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High-resolution satellite data reveal an increase in peak growing season gross primary production in a high-Arctic wet tundra ecosystem 1992–2008

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ABSTRACT

Arctic ecosystems play a key role in the terrestrial carbon cycle. Our aim was to combine satellite-based normalized difference vegetation index (NDVI) with field measurements of CO_2 fluxes to investigate changes in gross primary production (GPP) for the peak growing seasons 1992–2008 in Rylekærene, a wet tundra ecosystem in the Zackenberg valley, north-eastern Greenland. A method to incorporate controls on GPP through satellite data is the light use efficiency (LUE) model, here expressed as $GPP = \varepsilon_{peak} \times PAR_{in} \times FAPAR_{green\_peak}$; where ε_{peak} was peak growing season light use efficiency of the vegetation, PAR_{in} was incoming photosynthetically active radiation, and $FAPAR_{green\_peak}$ was peak growing season fraction of PAR absorbed by the green vegetation. The ε_{peak} was measured for seven different high-Arctic plant communities in the field, and it was on average 1.63 g CO_2 MJ^{-1}. We found a significant linear relationship between $FAPAR_{green\_peak}$ measured in the field and satellite-based NDVI. The linear regression was applied to peak growing season NDVI 1992–2008 and derived $FAPAR_{green\_peak}$ was entered into the LUE-model. It was shown that when several empirical models are combined, propagation errors are introduced, which results in considerable model uncertainties. The LUE-model was evaluated against field-measured GPP and the model captured field-measured GPP well (RMSE was 192 mg CO_2 m^{-2} h^{-1}). The model showed an increase in peak growing season GPP of 42 mg CO_2 m^{-2} h^{-1} y^{-1} in Rylekærene 1992–2008. There was also a strong increase in air temperature (0.15 °C y^{-1}), indicating that the GPP trend may have been climate driven.

1. Introduction

Climate warming is proceeding faster in the Arctic than elsewhere on Earth, and current estimates suggest a substantial potential for change in these regions (ACIA, 2005). Terrestrial ecosystems of the Arctic currently store large amounts of carbon, and while the northern permafrost region covers only about 16% of the global soil area, it holds approximately 50% of the global belowground organic carbon pool (McGuire et al., 2009; Tarnocai et al., 2009). Wet tundra ecosystems play a key role in controlling the terrestrial carbon cycle since the prevailing waterlogged, anoxic and cool soil conditions effectively reduce the rates of soil organic matter decomposition, which favors the formation of peat. Peat accumulation is primarily governed by the balance between carbon uptake by gross primary production (GPP) and carbon release through respiration. Changes in the sink strength of high-Arctic ecosystems are therefore highly affected by responses of these processes to climate variations. Several studies that investigated remotely sensed data from satellites and the normalized difference vegetation index (NDVI) have shown that there is a greening trend in northern ecosystems, indicating an increase in plant productivity (e.g. Myneni et al., 1997; Verbyla, 2008). These studies were mainly based on remote sensing data, and did not include in situ measurements. Additionally, they have mainly focused on boreal, low-Arctic, and sub-Arctic areas and very few studies exist from the high-Arctic. In the high-Arctic, temperatures are colder, and the growing season is shorter than in lower Arctic regions. Consequently, high-Arctic ecosystems normally experience greater temperature constraints, which presumably make them more sensitive to rising temperatures.

A widely applied approach within remote sensing is to estimate plant productivity by a light use efficiency (LUE) model (Monteith,

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1972, 1977). The LUE-model allows GPP to be estimated from the photosynthetically active radiation absorbed by the green vegetation ($APAR_{green}$). $APAR_{green}$ can in turn be computed from incoming photosynthetically active radiation (PAR_{in}) and the fraction of photosynthetically active radiation absorbed by the green vegetation ($FAPAR_{green}$). This turns the LUE-model into:

$$GPP = \varepsilon \times PAR_{in} \times FAPAR_{green} \quad (1)$$

where ε is the light use efficiency of the vegetation. Here, GPP was defined as the total hourly ecosystem photosynthesis (g CO_2 m^{-2} h^{-1}). The LUE-coefficient (ε) was initially considered to be relatively constant, but substantial differences have been found between plant communities, development stage, species composition, and stress level (Goetz and Prince, 1996; Gower et al., 1999). It is therefore important to assess LUE for various plant communities when GPP is to be estimated over a larger area. Several studies including various vegetation types have shown a near-linear or linear correlation between FAPAR and NDVI (e.g. Huemmrich et al., 2010; Myneni and Williams, 1994). Consequently, satellite-based NDVI is commonly used to estimate FAPAR.

The main objective of the study was to investigate if there has been a change in peak-growing season GPP from 1992 to 2008 in Rylekærene, a high-Arctic wet tundra ecosystem. A second aim was to parameterize the LUE-model for the peak growing season for the plant communities dominating the area, and to investigate the relationship between in situ measured $FAPAR_{green}$ from the peak growing season and remotely sensed NDVI.

2. Materials and methods

2.1. Site description

The study took place in Rylekærene, a wet tundra ecosystem in the Zackenberg Research Area (74°28′N 20°34′W), in north-eastern Greenland. The Zackenberg valley is located in the high-Arctic zone but has a relatively mild climate due to its coastal location. Average temperature of the warmest month is 5.8 °C, and mean annual temperature is −9 °C (GeoBasis, 2010). The Zackenberg valley is underlain by continuous permafrost and the active layer thickness ranges between 0.5 and 1.0 m (GeoBasis, 2010). Since 1995, extensive ecological, biogeographic, climatic, and hydrological research and monitoring has been carried out in the Zackenberg research area (Meltofte et al., 2008).

