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Effects of climate variability on vegetation and carbon uptake in a North-Norwegian coastal wetland

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Scientific report

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Sammendrag

Bakgrunn

Våren 2008 tok Bioforsk et initiativ overfor NILU om å etablere en målestasjon for karbonflukser mellom jordsmonn og atmosfære etter at de hadde fått lånt utstyret til en Eddy covariance fluksstasjon fra Smithsonian Environmental Research Center (SERC), USA. Valget for et egnet sted falt i løpet av våren på en myr på Andøya (Andmyran ved tettstedet Saura, ca. 20 km sør for kommunesenteret Andenes), fordi dette stedet har et unikt økosystem som anses å være en potensiell kilde til store utslipp av klimagasser (spesielt CO2) under en global oppvarming. Så langt (og fram til i dag) har ikke dette vært representert i det europeiske karbonfluksnettverket. Samtidig hadde plassen en god teknisk infrastruktur med installasjoner av Andøya Rocket Range (ARR) like i nærheten. Stasjonen ble installert og målingene startet i begynnelsen av juni 2008 av eksperter fra SERC, samt forskere fra Bioforsk og NILU og personell fra ARR.
NILU og Bioforsk drev stasjonen stort sett med interne midler og teknisk støtte fra ARR til desember 2014. Til tross for en rekke søknader sammen med andre aktører innenfor samme felt (UMB/NMBU, Skog og Landskap, Universitetet i Tromsø, UNIS, samt en rekke utenlandske partnere spesielt i Skandinavia) lyktes det ikke å skaffe ekstern finansiering. Aktiviteten måtte derfor legges ned i slutten av 2014. Resultatene angående CO2-flukser fra årene 2008-2012 har blitt publisert av Lund et al. (2015), mens det ikke er tilfellet for de (meget gode) dataene fra 2013 og 2014 samt målingene av andre parametere under hele eller deler av måleperioden, som metanflukser, spektralmålinger av vegetasjonen og akvatiske karbonflukser. Det er disse målingene det foreliggende prosjektet fokuserte på.

Meteorologiske forhold 2013-2014

Begge år, men mest 2013, var tydelig varmere enn den klimatiske normalen fra 1961-1990. I 2013 var månedsgjennomsnittene opp til 3 grader over normalen i perioden mai til desember, mens det samme var tilfellet for perioden juli til desember i 2014. Samtidig var 2013 et av de fuktigste årene i prosjektperioden 2008-2014, mens 2014 var tørrere enn langtidsgjennomsnittet, spesielt gjennom sommeren. Som en konsekvens var vanninnholdet i jordsmonnet i 2013 like høy som i de fuktige og kjølige årene 2010 og 2012 gjennom hele vekstsesongen, 2014 lignet heller det varme og forholdsvis tørre året 2011, men ikke årene 2008 og 2009 med ekstremt tørre vekstperioder.

Karbondioksidflukser

Med denne meteorologiske bakgrunnen var det overraskende at den akkumulerte karbondioksid-fluksen ikke ble større, men heller ble noe mindre enn den i de foregående årene 2011 og 2012 som også var ganske like til tross for de vidt forskjellige meteorologiske betingelsene. Samtidig viser tallene og figur 7 i vedlegget at dette bare gjelder den akkumulerte verdien ved slutten av året, mens det kan være betydelige forskjeller gjennom året. Mens karbonopptaket i 2013 startet tidligst av alle år i måleserien (rundt dag 125 eller 5. mai), var det en del forsinket og skjøt fart først fra slutten av juni i 2014. Det var også en tidlig reduksjon av opptaket på sensommeren (ca. fra dag 195) som faller sammen med tørre jordforhold. Så økte den igjen for å nå 2013-opptaksverdien rundt dag 240. De to årene skiller seg så ved forskjellige CO2-utslippsrater gjennom høsten og tidlig vinter, slik at det akkumulerte opptaket i 2013 er mindre enn i 2014.

Disse resultatene er imidlertid svært usikre pga. den lave påliteligheten av målingene utenfor vekstsesongen.

Metanflukser

Metanflukser ble målt av våre samarbeidspartnere ved Universitetet i Lund i en kort periode sommeren og høsten 2012. Instrumentet viste seg dessverre å ikke være robust nok til forholdene på stasjonen, og måtte tas ut igjen etter ca. 4 måneder. Målingene fra den korte perioden viser metanutslipp på ca. 2 g CH_4/m^2 i løpet av 2012 som er ca. en faktor 2 lavere enn den som ble målt ved Kaamanen i Nord-Finland, og er ca. en faktor 10 lavere enn den som ble målt ved stasjonen i Stordalen i Nord-Sverige. Dette kan i hovedsak forklares med de forholdsvis tørre forhold på Andøya og resulterende vegetasjon sammenlignet med de to andre stasjonene.

Akvatiske karbonutslipp

Løst organisk karbon og annen vannkjemi ble målt i et avløpsvassdrag fra myrområdet fra august 2011 til våren 2014, mens grunnvannsnivå og strømhastighet ble målt fra høsten 2012 til høsten 2014. Dataene ble brukt til å kalibrere den prosessbaserte modellen INCA-C som beregnet uttransport av karbon fra økosystemet. Resultatene fra observasjonsperioden gir et akvatisk tap av karbon som tilsvarer ca. 35% av fluksene mellom jordsmonn og atmosfære. De indikerer også at økosystemet i perioder har et netto-tap av karbon.

Spektrale observasjoner av vegetasjonen

NINA og NILU har drevet et instrumentsett for hyperspektrale strålingsmålinger på Andøya siden 2003. I 2009 ble instrumentene flyttet til featuresstasjonen og kjørt til slutten av 2014. Instrumentet måler innkommende solar stråling og stråling reflektert fra bakken i bølgelengdeområdet 320 til 950 nm (UV-A til nær-IR), som så brukes til å beregne «Normalized Difference Vegetation Index» (NDVI) og «Photochemical Reflectance Index» (PRI). Sistnevnte indeks er en god indikator på fotosyntetisk effektivitet og har også vist seg som en bra indikator for dynamikken i karbondioksidfluksen. Både NDVI-målingen og PRI målingene ble sammenlignet med karbondioksidflukser og satellittfjernmålte data. Foreløpige resultater for 3 år viser at PRI-målingene har høyere verdier (ved null og litt lavere) i begynnelsen og slutten av vekstsesongen når myra slipper ut karbondioksid og lavere verdi når den tar opp karbondioksid (under null). Likeledes samsvarer NDVI-målingene bra med høyere NDVI-verdier når det er opptak av karbondioksid i myra og lavere NDVI-verdier når myra slipper ut karbondioksid. Også den forsinkete vekstsesongen i 2010 med forsinket opptak av karbondioksid vises både i NDVI- og PRI-målingene fra spektrometeret. NDVI-målingene fra spektrometeret samsvarte bra med NDVI-målinger fra både MODIS og GIMMS (med hensyn til sommerperioden og «peak-NDVI). Imidlertid viste det seg at den høye andelen av lav og moser i «fotavtrykket» til spektrometeret (0.9 m^2) sammenlignet med fotavtrykket til satellittene (mer enn 236 m x 236 m) førte til at NDVI-verdiene fra spektrometeret avvek (høyere verdier) fra satellittmålingene, spesielt utover høsten på grunn av fortsatt fotosyntese i både lav og moser. Arbeidet med å ekstrahere ut nye indekser fra spektrometermålingene for årene 2013 og 2014 vil foregå utover vinteren og vi avventer nå en ny kalibrering av MODIS-målingene fra NASA (versjon 6) - så vi slipper å gjøre dette på nytt igjen før innsendelse av manus. Dette arbeidet vil være et samarbeid mellom NINA, Universitet i Lund (Sverige), Boston University/NASA og Universitetet i Milano.

