Methane Emission from Siberian Wet Polygonal Tundra on Multiple Spatial Scales: Process-Based Modeling of Methane Fluxes on the Regional Scale, Lena Delta

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Abstract

Uncertainties in the carbon budget of high latitude ecosystems are partly due to difficulties in assessing the spatially and temporally highly variable methane emissions of permafrost soils. CH_4 contributes significantly to global warming. Arctic regions are most critically influenced by a changing climate. Modeling approaches are important tools to determine CH_4 fluxes of arctic environments. We present two process-based models to calculate methane emission from permafrost soils. Model forcing consists of ECMWF (European Center for Medium-Range Weather Forecasts) meteorological data which are validated against field measurements. Auxiliary input data is derived from satellite imagery and field measurements. A MERIS-FR land classification scheme is used to upscale emissions. Model results are validated using methane flux measurements on the landscape and small scale carried out in 2006 in the Lena Delta (72°N, 126°E) by Alfred Wegener Institute for Polar and Marine Research. The study site is characterized by arctic tundra ecosystems and continuous permafrost.

Keywords: Arctic; climate change; methane emissions; modeling; permafrost; tundra.

Introduction

Introduction

The radiative forcing due to methane—the second largest of the long-lived greenhouse gases after carbon dioxide—and its Global Warming Potential (GWP), which is about 20 times higher than the GWP of CO_2 (IPCC 2001), demonstrate the significant contribution of methane to warming of the atmosphere. The global atmospheric methane concentration has risen from a pre-industrial value of about 715 ppb to a current value of about 1774 ppb (IPCC 2007).

The observed increase in methane concentrations is very likely due to anthropogenic activity, mainly agriculture, burning of fossil fuels, and landfills. Contributions of further sources to the global atmospheric methane budget are not well determined yet (IPCC 2007) due to the difficulty in assessing the global emission rates of the natural sources, the strengths of which are highly variable in space and time (IPCC 2001).

Permafrost soils represent a large carbon reservoir, with an estimated carbon pool of about 900 Gt for frozen yedoma (ice-rich soils with high labile carbon content [Walter et al. 2003]) and non-yedoma soils excluding peatlands. The permafrost carbon reservoir exceeds that of the atmosphere (~730 Gt) and vegetation (~650 Gt) (Zimov et al. 2006).

Due to high sensitivity of the arctic soil carbon reservoir to increasing temperatures and to the large surface area, arctic regions are most critically influenced by changing climate. In thawed permafrost soils, methane is produced by specially adapted microbes under anaerobic conditions and released into the atmosphere. Extensive thawing of permafrost will release the carbon contained in the soils, hence further affecting the global carbon cycle. Model scenarios predict a severe degradation of permafrost in the Northern Hemisphere, including a northward shift of the permafrost boundary as well as an increase in active layer depth (Lawrence & Slater 2005, Zhang et al. 2007).

Studies on measuring methane flux on the landscape scale using the eddy covariance technique have been conducted by only by a few research groups (Fan et al. 1992, Friborg et al. 2000, Hargreaves et al. 2001, Harazono et al. 2006, Wille et al. 2007). Very few studies on modeling methane emission in Siberian permafrost regions on the regional scale have been performed (Bohn et al. 2007).

This study aims at modeling the methane budget of a high latitude permafrost-affected region for determining source strength, and at understanding emission patterns on a regional scale. Remote sensing techniques and ground-truth measurements are used to derive information needed as input for process-based models and to upscale modeling from single point to regional scale. We present a new approach where the methane model by Walter (1998) is modified for permafrost conditions and applied to a study site characterized by continuous permafrost.

