by stomata) and Rubisco capacity. It was found in this previous study that for the midday hours on sunny days (as on 29 July) the major limitation was the low Rubisco capacity (controlled by the low temperatures and low soil nitrogen content) rather than light limitations. The two periods of the day with marginally lower temperatures, around 10 am and 5 pm, seem also to have a negative effect on photosynthesis as can be seen at the two neighbouring sites; willow and fen. This indicates that temperature has a limiting effect on photosynthesis, at least at these two sites.

The CH_4 flux on 29 July also shows clear diurnal variations; from midnight to 5 am, the measured fluxes are very small even with a small uptake at 3 and 5 am. From 6 am and continuing through the rest of the day, the measured emission rates are between 3.5 and 6.5 mg m^{-2} h^{-1}, with the highest emission rates during morning and evening. It is well known that the emission of CH_4 has a high degree of spatial variance (Christensen et al., 1995), reflecting the structural heterogeneous nature of the soil. Chamber measurements, made in the fen, showed that this was especially the case for the methane exchange, whereas photosynthesis did not show a high degree of spatial variability. It is likely that some of the temporal variation observed in the CH_4 flux on 29 July can be related to the heterogeneity of the source area. For the eddy correlation measurements, the most profound change in the flux (between 5 and 6 am) occurs simultaneously with a change in the wind direction from a land to a sea breeze (figure 7). During the night wind speed was very low which often caused unpredictable measurements of the fluxes. This is due to stable conditions which are likely to cause a storage of e.g. CH_4 in the lowest atmospheric layer. The uptake of CH_4 found during early morning hours can, therefore, be attributed to storage in the lowest part of the atmosphere. Likewise, it is possible that the high emission rates found from 7 to 9 am are caused by increasing wind speeds, in combination with the mentioned changed in wind direction, rather than by a sudden increase in the production of methane in the soil.

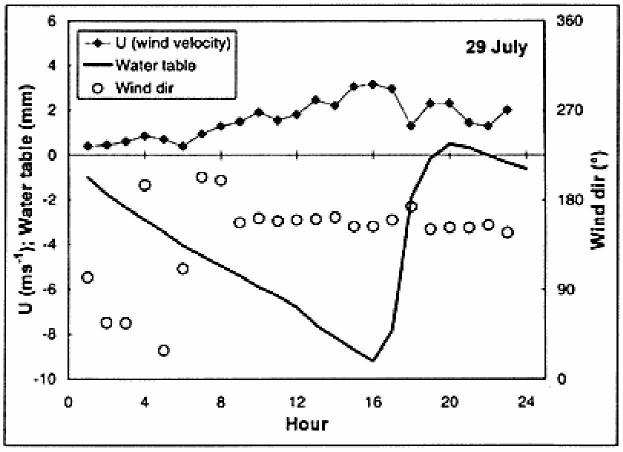

Figure 7: Water table level (line) and wind direction (open circle) and wind speed at the fen site 29 July 1997.

From 7 am and throughout the day, the wind direction was stable from the south, and the variations in the flux can be mainly associated with variations in the water table level and soil temperature. From 8 am, the soil temperature increased (fig. 5), and reached a maximum for the day during late afternoon and early evening. However, during the period from midnight to 4 pm, the water table level marginally decreased (fig. 7), which may have caused increased oxidation of methane in the aerobic soil layer, leading to reduced methane emissions during this period. The highest emission rates are found during the evening which corresponds to the high soil temperatures and an increased water table level.

The seasonal carbon budget

Above examples show the CO_2 and CH_4 flux measured at the three sites representing the dominant vegetation types within the Zackenberg valley. To fill in the gaps in the measurements and expand the period of validity of the findings, to also cover other parts of the year, well known models for photosynthesis (Collatz et al., 1991) and soil respiration (Lloyd and Taylor, 1994) have been used. Soegaard and Nordstroem (1999) found that these models were found to be applicable in the reproduction of the measured 1996 data with respect to both photosynthetic CO_2 uptake rates and soil respiration for the fen site in Zackenberg. The same models were applied on the 1997 data and it was confirmed that the models reproduced both CO_2 uptake and soil respiration accurately and were able to reproduce precise seasonal variations. Over the full season of 1997, the combination of the two models explained more than 80% of the day to day variation in the measured CO_2 net exchange. It was also found that differences in the net CO_2 flux between the three different vegetation types at the 3 sites could be related to variations in LAI and surface temperature. By using the models it was possible to estimate the summer season (June - August) CO_2 balance, which showed that all three sites were CO_2 sinks. Model estimates showed that, in correspondence with the differences in LAI found between the sites, the fen was the largest sink of CO_2 followed by the willow site, whereas the heath site was close to neutral in terms of the CO_2 balance.

The methane flux measurements covered approximately half of the days during the summer season, and a modelling attempt using this data has been made to estimate seasonal emissions. An empirical model (Suyker et al., 1996) based on the relationship between daily integrated emission rates and environmental parameters including water table level, soil temperature and thickness of the active layer can explain 82% of the measured variance. If the fen and grassland areas in the Zackenberg valley are assumed to be the only active surface types in terms of methane exchange (chamber measurements indicate this), the flux for the season can be estimated as an emission of 0.85 g C m^{-2} for the whole valley.

By scaling the fluxes of CO_2 and CH_4 from the individual surface types by their respective areal coverage, using the vegetational map produced by Bay (1998) it was possible to calculate the total carbon balance for the Zackenberg valley during the 1997 summer season (June to August). An estimate for this period shows the valley is a sink of carbon with a magnitude of 10.5 g C m^{-2}, mainly due to the high uptake rates of the fertile fen and grassland areas.

Conclusion

Based on the relationship between environmental parameters and the exchange of the greenhouse gases of CO_2 and CH_4, it is possible to reproduce the measured fluxes of these gases fairly accurately. Using the modelled and measured data from the Zackenberg valley an estimate for the carbon balance for the summer season can be calculated as shown. To estimate the yearly carbon balance of the high-arctic valley, additional work will be needed, primarily due to the magnitude of the wintertime fluxes which are still very uncertain. No attempts have been made to estimate the yearly methane emissions. This is due mainly to the lack of environmental data of water table level and active layer thickness.

Acknowledgments

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