Effects of climate variability on vegetation and carbon uptake in a North-Norwegian coastal wetland

1 Background

Carbon dioxide and methane - besides water vapour the most powerful greenhouse gases (GHG) - have been increasing rapidly in atmospheric concentration in recent decades. Peatlands, mostly in arctic and boreal regions, contain an estimated 400 Gt of C that might be released to the atmosphere in a warming climate and are highly susceptible to climate change. Current assessments estimate that the potential release of C by 2100 from peatlands could reach 100 Gt (Davidson and Janssens, 2006), or about 1/7th of the total amount of CO_2 currently observed in the atmosphere. In Norway, about 8% of the total land area are covered by peatlands (Lappalainen 1996). Peatlands are also potentially very strong emitters of methane (CH_4), which has a greenhouse effect per unit gas molecule 21 times higher than that of CO_2. Finland, Sweden and Denmark have investigated terrestrial carbon fluxes for almost 2 decades, and research communities, e.g., at the University of Lund and the University of Helsinki, belong to the most prominent research groups in Europe and worldwide. In contrast, Norway has lacked any infrastructure to assess fluxes of both gases from unique boreal ecosystems, e.g., sub-Arctic peatlands exposed to oceanic climate.

In 2008, the Norwegian Institute for Agricultural and Environmental Research (Bioforsk) and the Norwegian Institute for Air Research (NILU), in cooperation with the Smithsonian Environmental Research Center (SERC), agreed to establish a measurement site for terrestrial carbon fluxes on the Norwegian mainland, preferably at a location that could contribute with a unique ecosystem type to the network of Northern European stations. The site that was chosen was the Andmyran peatland on the island of Andøya in Northern Norway (69º08’34’’ N, 16º01’20’’ E, 17 m.a.s.l.). Despite the high latitude, the site does not have permafrost conditions due to the influence of the nearby Atlantic Ocean. Thus, the site is an oceanic mire/wetland, characterized by oligotrophic vegetation types dominated by crowberry (*E. nigrum ssp. hermaphroditum*), cloudberry (*R. chamaemorus*), sedges (*Carex spp.*), cotton sedges (*Eriophorum spp.*), peat mosses (*Sphagnum spp.*) and other bryophytes. For logistical reasons (power supply, short walking distance in an experimental phase), the station was set up relatively close to the edge of the vast wetland area. This implies the potential of measurement influence by both agricultural areas east and south of the station, and from a large peat exploitation area north of the station.

The eddy covariance flux system established at the Andøya site consisted of a LI-7500 open-path gas analyzer (Li-Cor, USA) and a CSAT3 3D sonic anemometer (Campbell Sci., UK). Data from both sensors were collected at a frequency of 10 Hz on a CR3000 data logger (Campbell Sci., UK). Supporting half-hourly ancillary data include air temperature (Ta) and relative humidity (RH; HMP45C, Vaisala, Finland), photosynthetic photon flux density (PPFD; LI-190, Li-Cor, USA), net radiation (Rn; Q*7, REBS, USA), soil temperature (Ts; TCAV-L, Campbell Sci., UK) and soil water content (SWC; CS616, Campbell Sci., UK) from the nearby meteorological tower (at 10 m distance).

2 Climatology

The location chosen for our observations is characterized by an oceanic, sub-Arctic climate. The Norwegian Meteorological Institute has performed observations at the nearby town of Andenes (about 20 km north of the flux station) from 1867 until 1972 and from the airport at Andenes since 1958. This yields reliable reference data to compare the 7-year measurements period with. The 1961-90 normal annual mean temperature is 3.6° C with a minimum of -2.2° C in February and a maximum of 11° C in both July and August. The 1961-90 normal annual precipitation is 1060 mm, with a maximum monthly precipitation of 144 mm in October and a minimum precipitation of 53 mm in May.

The seven-year period of flux measurements (2008-2014) is characterized by significantly warmer and drier conditions than the 1961-1990 normal: The mean annual temperature is 4.6° C and the annual precipitation is 953 mm. While the temperature change is almost equally distributed over the year, there is more intra-annual variability of the precipitation trend, with a marked increase in March, virtually no change in February, May and November and significant decrease in all other months. However, there is a large contribution from extreme events in the 7-year period, such as the extremely dry January 2014, and the very wet May and July 2012. Figure 1 shows the individual air temperature monthly means at Andenes Airport of all 7 years covered by the flux measurements as well as their 7-year average and the 1961-1990 normal mean monthly temperatures. Figure 2 shows the same data for monthly accumulated precipitation.

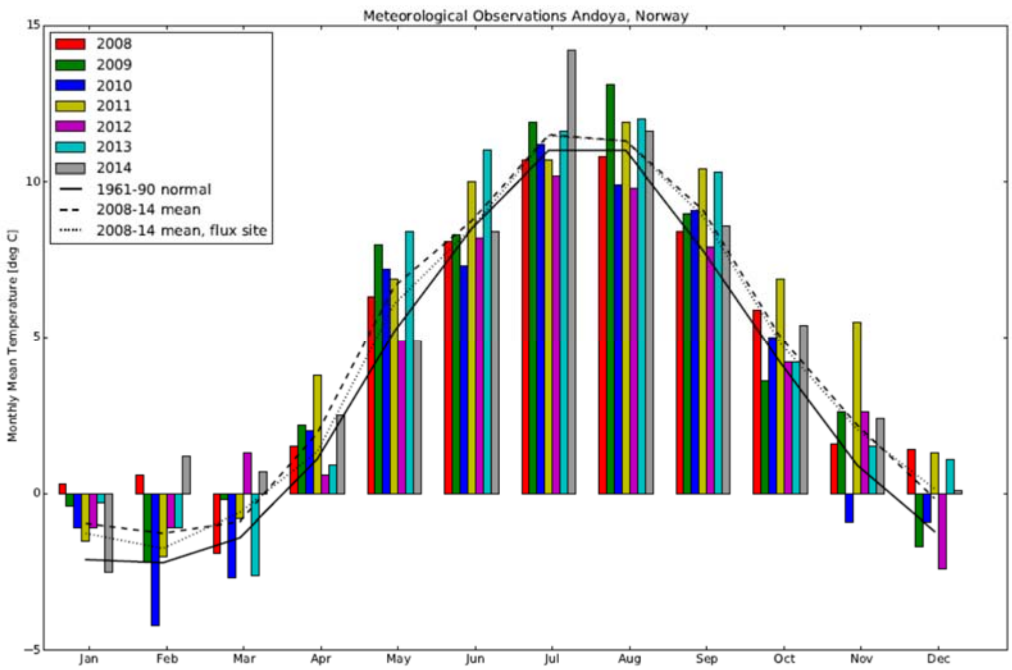

Figure 1: Monthly mean temperatures Andenes 2008-2014 (from Norw. Met. Inst.) and 1961-1990 normal.

A question to be considered is whether the data from Andenes Airport can be directly transferred to the flux measurement site. A comparison of temperature measurements, considering all reliable 2-m air temperature measurements at the site revealed that they, on an average are 0.3° C lower than at Andenes Airport; these data are also shown in Figure 1. Precipitation measurements were only performed at the flux site in 2013 and 2014 and never properly calibrated. A comparison of these data with those of the meteorological station revealed a discrepancy of in the order of 20% (the flux site being drier) which is clearly more than one would expect from location impact. We, therefore, do not consider the precipitation measurements from the flux site.

As already mentioned (and Figure 1 and Figure 2 demonstrate), the year-to-year variation of monthly mean temperature and especially precipitation is very large.