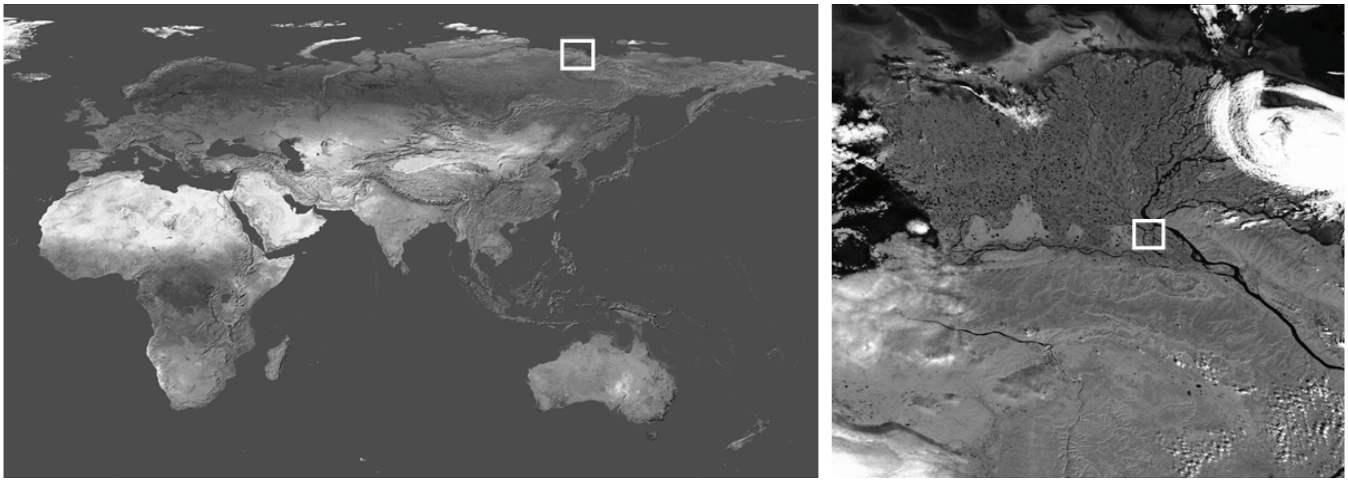

Figure 1. Geographical settings of the Lena River Delta and Samoylov Island shown in boxes (left panel: RGB composite of the globe based on MODIS data; right panel: RGB image for August 26, 2006, based on MERIS-FR data).

Materials and Methods

Study site

The Lena River Delta is located at the Laptev Sea coast in northeast Siberia (Fig. 1). It is considered a key region for understanding the underlying processes of the development and dynamics of permafrost in the Arctic under a warming climate. The region is characterized by arctic tundra ecosystems and is underlain by deep continuous permafrost.

The delta, situated at the north coast of Siberia, is the largest delta in the Arctic and one of the largest in the world (Walker 1998). It is characterized by a highly heterogeneous landscape of smaller and wider river branches and channels, as well as more than 1500 islands of various sizes on an area of about 32,000 km^2 (Walker 1998). Three major fluvial terraces with different geomorphological characteristics form the delta (Schwamborn et al. 2002). The 30-year (1961–1990) averages of mean air temperature and total precipitation measured at the meteorological station in Tiksi (eastern delta) are -13.5°C and 323 mm, respectively (Roshydromet 2004). The vegetation is mainly characterized by sedge/grass/moss wetland and sedge/moss/dwarf-shrub wetland, as well as dwarf-shrub tundra (CAVM Team 2003). The growing period is short, lasting for 60–80 days (Grigoriev 1993). The surface is characterized by wet polygonal tundra with a pronounced micro-relief (Wille et al. 2007).

Since 1998, yearly expeditions have been conducted by Alfred Wegener Institute for Polar and Marine Research, Potsdam (AWI) to study carbon dynamics and involved microbial processes and communities as well as the energy and water budget of Arctic tundra. Campaigns have been carried out on Samoylov Island (Fig. 1). Samoylov (72°22′N, 126°28′E) is representative of the active and youngest part of the Lena Delta and covers an area of approximately 7 km^2.