To obtain a detailed description of the plant communities within the Rylekærene area, the dominant plant communities were recorded in the field every 15 m^2 within a 1.4 km^2 rectangle surrounding Rylekærene (Fig. 1). The 15 m^2 sampling plots were separated into the dominant plant communities identified in the area; continuous fen (flat areas dominated by *Eriophorum scheuchzeri*, *Carex stans* and *Dupontia psilosantha*), hummocky fen (hummocks dominated by *Eriophorum triste, Salix arctica* and *Arctagrostis latifolia*), grassland (dominated by *A. latifolia*, *E. triste*, and *Alopecurus alpinus), S. arctica* snowbed, *Cassiope tetragona* heath, *Dryas octopetala* heath, and *Vaccinium uliginosum* heath. Non-vegetated areas were separated into gravel and water. This 1.4 km^2 rectangle will from now on be referred to as the study area.

2.2. Snow data, in situ NDVI and satellite-based NDVI

The start of the growing season carbon exchange is highly governed by day of year (DOY) of snowmelt in Arctic ecosystems (Mastepanov, 2010). The snow depth has been measured continuously since 1998 at the climate station (C1) in the center of the Zackenberg valley (Fig. 1) (GeoBasis, 2010). The floor of the Zackenberg valley is relatively flat, and it is assumed that the conditions at C1 are also representative for the study area. The DOY when snow depth decreased below 10 cm was used as a proxy for DOY of snowmelt end (DOY_{10cm}). Modeled snow cover from 1989 to 2004 (Buus-Hinkler et al., 2006) were used to estimate DOY_{10cm} before 1998. An ordinary least-squares linear regression was fitted between the DOY_{10cm} and modeled DOY with 18% snow cover of the Zackenberg valley for the years 1998–2004 ($R^2 = 0.96$, $p < 0.0001$, $df = 5$). Snow cover of 18% was used as a proxy for DOY of snow melt end since the major snow period is considered to end when the snow cover drops below this percentage (Buus-Hinkler et al., 2006). The regression line was then used to estimate DOY_{10cm} for 1992 to 1997.

In 2008 and 2009, incoming and reflected red (centered at 655 nm, bandwidth 48 nm) and near infrared (centered at 856 nm, bandwidth 56 nm) radiation was measured at the tower site (Fig. 1) using vertically oriented hemispherical two channel sensors (SKR 1800, Skye instruments, Llandridod wells, UK) during the periods 24 June to 1 September 2008, and 16 May to 26 August 2009. These data were used in a pre-analysis to determine the peak-period of NDVI during the growing season. The in situ measured radiation was used to estimate NDVI as:

$$NDVI = (\rho_{NIR} - \rho_{red})/(\rho_{NIR} + \rho_{red}) \quad (2)$$

where ρ_{NIR} and ρ_{red} are the hemispherical-directional reflectance factors in the near infrared (NIR) and the red bands, respectively. Based on the in situ measurements of NDVI in 2008 and 2009, the period between 35 and 51 days after DOY_{10cm} were empirically chosen to represent the peak season (Fig. 2). High-resolution satellite images acquired on cloud free days with high quality within this period of the growing seasons 1992–2008 were downloaded from EarthExplorer (2010) and included in the analysis (Table 1). Satellite data at this high-Arctic site are not stored on a regular basis. Furthermore, cloudy conditions decrease the number of available images. Therefore, we have chosen to combine data from different sensors in the analysis.

Radiance measured from satellites is affected by the atmosphere (aerosols, haze, cloud shadows, atmospheric depth and water vapor), illumination variations, and slope of the terrain (reflections from adjacent pixels and shadowing effects). To be able to compare images between dates and years, all satellite imagery was converted to reflectance and atmospheric and terrain corrections were performed with the software ATCOR 3. This method uses look-up tables derived with the Modtran® 4 radiative transfer code covering a wide range of weather conditions, sun angles, and ground elevations. In addition to the preprocessing of the satellite images, sixteen ~100 m^2 points of non-vegetated flat rock surfaces assumed not to vary in reflectance between years were used as reference points to enable comparison of satellite reflectance data between years. Linear regressions with intercept set to zero were fitted with reference reflectance of all the satellite images against reference reflectance 2007. The slope of the lines was used as correction factors to recalculate reflectance of all satellite images to be comparable with 2007 (ρ_{red}: R^2 range 0.32–0.95, average R^2 0.66; ρ_{NIR}: R^2 range 0.27–0.91, average R^2 0.55). The satellite sensors provide different spatial resolution and to match data when comparing satellite imagery with differently sized pixels all images were resampled to 1 m^2 using nearest-neighbor interpolation. The average reflectance for the corresponding 15 m vegetation cover plots was subsequently calculated for each image. Finally, the NDVI was estimated according to Eq. (2) for all satellite images. The relationship between FAPAR and NDVI is relatively insensitive to pixel heterogeneity, i.e., the combination of FAPAR and NDVI is insensitive to vegetation types and different configurations of ground cover and leaf area index (Myneni and Williams, 1994). This also results in a scale independent relationship in which the same NDVI is likely to correspond to the same FAPAR, irrespective of pixel