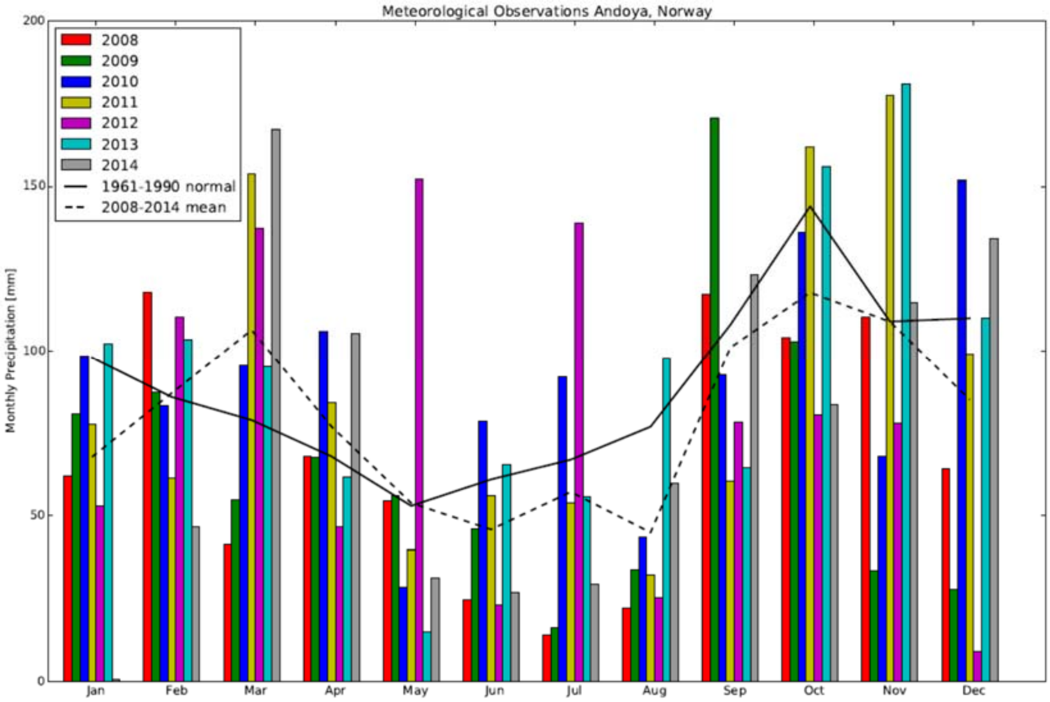

Figure 2: Monthly accumulated precipitation Andenes 2008-2014 (from Norw. Met. Inst.) and 1961-1990-normal.

February and March 2010, December 2012 and March 2013 were much colder than the 1961-90 norm, while August 2009 and July 2014 were significantly warmer than the normal. The most consistent homogeneous trend (smallest year-to-year variability) seems to occur in autumn and early winter. With respect to precipitation, the most noticeable feature is the large number of months in the period May-August with severe deficits compared to the normal, in several years less than 50%. This is, of course, of particular interest for a wetland ecosystem, as the dry period coincides with the growing period. Both 2008, 2009, 2014 and to some degree 2011 fall into this class. Dry and cold periods in winter, on the other hand, such as January and February 2014, and December 2012 may cause severe plant damage through deep freezing and icing.

The years 2013 and 2014 included in this final analysis, add several interesting conditions to the dataset analyzed and published by Lund et al. (2015). 2013 was a warmer and wetter year than both the normal and the 7-year period, especially from

May and through December. 2014, on the other hand was characterized by a cold spring and early summer, followed by a very warm summer and autumn, which in addition were very dry. In particular, much of June experienced a cold spell which brought vegetation on hold for almost two weeks, while July was characterized by virtually mid-latitude drought conditions.

The precipitation patterns have a great influence on the soil water content, which in turn is very important for a wetland ecosystem. Figure 3 summarizes this parameter as measured on a wet spot at the flux site.

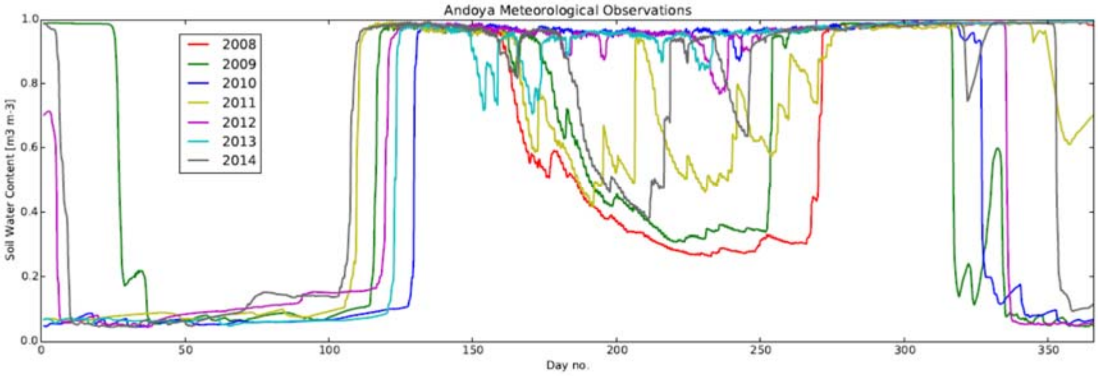

Figure 3: Soil water content [m3 m-3] at a wet spot at the Andøya flux site, all years 2008-2014.

While in 2010, 2012 and 2013 soil water content was close to 1.0 from thawing in spring to re-freezing late in the year, there were extended periods of severely reduced soil water content in 2008, 2009, 2011 and 2014. In 2008, the summer drought practically persisted over the complete growing season (DOY 160 – 270).

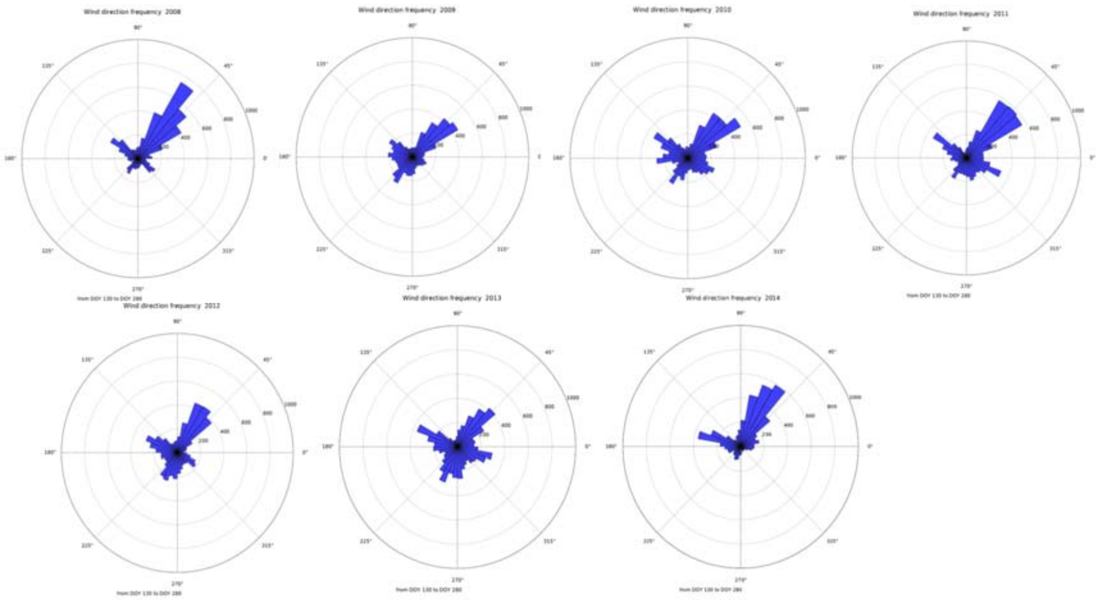

Figure 4: Polar diagrams of wind direction (direction the wind is blowing from) for the period DOY 130 to 280. Upper row from left: 2008 – 2011, lower row from left: 2012 – 2014

The comparatively dry conditions during the summer half year are accompanied by a consistent picture of the wind regime. An evaluation of wind data recorded at the flux site revealed that in practically all years, the dominant wind direction during the growing period is Northeast. This is particularly pronounced in the dry years of 2008 and 2014. Wet summers, such as 2010 and 2012, have much more frequent winds from the western half circle, while in the warm and wet year 2013, winds are almost balanced between all segments of the wind direction circle. The polar diagrams of wind directions for all years during the growing season are shown in Figure 4.