Model description

The methane emission model (Walter 1998) is a one-dimensional process-based climate-sensitive model to derive methane flux from natural wetlands. The processes leading to methane emission are modeled within a one-dimensional soil column which is discretized in 1 cm thick soil layers. Three different transport mechanisms that contribute to methane release from soils are taken into account and modeled explicitly; namely diffusion, ebullition, and plant-mediated transport.

Methane production strongly depends on the position of the water table (Roulet et al. 1992, Bubier et al. 1995), which is a measure for dividing the soil column into an anaerobic and aerobic zone (Fig. 2). Methane is only produced under the absence of oxygen and, hence, only in water-saturated parts of the soil column (Fig. 2a). The production of methane by methanogenic bacteria is a function of substrate availability, pH and temperature (Walter 1998). The temperature dependence of methane production rates can be described by Q_{10} values which depict the relative increase in activity after a temperature rise of 10°C (van Hulzen et al. 1999). The gas is then transported to the soil/water interface by molecular diffusion, ebullition and, if vascular plants occur, by plant-mediated transport. When the water table drops below the soil surface, oxygen can enter the soil pores, and the methane produced in lower, still water saturates (anaerobic) parts of the soil body and is transported upwards and oxidized in the aerobic zone by methanotrophic bacteria (Fig. 2b). Methane oxidation can be described by Michaelis-Menten kinetics (Bender & Conrad 1992).

The model is driven by meteorological data and needs auxiliary input data, such as vegetation and soil characteristics, land classification schemes, fraction of cover, and Net Primary Productivity (NPP). NPP is parameterized as a measure for substrate availability and, thus, is an important input parameter. Since the model was modified for permafrost conditions, many parameters are time-dependent with successive thawing of the soil body, and only a few fixed parameters are used in the simulation runs.

NPP of high latitude tundra ecosystems is calculated by the process-based vegetation model BETHY/DLR (Biosphere Energy Transfer Hydrology Model) (Knorr 1997,

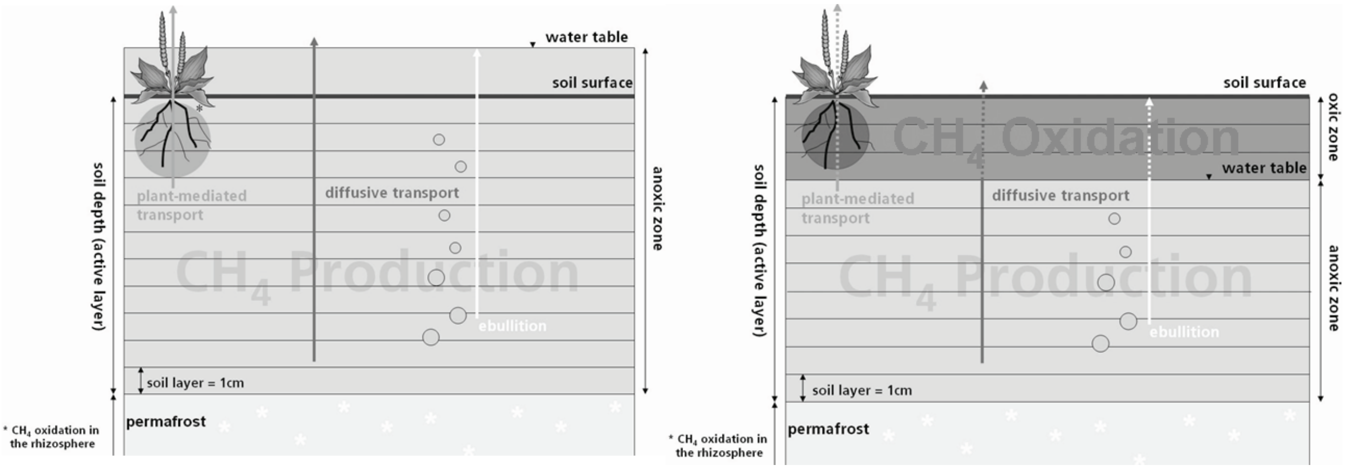

Figure 2. Schematic presentation of a soil column in the methane model. (a) Methane production and different transport mechanisms under water saturated conditions (anaerobic); (b) methane production and consumption as well as different transport mechanisms under partly aerobic conditions.

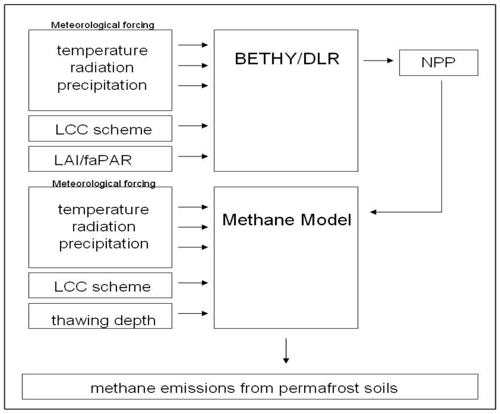

Figure 3. Flow chart illustrating the coupling of the BETHY/DLR model (NPP), the methane model, and their required input data.

Wisskirchen 2005). For simulations with BETHY/DLR, information about the state of vegetation is required; for example, time series of LAI (Leaf Area Index). Figure 3 shows the methodical structure of how the two models are coupled to work as a stand-alone package for modeling methane emission in permafrost regions.

Data

Both models need meteorological forcing data. Datasets provided by the European Centre for Medium Range Weather Forecast (ECMWF) are applied in modeling NPP and methane fluxes.

Auxiliary input data must be provided for both models. For simulations with the vegetation model BETHY/DLR, information about vegetation type and the state of vegetation (time series of LAI) is required. Running the methane model, additional input data such as vegetation parameters (e.g., rooting depth), soil characteristics (e.g., pore volume), land classification schemes (e.g., wetland distribution), fraction of cover, and NPP are needed.

Thawing of permafrost is described in the model by using measurements of active layer depth taken during field campaigns. Thawing/freezing is accounted for in order to characterize permafrost-related processes more realistically. The simulation starts with the first thawing of permafrost soil. Methane emission increases with increasing thawing depth, subsequently slowly decreases, and eventually comes to an end with permafrost re-freezing.

During the field campaign "System Laptev Sea – LENA2006" carried out from May to September 2006, Medium Resolution Imaging Spectrometer Full Resolution (MERIS-FR) data were acquired for the full growing season. MERIS-FR data were processed to derive information on vegetation characteristics needed as model input.

Vegetation characteristics

Vegetation characteristics play an important role in the presented modeling approach. In the vegetation model BETHY/DLR, LAI is used to describe the seasonal development of vegetation. It is needed as a continuous input variable to assess NPP.

In order to obtain realistic time series of LAI for the growing season 2006 of the Lena Delta, an approach using the MERIS Global Vegetation Index (MGVI), also called Top of the Atmosphere Vegetation Index (TOAVI), was used. FAPAR (Fraction of Absorbed Photosynthetically Active Radiation) can be retrieved by remote sensing techniques with acceptable accuracy using TOAVI values (Gobron et al. 2004) and can subsequently be used to estimate LAI. For homogeneous vegetation cover, LAI_{hom} is calculated using the equation (Monteith & Unsworth 1990):

$$LAI_{\mathrm{hom}_i} = LAI_{\max} \cdot \frac{\log(1 - FAPAR_i)}{\log(1 - FAPAR_{\max})} \tag{1}$$

$LAI_{\max}$ is chosen according to in situ measurements (Eq. 3). $FAPAR_i$ and $FAPAR_{\max}$ are derived from MGVI values.

During the field campaign 2006, field spectral measurements were taken using a portable ASD FieldSpecFR spectrometer (Analytical Spectral Devices Inc.). The spectrometer covers a wide spectral range from 350–2500 nm. Due to the highly heterogeneous surface patterns of wet polygonal tundra, different plant communities with different vegetation cover have evolved on a small scale in high and low center polygons and polygon rims, depending on changes in substrates and hydrologic regimes. Spectral measurements were taken in order to derive data on vegetation characteristics such as NDVI (Normalized Difference Vegetation Index) and LAI which can then be used to differentiate between plant communities as well as to validate satellite data.