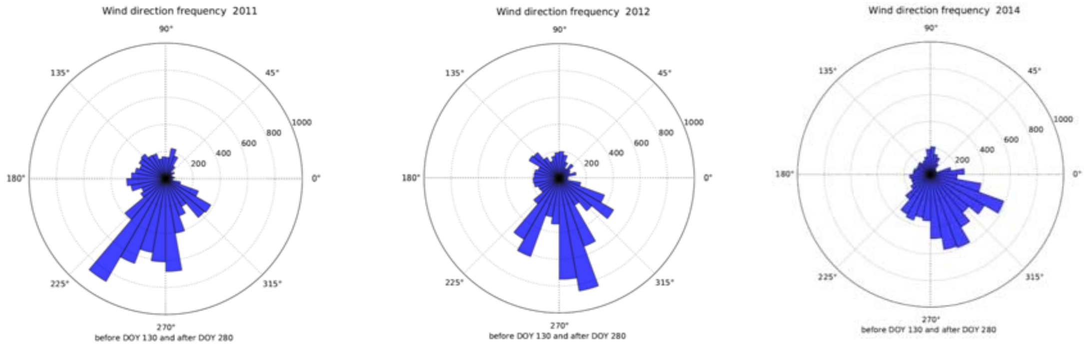

Figure 5: Polar diagrams of wind direction (direction the wind is blowing from) for the periods DOY 0 - 130 and 280 - 365. Left: 2011, centre: 2012, right: 2014.

On the other hand, during the winter half year, winds are generally blowing from the south, more from the Southeast in cold and dry winters and rather from South and West in mild and wet winters, while Northeasterly winds occur very rarely. Figure 5 shows two examples (winter seasons 2011 and 2012); in 2011 the site was almost permanently covered with snow, while in 2012 there were extended periods of bare frozen ground.

3 Eddy covariance flux measurements

The mean annual CO_2 budget of the Andøya blanket bog across all complete measurement years (2009–2012) amounted to −19.5 ± 18.3 g C m^{-2}. However, these estimates should be interpreted with caution as the total uncertainty was estimated to be on average 75.1 ± 4.9 g C m^{-2}. Of the separate components in the uncertainty analysis, the uncertainty relating to the choice of temperature threshold for applying the self-heating correction (Burba et al 2008) was overriding all other compo- nents (Table 1). For the period May–September, the CO_2 budget was −111.8 ± 10.3 g C m^{-2}, with an associated uncertainty of 51.9 ± 5.5 g C m^{-2} (Table 1).

Table 1: Total uncertainties for annual and seasonal (May-September) CO2 sums in g C m-2

Annual		
Year	CO_2-C	Uncertainty
2009	-7.2	78.6
2010	-0.5	72.7
2011	-34.5	69.4
2012	-35.7	79.8
Seasonal		
Year	CO_2-C	Uncertainty
2009	-118.0	53.3
2010	-96.4	55.1
2011	-117.6	43.7
2012	-115.1	55.4

Reduced wetness in the top-soil during summer- time in 2008 and 2009 did not have an apparent effect on NEE (net ecosystem exchange of CO2) and its components (GPP, gross primary production and Reco, ecosystem respiration). Instead, the wettest year, 2010, had the lowest summertime values of net CO2 uptake (lowest NEE), GPP and Reco (Figure 6). This year was characterized by low Ts (Figure 1) and low PPFD during June–July, which may have slowed down vegetation growth. Light response curves based on data from July each year indicate that 2008 and 2010 had the lowest CO_2 uptake rates at PPFD > 1000 µmol m^{-2} s^{-1}.

The estimated annual CO_2 budget 2009–2012 of the Andøya blanket bog (−19.5 ± 18.3 g C m^{-2}) is higher (i.e. weaker CO_2 sink) than a 3-year mean from the Stordalen subarctic mixed peatland (−90.0 ± 5.6 g C m^{-2}; Christensen et al (2012)), a 12- year mean from the Degerö boreal fen (−58.0 ± 21.0 g C m^{-2}; Peichl et al (2014)), and a 9-year mean from the Glencar Atlantic (i.e. maritime) blanket bog (−55.7 ± 18.9 g C m^{-2}; McVeigh et al (2014)), but similar to a 6-year mean from the Kaamanen subarctic fen (−21.5 ± 19.8 g C m^{-2}; Aurela et al (2004)).

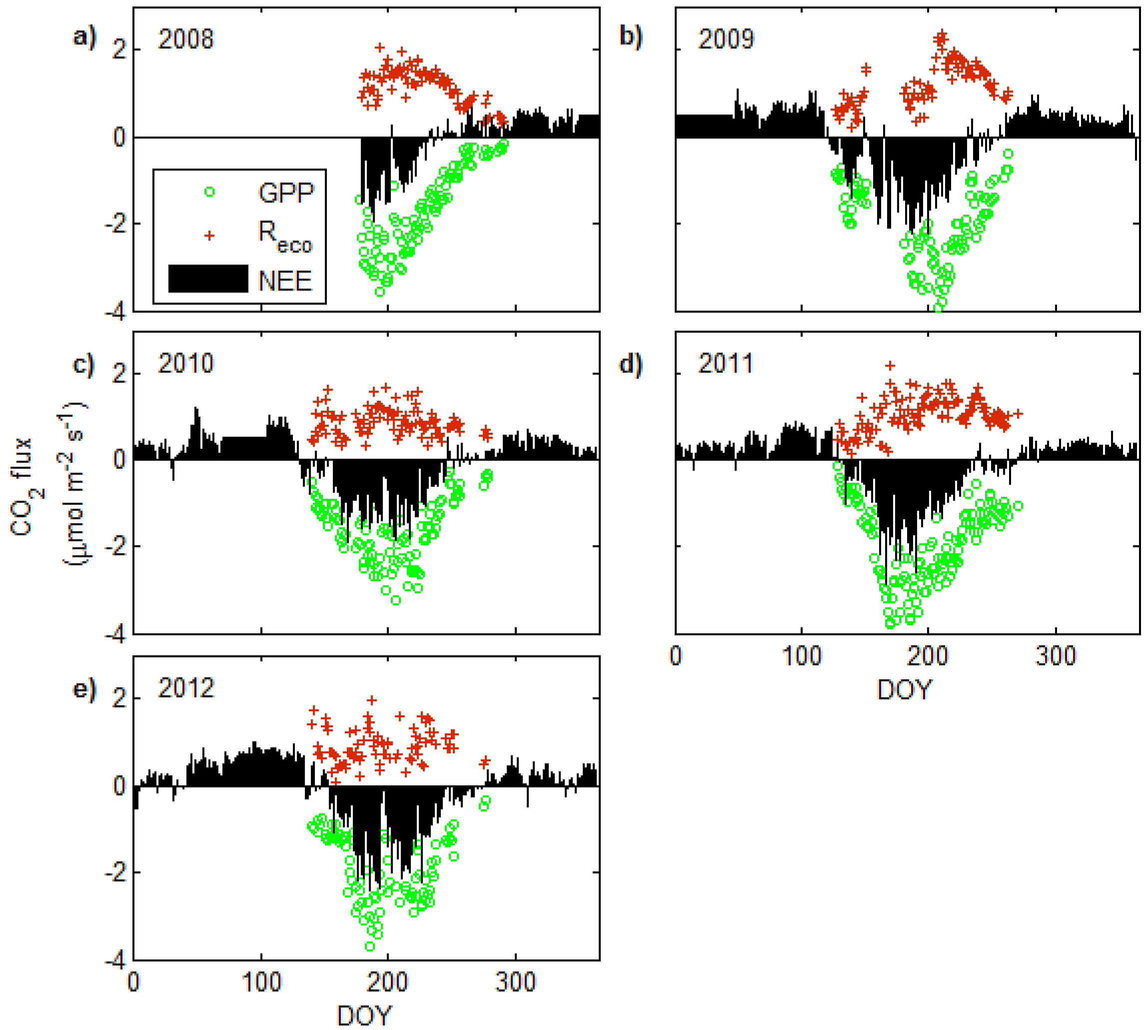

Figure 6: . Daily means of measured and gap-filled NEE and modelled GPP and Reco 2008-2012 (from Lund et al., 2015).