Spectra have been processed using ENVI software. Processing is inevitable in order to correct for sensor properties and reference measurements using a spectralon panel. Biophysical indices (NDVI and LAI) were calculated and compared with NDVI and LAI values derived from MERIS-FR data.

NDVI was calculated from spectral data using the equation (Rouse et al. 1974):

$$NDVI = \frac{(R_{864} - R_{671})}{(R_{864} + R_{671})} \tag{2}$$

where R_{864} and R_{671} denote the reflectance at wavelengths 864 nm (near infrared) and 671 nm (red), respectively.
LAI was then calculated after Gardner & Blad (1986):

$$LAI = -1.248 + 5.839 * NDVI \tag{3}$$

LAI_{max} in equation (1) was set according to LAI values derived from equation (3).

Results and Discussion

Leaf Area Index (LAI)

Figure 4 shows results of the two approaches described above and presents a comparison between LAI calculated from field spectra and remote sensing data, respectively. The datasets compare reasonably well with slightly higher LAI values derived from in situ measurements. Additionally, a steeper slope can be observed in the in situ dataset. Possible explanations might be (1) an inaccurate atmospheric correction of MERIS-FR data due to high sun zenith angles and (2) the spatial resolution of MERIS-FR data (300 m) being unable to capture the high spatial heterogeneity of wet polygonal tundra.

However, it can be seen that the temporal variation of LAI during the vegetation period of 2006 is represented realistically. After slowly increasing at the beginning of the growing season, LAI reaches its maximum in mid-August (DOY 229) and then starts decreasing again. This agrees with ground truth observations from field campaigns in the delta.

Handling optical satellite data for high-latitude regions is often problematic due to high cloud contamination and high sun zenith angles. Here it is shown that for arctic regions like the Lena River Delta, information on vegetation characteristics can be retrieved from optical satellite-based measurements. Ground-truth data are useful for validating satellite-derived plant biophysical parameters. Working with both ground-truth and remote sensing approaches as presented here provides a powerful tool to estimate vegetation characteristics on the small scale and to upscale these characteristics to the regional scale.

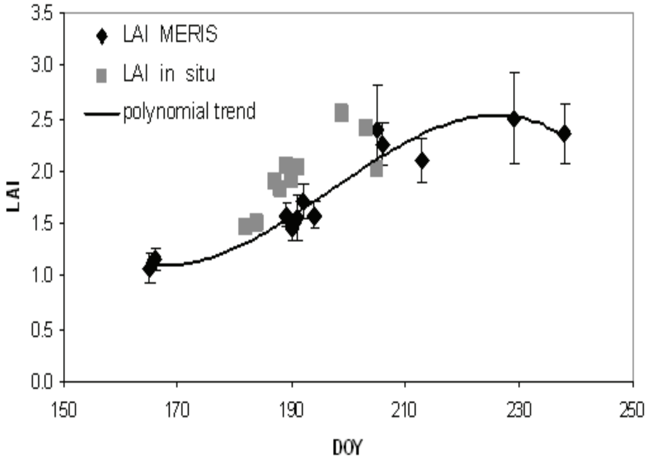

Figure 4. Time series of LAI for Samoylov Island for the growing season 2006. Diamonds: seasonal course of LAI derived from MERIS FAPAR values and polynomial fit, error bars indicate SD; triangles: LAI derived from field spectral measurements.