However, as noted previously, annual budget estimates derived from EC measurements with an open-path sensor should be interpreted with caution, due to uncertainties regarding the application of the self-heating correction (Burba et al 2008). This correction especially applies to measurements during wintertime in cold areas, and, therefore, several previous studies on northern peatlands using a similar sensor have not applied the self-heating correction to growing season data (see Kwon et al 2006, Lafleur and Humphreys 2007, Humphreys and Lafleur 2011, Parmentier et al 2011, Christensen et al 2012, McVeigh et al 2014). As such, our growing season fluxes are directly comparable with those studies. The seasonal (May–September) CO2 sink at Andøya (−111.8 ± 10.3 g C m^{-2}) was slightly stronger compared with Glencar, where the corresponding budgets varied from −75 to −100 g C m^{-2} (McVeigh et al 2014), likely due to higher mid-summer radiation and higher plant cover.

Based on mean summer-time fluxes and annual budgets, there was no apparent long-lasting effect of dry conditions on the CO_2 exchange, indicating an inherent resistance of the Andøya peatland to dry conditions. However, for extended drought periods, increased heterotrophic respiration may become increasingly important for the R_{eco} signal (Ise et al 2008). As the summer months during our study period were not significantly warmer than the long-term average, although slightly drier, we may not yet have captured an extreme drought event in our measurement record.

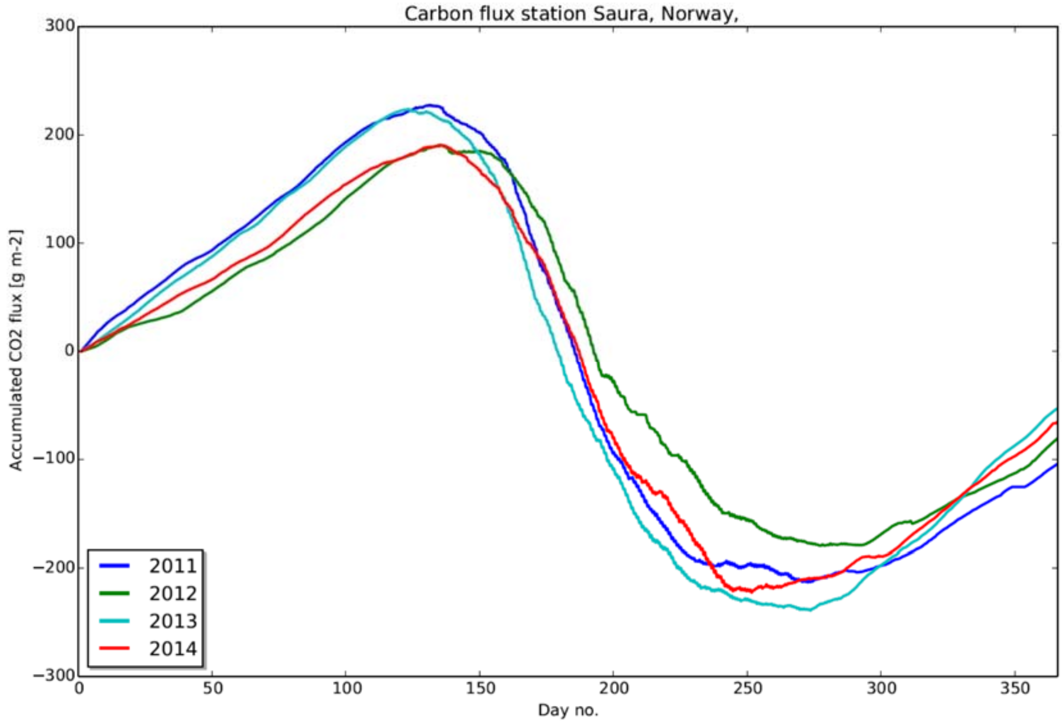

Figure 7: Accumulated carbon fluxes in the course of one year in 2011, 2012, 2013 and 2014, calculated with a preliminary analysis package by G. Hansen.

Carbon flux measurements in 2013 and 2014 have been analyzed with a preliminary analysis package, which makes a direct comparison with the above results difficult, because small, but systematic, differences in the flux calculation accumulate to rather large discrepancies over a period of one year. Figure 7 shows the accumulated fluxes of these two years compared to 2011 and 2012, all calculated with the preliminary analysis package. Over long periods of the year, 2011 and 2013 develop similarly, and so do 2012 and 2014. The differences occurring throughout the year can partially be linked to meteorological conditions:

- The earlier onset of carbon accumulation in 2013 compared to 2011 coincides with higher May temperatures in 2013
- Lower accumulation rates in June in 2012/2014 compared to 2011/1013 relate to lower temperatures in June in these two years
- The slowing carbon uptake in 2014 from day 190 to day 220 followed by an acceleration coincides with dry soil conditions in the first period followed by a significant increase in soil water content.

On the other hand, there are also significant dissimilarities, especially at and after the end of the growing season. E.g., both temperatures and precipitation are rather similar in the period September – December in 2011 and 2013, while the accumulated carbon fluxes differ strongly. Of course, one has to keep in mind that the accuracy of an open-system EC flux system is strongly reduced in the non-growing season, so EC flux stations at high latitudes (where the non-growing season is rather long) should preferably equipped with a closed system or – even better – both systems.

4 Methane flux measurements

In 2012, the eddy covariance setup at the station was extended with a Los Gatos Fast Methane Analyser to ascertain the amount of methane emitted from the Saura flux site. Methane fluxes were measured with the closed path eddy covariance technique, where air is sucked through a tube into an analyser, rather than the open path technique used for CO_2 and water vapor. The advantage of this technique is that sensor heating is not an issue (Burba et al., 2008), which leads to less uncertainty compared to the CO_2 measurements.