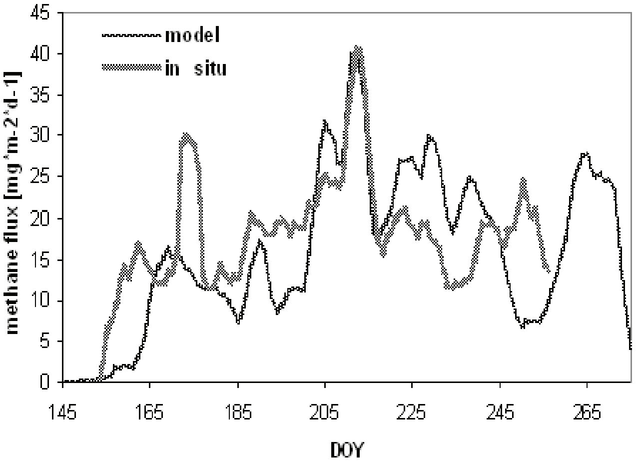

Figure 5. Measured and modeled methane fluxes (5-day running means) from a one-dimensional model run for the growing season 2006 and model coordinates 72°N, 126°E (Samoylov Island).

Realistic time series of plant canopy characteristics like LAI can be used as model input and to validate literature values when information about the state and seasonal variation of vegetation is required (BETHY/DLR).

Methane flux modeling

Methane flux was modeled one-dimensionally for the growing seasons of 2003–2006. Figure 5 shows a comparison of measured and modeled fluxes for the growing season of 2006. Flux measurements on the landscape scale using eddy covariance technique were carried out on Samoylov Island from June 9, 2006, through September 19, 2006, (Sachs et al. 2008). An eddy flux tower 3.6 m in height was used for methane flux measurements as well as for additional meteorological measurements. The seasonal course of modeled methane fluxes is limited by soil thawing and freezing.

In situ flux time series are used to validate the methane model and adjust model parameters, like Q_{10} values characterizing methane reduction and oxidation, to the study site. Between DOY 151 and 256, during overlap of the two curves, modeled methane flux is in good accordance with observed data. Flux integrals for both curves for the overlapping period are 1686 mg CH_4 m^{-2} (model) and 1895 mg CH_4 m^{-2} (measurements), respectively, which indicates a model underestimation of about 10%. This result agrees well with other studies using the same methane emission model; for example, when applied in Western Siberia (Bohn et al. 2007).

As can be seen in Figure 5, the time series of modeled methane emission shows less variation between days than the measured flux. This difference in seasonal fluctuation is due to the high variability of methane emission, both spatially and temporally (Joabsson et al. 1999, Wagner et al. 2003) and can be explained by the main factors controlling methane release. Wille et al. (2007) identified soil temperature and near-surface turbulence to be the driving parameters of methane emission in the Lena Delta.

The observed small-scale variability shown in the in situ data cannot fully be represented in the model results. Model input data on soil temperatures derived from ECMWF have a spatial resolution of 0.5°, and thus, variations in soil temperature due to the micro-relief of wet polygonal tundra cannot be taken into account.

Additionally, no data on wind distribution, wind direction, and wind speed are considered in the methane model.

However, since the project aims at quantifying methane emission on a regional scale, well-founded knowledge of small-scale process variability is an important factor for model understanding but cannot be fully implemented in the model.

Conclusions

For the growing season 2006, methane fluxes were modeled using two process-based models, a vegetation, and a methane emission model. Simulated methane fluxes are in agreement with in situ flux measurements ($r^2 = 0.63$). Time-integrated fluxes are 1686 mg CH_4 m^{-2} (model) and 1895 mg CH_4 m^{-2} (measurements), respectively. This indicates a model underestimation of about 10% which agrees with results of a study conducted in Western Siberia using the same methane emission model, where a model underestimation of about 10% was observed as well (Bohn et al. 2007).

Leaf Area Index needed as input for the vegetation model was calculated using two different approaches. LAI was derived (1) from satellite-based measurements and (2) by processing field spectral measurements. In situ data were applied in validating satellite data. It could be shown that information about the state and seasonal variation of the vegetation in arctic regions can be retrieved by remote sensing techniques. Used for deriving time series of LAI for the study site, the satellite measurements provide realistic results and compare reasonably well with LAI calculated from in situ spectral measurements.