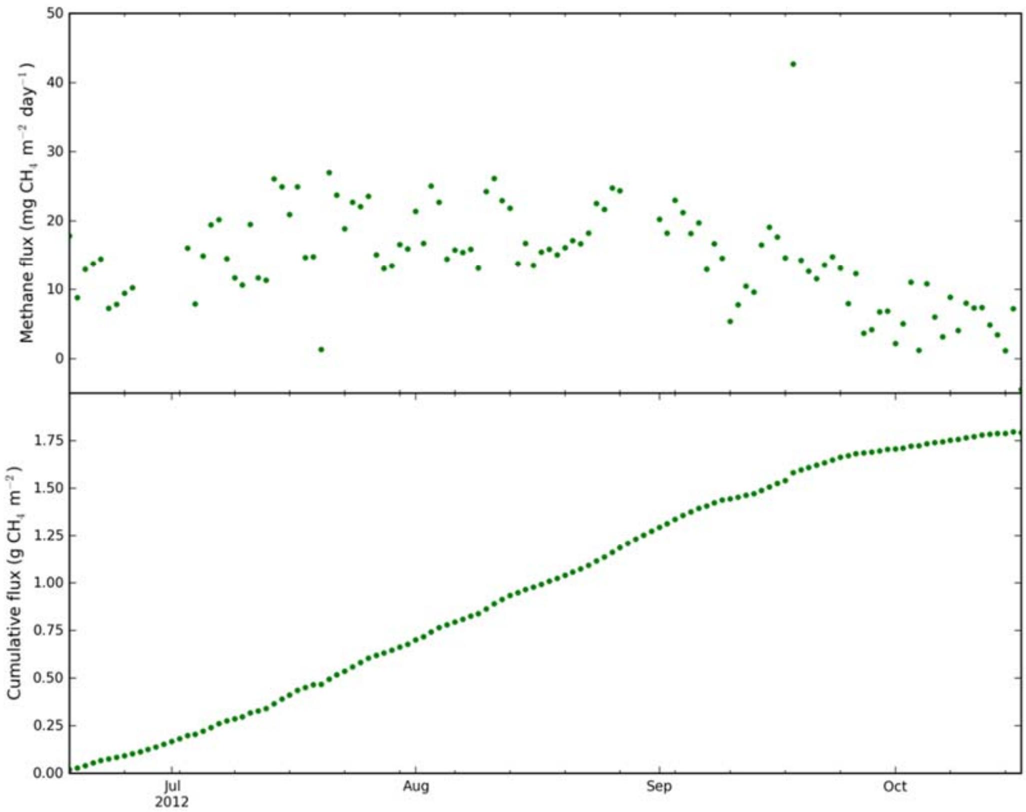

Figure 8: Daily average methane flux in mg CH4 day-1 (top panel) and cumulative flux in g CH4 (bottom panel).

From the measurements, it is apparent that the Andøya peatland is a source of methane with an average July/August flux of 17.9±5.2 mg CH_4 m^{-2} day^{-1} (Figure 8). During the 2012 measurement period, a total of ~1.8 g CH_4 m^{-2} was emitted from the peatland, but this excludes the spring period when the methane analyser was not yet installed. Spring fluxes can be relatively high, so it's reasonable to assume that the total amount of methane emitted during 2012 exceeded 2 g CH_4 m^{-2}. At the end of our measurement period, by the middle of October, fluxes returned to near zero and winter fluxes are expected to be low in this permafrost-free environment.

Methane emissions of this magnitude are comparable to other Arctic sites (Fan et al., 1992; Grant et al., 2015; Sachs et al., 2010) and only a factor of two lower than the Kaamanen peatland located at the same latitude in Finland (Hargreaves et al., 2001). However, the amount of emitted methane is small compared to Stordalen (148.8 ± 62.4 mg CH_4 m^{-2} day^{-1} (Jackowicz-Korczyński et al., 2010), which is located about 150 km inland from Andøya. This is probably due to the large difference in vegetation between the two sites. The Stordalen mire has a large fen with standing water, highly productive vascular plants and warmer summers – all factors that strongly contribute to high methane fluxes. The Andøya peatland, despite its high precipitation, has few spots with water above the surface and the cover of cryptogams (lichens and bryophytes/mosses) is almost twice as high as the cover of vascular plants (76% versus 44%). Vascular plants are a strong control on methane fluxes, since they transport methane to the atmosphere effectively through their aerenchyma and also supply substrate to methane producing microorganisms. The lower amount of vascular plants may therefore explain the lower fluxes from the Andøya peatland. Still, the observed fluxes can't be ignored when the net greenhouse gas budget of the peatland is considered and methane emissions may change significantly from year to year. In the long-term, changes in precipitation, temperature, vegetation structure and peatland management are certain to affect methane fluxes from this environment (Petrescu et al., 2015). Continued monitoring and modeling of the peatland can provide more insight into the development of the carbon balance of this peatland with climate change.

5 Aquatic dissolved organic carbon export

Aquatic dissolved organic carbon export from the peatland was quantified with a combination of empirical measurements (discharge and water chemistry) and the process-based model INCA-C. INCA-C is a dynamic, semi-distributed, process-based model that requires daily time series of precipitation, temperature, soil moisture deficit, and hydrologically effective rainfall to simulate daily discharge and daily DOC concentrations (biogeochemical sub-model) (Futter et al. 2007).

Water flow velocity and water level were monitored from December 2012, in the culvert (1.095 m in diameter) with an ISCO 2150 Area Velocity module that uses continuous wave Doppler technology to measure streamflow and a pressure transducer to measure water height. The pressure transducer was manually calibrated when monitoring started on 1 December, 2012. Discharge is calculated automatically using diameter, flow, and height with the software Flowlink. Logging intervals are 15 minutes, and data are sent twice weekly to the Norwegian Institute for Water Research (NIVA). Daily discharge was calculated as the mean of daily observations.

The stream that drains the catchment was monitored for water chemistry from August 2011 until May 2014. Grab samples were taken by local observers, mostly at two to three week intervals and occasionally longer when thick snow layers hindered sampling. The samples were taken according to monitoring procedures under the International Cooperative Programme on Assessment and Monitoring Effects of Air Pollution on Rivers and Lakes and the national acid deposition monitoring programme (ICP Waters 2010), stored overnight in the dark at 4 ^{o}C before being sent by airmail to the accredited laboratory at NIVA. Here, water samples were analyzed for pH, major cations and anions and total organic C (TOC). Sixty percent of all samples were also analyzed for DOC (filtered by 0.45 µm). DOC was on average 96% of TOC, which justifies our assumption that TOC can be used as a proxy for DOC.

Climate data from the nearby met.no station in Andøya and modelled deposition data were used to run a hydrological model to simulate discharge, and which was calibrated using measured daily discharge. Streamwater DOC was used to calibrate INCA-C for 2011-2013 (see Figure 9), which was then run for the period 2000 to 2013. Key parameters controlling DOC production and transport include thermal conductivity of the soil, temperature-dependency and soil moisture dependency of process rates, rates of DOC production, sorption and desorption in topsoil and subsoil, litter production, DOC production from litter, sensitivity of (de)sorption rates to soil solution chemistry, and fraction of labile soil organic carbon C of the soil organic carbon C pool.

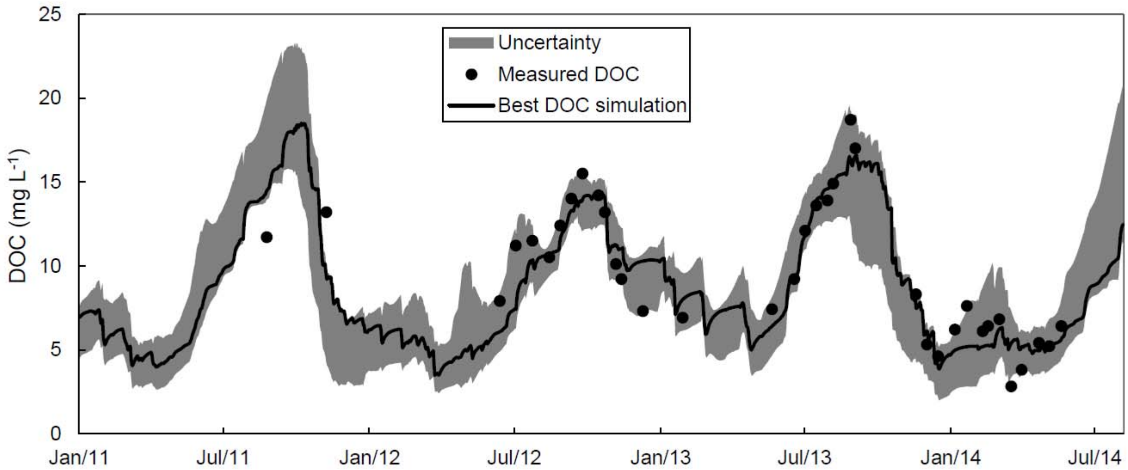

Figure 9: Measured and simulated DOC in the stream at the Andøya peatland. Grey area indicates uncertainty in the simulations.