The results demonstrate the important role of modeling techniques in assessing methane emissions for High Arctic permafrost-influenced ecosystems. Understanding of micro-scale processes studied through scientific field work is absolutely necessary when applying process-based models.

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References

Bender, M. & Conrad R. 1992. Kinetics of CH_4 oxidation in oxic soils exposed to ambient air or high CH_4 mixing ratios. *FEMS Microbiology Ecology* 101: 261-270.

Bohn, T.J, Lettenmaier, D.P., Sathulur, K. & Bowling, L.C. 2007. Large scale modeling of wetland methane emissions. *Integrated Land Ecosystem – Atmosphere Processes Study Newsletter* 4: 40-42.

Bubier, J.L., Moore, T.R., Bellisario, L., Comer, N.T. & Crill M.C. 1995. Ecological controls on methane emissions from a northern peatland complex in the zone of discontinuous permafrost, Manitoba, Canada. *Global Biogeochemical Cycles* 9(4): 455-470.

CAVM Team, 2003. Circumpolar Arctic Vegetation Map. Scale 1:7,500,000. Conservation of Arctic Flora and Fauna (CAFF) Map No. 1. U.S. Fish and Wildlife Service, Anchorage, Alaska.

Fan, S.M., Wofsky, S.C., Bakwin, P.S. & Jacob, D.J. 1992. Micrometeorological Measurements of CH_4 and CO_2 exchange Between the Atmosphere and Subarctic Tundra. *Journal of Geophysical Research* 97(D15): 16627-16643.

Friborg, T., Christensen, T.R., Hansen, B.U., Nordstroem, C. & Soegaard, H. 2000. Trace gas exchange in a high-arctic valley 2. Landscape CH_4 fluxes measured and modeled using eddy correlation data. *Global Biogeochemical Cycles* 14(3): 715-723.

Gardner, B. & Blad, B. 1986. Evaluation of spectral reflectance models to estimate corn leaf area while minimizing the influence of soil background effects. *Remote Sensing of Environment* 20:183-193.

Gobron, N., Mélin, F., Pinty, B., Taberner, M. & Verstraete, M.M. 2004. MERIS Global Vegetation Index: Evaluation and Performance. *Proceedings of the MERIS User Workshop, Frascati, Italy, November 10-13, 2003.*

Grigoriev, M.N. 1993. Cryomorphogenesis in the Lena Delta. Yakutsk (in Russian), 173 pp. In: J. Schneider, 2005, *Bilanzierung von Methanemissionen in Tundragebieten am Beispiel des Lena-Deltas, Nordostsibirien, auf der Basis von Fernerkundungsdaten und Gelaendeuntersuchungen*. Alfred Wegener Institute for Polar and Marine Research, Research Unit Potsdam, Master Thesis, 103 pp.

Harazono, Y., Mano, M., Miyata, A., Yoshimoto, M., Zulueta, R.C., Vourlitis, G.L., Kwon, H. & Oechel, W.C. 2006. Temporal and spatial differences of methane flux at arctic tundra in Alaska. *Mem. Natl Inst. Polar Res., Spec. Issue* 59: 79-95.

Hargreaves, K. J., Fowler, D., Pitcairn, C.E.R. & Aurela, M. 2001. Annual methane emission from Finnish mires estimated from eddy covariance campaign measurements. *Theoretical and Applied Climatology* 70: 203-213.

IPCC 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, & C.A. Johnson (eds.), Cambridge, UK & New York, NY: Cambridge University Press, 881 pp.

IPCC 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor & H.L. Miller (eds.), Cambridge, UK & New York, NY: Cambridge University Press, 996 pp.

Joabsson, A., Christensen, T.R. & Wallén, B. 1999. Vascular plant controls on methane emissions from northern peat forming wetlands. *Trends in Ecology & Evolution (TREE)* 14(10): 385-388.

Knorr, W. 1997. Satellitengestützte Fernerkundung und Modellierung des globalen CO2-Austauschs der Landbiosphäre: Eine Synthese. Max-Planck-Institute for Meteorology, Examensarbeit Nr. 49 (in German), Hamburg, Germany.