Simulated mean annual DOC export between 2000 and 2013, based on the best parameter set, was 7.2±0.7 g C m^{-2}, with a maximum of 8.3 g C m^{-2} in 2013 and a minimum of 5.9 g C m^{-2} in 2009. The interannual variation was similar to the uncertainty interval of simulated annual DOC export (±15%), calculated as the 1.96 standard deviations of the mean of the 100 best performing, equally likely, parameter sets. The aquatic DOC export was roughly 35% of the net ecosystem land-atmospheric CO2 exchange at Andøya during 2009 to 2012.

The size of the aquatic DOC export indicates that the peatland in some years may be a source of CO_2 to the atmosphere. For a full carbon balance, aquatic export of inorganic C should also be estimated. However, in this peatland hydrological contact with the subsurface geological calcareous layer leads to large increases in alkalinity, as indicated by the streamwater monitoring data. Thus, CO_2 from soil weathering also contributes to streamwater CO_2 and should be factored out in an estimation of streamwater CO_2 export. Daily average NDVI values during growing seasons 2009-2012 indicated maximum values between 0.6 and 0.7 (Figure 9). There were no apparent differences across years in NDVI evolution using unfiltered data, which can be partly attributed to extended periods with missing data and a fairly high variation in the time series.

6 Spectrometer measurements and remotely sensed data

Approximately 30 m south of the eddy covariance system, an existing mast was equipped with two autonomous TriOS Ramses hyper-spectral radiance sensors (wave-length range: 320-960 nm). One sensor measured incoming radiance (irradiance), while the second, mounted at an (downward) angle of 45°, measured surface reflected radiance. The TriOS sensor has a wavelength range of 320 - 950 nm. The radiance sensor measured the surface at an angle of 45° while the irradiance meter was faced vertically up (90°). Since the sensors do not cover the SWIR wavelengths, only the NDVI-values (Tucker 1979) were used in this study in order to monitor the development of the growing season from year to year. Normalized difference vegetation index (NDVI) was calculated based on the spectral data set. The spectrometers were not in use in the beginning of the growing season 2010 and were also switched off in Mid-October due to maintenance.

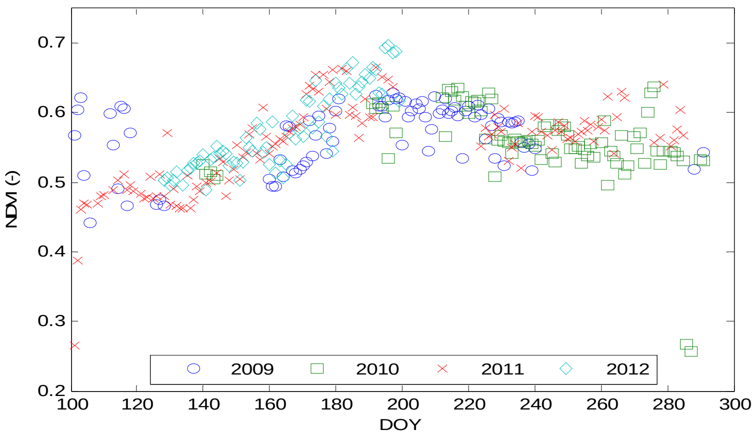

Figure 10: NDVI-plots for the years 2009-2012 for the Saura eddy flux tower site.

We have plotted the NDVI-curves using filtered data for the years 2009, 2010 and 2011 based on the spectrometer data in Figure 11, and we can now observe the steep increase of the NDVI curves in the beginning of the growing season with a subsequent maximum in July.

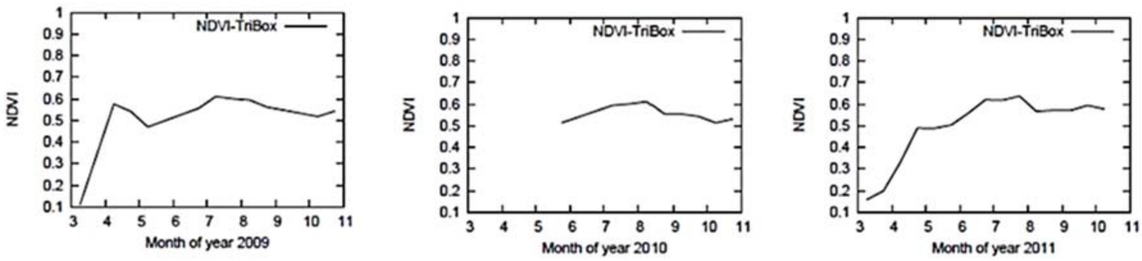

Figure 11: NDVI-plots for the years 2009-2011 for the Saura eddy flux tower site. The device was not in use in the beginning of the growing season 2010 (until day 145).

The exception is the year 2010 in which the peak of NDVI was in August, a month later than in 2009 and about two weeks later than in 2011. The slight reduction of the NDVI measured during the autumn indicates another development of the growing season compared to e.g. deciduous forests and grasslands (Tucker 1979). The reason for this is that the bog system mainly consist of mosses (*Sphagnum* spp.) and lichens (*Cladonia* spp.). Mosses exhibit distinctly different spectral characteristics from vascular plants in the visible, near-infrared (NIR) and short-wave infrared (SWIR) regions. The moss reflectance in the NIR spectral region is typically less reflective than the same region in vascular plants and is characterized by strong water absorption features located at approximately 1000 and 1200nm.

Since the absorption of *Sphagnum* reflectance is narrow both for NIR (peak 850nm) and the red, the NDVI methods do not work well for characterization of biomass or greenness in peat mires (Bubier et al. 1997). Lichens have also reduced contrasts between NIR and Red (Bubier et al. 1997), but Nordberg & Allard (2002) used NDVI in order to monitor lichen cover with satisfactory results. Since NDVI is commonly used also in monitoring of bogs (Schubert et al. 2010), we chose this index in this study.

In addition, the Photochemical Reflectance Index values (PRI) values were calculated on the basis of the spectrometer data. The Photochemical Reflectance Index (PRI) derived from the narrow-band spectrometer or hyperspectral sensors is a spectral index increasingly being used as an indicator of photosynthetic efficiency (Garbulsky et al. 2011). Because the PRI measures plant responses to stress, it can be used to assess general ecosystem health using continuous hyper-spectral measurements and remote sensing. PRI is defined by the following equation:

$$PRI = \frac{(p531 - p570)}{(p531 + p570)}$$

The PRI values are mainly below -0.1 when the environment is taking up CO_2 and near and above 0 when the environment emits CO_2 (Gamon et al. 1992; Garbulsky et al. 2011).

In Figure 12, we present the PRI-measurements from the Saura-site. The curves plotted for the three years in Figure 12 indicate that bog emitted CO_2 in the beginning of the growing season, took up CO_2 (acted as a sink) between day 150 and day 270, with a subsequently increase and hence release of CO_2 in the end of growing season. We compared PRI-values with the CO_2 flux data obtained from the Eddy-Covariance tower and this comparison assumed higher PRI-values in the beginning (before day 125) and the end of the growing season (after day 280) when the bog emits CO_2 and lower values in the peak season when the bog take up CO_2. The exception is also here the growing season of 2010 - with a significant later indication of the start of the CO_2 uptake (around day 200) compared to 2009 and 2011 (Figure 12).