Lawrence, D.M. & Slater, A.G. 2005. A projection of severe near-surface permafrost degradation during the 21st century. *Geophysical Research Lett*ers 32: L24401.

Monteith, J.L. & Unsworth, M.H. 1990. Principles of environmental physics. In: E. Arnold (ed.), London, 291 pp. In: P.J. Sellers, S.O. Los, C. Tucker, C.O. Justice, D.A. Dazlich, G.J. Collatz & D.A. Randall, 1996. *A Revised Land Surface Parameterization (SiB2) for Atmospheric GCMs.* Part II: The Generation of Global Fields of terrestrial Biophysical Parameters from Satellite Data. *Journal of Climate* 9(4): 706-737.

Roshydromet, Russian Federal Service for Hydrometeorology and Environmental Monitoring (2004). http://www.worldweather.org/107/c01040.htm.

Roulet, N., Moore, T.R., Bubier, J.L. & Lafleur, P. 1992. Northern fens: methane flux and climatic change. *Tellus* 44(B): 100-105.

Rouse, J.W., Haas, R.H., Schell, J.A. & Deering, D.W. 1974. Monitoring vegetation systems in the Greta Plains with ERTS. *Proceedings of the Third Earth Resources Technology Satellite-1 Symposium, Greenbelt, NASA SP-351,*301-317.

Sachs, T., Giebels, M., Wille, C., Kutzbach, L. & Boike, J. 2008. Methane emission from Siberian wet polygonal tundra on multiple spatial scales –vertical flux measurements by closed chambers and eddy covariance, Samoylov Island, Lena Delta. (this proceeding).

Schwamborn, G., Rachold, V. & Grigoriev, M.N. 2002. Late Quaternary sedimentation history of the Lena Delta. *Quaternary International* 89: 119-134.

Van Hulzen, J.B., Segers, R., van Bodegom, P.M. & Leffelaar, P.A. 1999. Temperature effects on soil methane production: an explanation for observed variability. *Soil Biology and Biochemistry* 31: 1919-1929.

Wagner, D., Kobabe, S., Pfeiffer, E.-M. & Hubberten , H.-W. 2003. Microbial Controls on Methane Fluxes from a Polygonal Tundra of the Lena Delta, Siberia. *Permafrost and Periglacial Processes* 14: 173-185.

Walker, H. J. 1998. Arctic deltas. *Journal of Coastal Research* 14(3): 718-738.

Walter, B. 1998. Development of a process-based model to derive methane emissions from natural wetlands for climate studies. Max-Planck-Institute for Meteorology, Examensarbeit Nr. 60, Hamburg, Germany, 160 pp.

Walter, K. M., Chapin III, F.S., White, D.M. & Zimov, S.A. 2003. Stratification of Thermokarst Lakes in NE Siberia based on Diffusive CH_4 Emissions. *Proceedings of the Arctic System Science Program All-Hands Workshop, Seattle, Washington, February 20–23, 2002:* 222.

Wille, C., Kutzbach, L., Sachs, T., Wagner, D. & Pfeiffer, E.-M. 2007. Methane Emission from Siberian arctic polygonal Tundra: Eddy Covariance Measurements and Modeling. *European Geosciences Union General Assembly 2007*, Abstract No. EGU2007-A-10277.

Wisskirchen, K. 2005. Modellierung der regionalen CO2-Aufnahme durch Vegetation. Dissertation (in German), Meteorologisches Institut der Rhein. Friedr.-Wilh.-Universität Bonn, 129 pp.

Zhang, Y., Chen, W. & Riseborough, D.W. 2007. Transient projections of permafrost distribution in Canada during the 21st century under scenarios of climate change. *Global and Planetary Change* (in press).

Zimov, S.A, Schuur, E.A.G. & Chapin III, F.S. 2006. Permafrost and the Global Carbon Budget. *Science* 312(5780): 1612-1613.