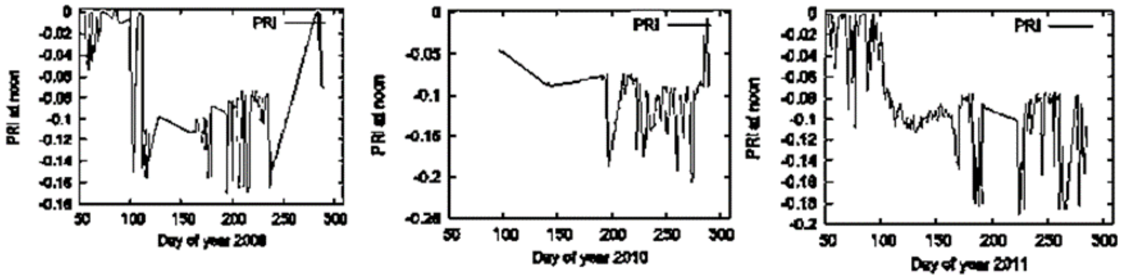

Figure 12: PRI-plots for the years 2009-2011 for the Saura eddy flux tower site. The spectrometer was not in use in the beginning of the growing season 2010 (until day 145).

The results show that the measurements vary a lot during the growing season. Care should be taken in evaluation and interpretation of the curves (Garbulsky et al. 2011), especially in the beginning and the end of growing season so far north which may be heavily influenced and confounded by multiple environmental factors (Garbulsky et al. 2011) like storms, rain and snow. Additionally, like any 2-band index that may be affected by multiple factors, the interpretation of PRI needs further work to understand and constrain these effects (Garbulsky et al. 2011).

Finally, we used remotely sensed data from the satellite Terra MODIS and the satellite series NOAA AVHRR in order to compare and scale up the spectrometer data. From the latter one we have received the latest version (third generation) of the Normalized Difference Vegetation Index (GIMMS $NDVI_{3g}$) data set generated from the Advanced Very High Resolution Radiometers (AVHRR) onboard a series of NOAA satellites (NOAA 7, 9, 11, 14, 16, 17 and 18) for use in this study. In Figure 13, we have plotted the NDVI-curves over the years 2008-13 for the Saura site.

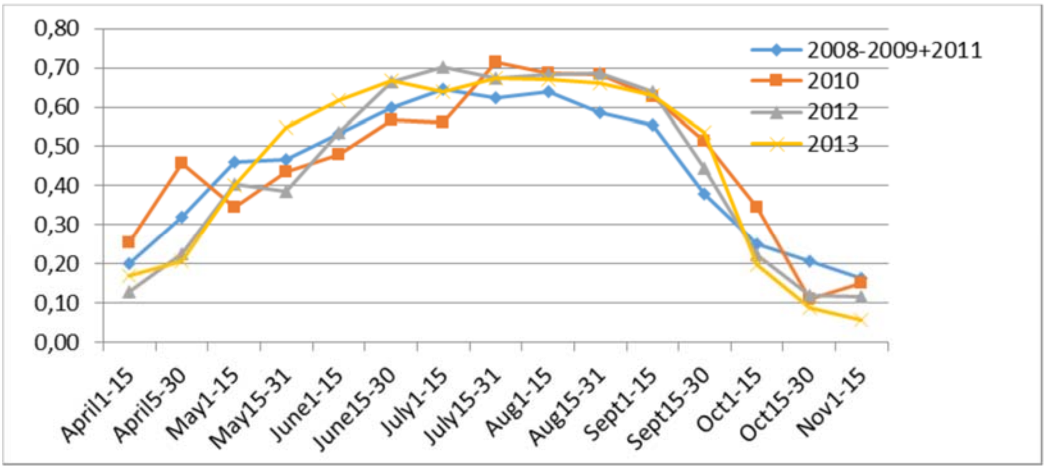

Figure 13: NDVI curves for the years 2008-2013 based on the AVHRR GIMMS3g data.

We can also here based on the GIMMS$_{3g}$ data observe that the year 2010 shows another development during the spring-early summer season and with a peak NDVI in the beginning of August. This is in accordance with the spectrometer based NDVI and PRI indices presented in Figure 11 and Figure 12, which show a later peak NDVI and later uptake of CO_2 that particular season, as also shown for the NDVI from 2010 in Figure 14.

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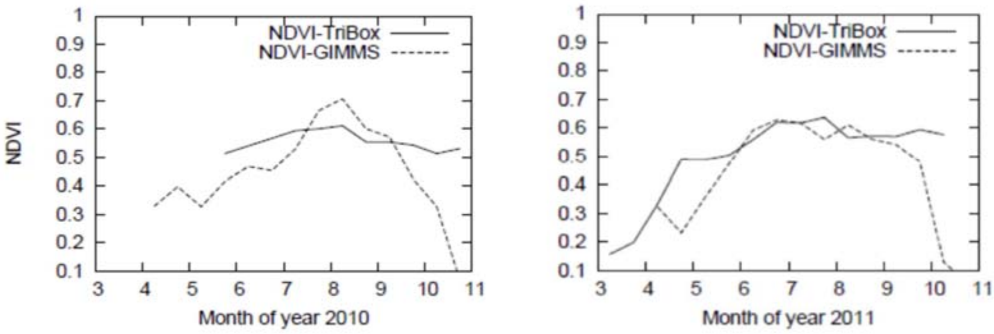

Figure 14: Spectrometer derived NDVI versus GIMMS3g derived NDVI for the years 2010 and 2011.

In Figure 14, we can observe that the peak of the season is coincides well for the two NDVI-curves with the development during the growing season. Partly this can be explained by the coarse spatial resolution of the GIMMS$_{3g}$ data set that integrates information from both bogs, lakes, shrubs and forests within one pixel, while the footprint of the spectrometer is only 0.9 m^2 of which more than 50% is lichens and mosses. This leads to another development of the curve especially in the autumn (see discussion about these phenomena above). We will use the latest version of MODIS (version 6, soon coming) in order to analyse this further.

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ABSTRACT
Greenhouse gas exchange between terrestrial ecosystems and the atmosphere are an important element of the climate system. Especially boreal and polar wetlands and peatlands may play a crucial role for the future development of atmospheric carbon dioxide and methane concentrations, because they contain stores of these gases in the same order of magnitude as the current atmospheric load. The aim of this project was to estimate the fluxes of CO2 and CH4 from an oceanic wetland in North-Norway. Seven years of observations reveal that carbon exchange from this ecosystem is comparable to that of moderate zone coastal wetlands, but distinctly different from alpine and continental wetlands at the same latitude in Sweden and Finland. The seven-year record of meteorological data reveals that the observed period was significantly warmer (especially during winter) and drier (especially in summer) than the climate reference period 1961-1990. Carbon fluxes during the growing season are sensitive to both draught, cold spells and soil climate conditions before the onset of the growing season, but the annual Net Ecosystem Exchange is much less variable.

NORWEGIAN TITLE
Effekter av klimavariabilitet på vegetasjon og karbonopptak I en nordnorsk kystmyr

KEYWORDS		
Climate	Greenhouse gas emissions	Terrestrial ecosystem

ABSTRACT (in Norwegian)
Drivhusgassutveksling mellom terrestre økosystemer og atmosfæren er et viktig element i klimasystemet, og utslipp fra boreale og polare våtmarksområder er muligens avgjørende for den videre utviklingen av atmosfæriske konsentrasjoner av CO2 og metan, fordi de inneholder like mye av disse gassene som atmosfæren i dag. Målet med dette prosjektet var å estimere flukser av CO2 og metan i en nordnorsk kystmyr. Sju år med observasjoner viser at disse er sammenlignbare med verdier fra kystmyr ved lavere breddegrader og klart forskjellige fra alpine og mer kontinentale myr i Nord-Sverige og Nord-Finland. Den også sju år lange serien av meteorologiske data dokumenterer at været i denne perioden var både signifikant varmere (hele året, men spesielt om vinteren) og tørrere (spesielt om sommeren) enn normalen fra perioden 1961-1990. Karbonflukser i vekstperioden er følsomme for både tørke, kulde og forholdene i jordsmonnet før vekstperioden, men netto-økosystem-utvekslingen for et helt år varierer langt mindre.

** Classification*	*A*	*Unclassified (can be ordered from NILU)*
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