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Controls for multi-scale temporal variation in ecosystem methane exchange during the growing season of a permanently inundated fen

Franziska Koebsch[a,*], Gerald Jurasinski[b], Marian Koch[b], Joachim Hofmann[b], Stephan Glatzel[c]

[a] Section Inorganic and Isotope Geochemistry, GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany
[b] Department for Landscape Ecology and Site Evaluation, University of Rostock, Justus von Liebig Weg 6, 18059 Rostock, Germany
[c] Department of Geography and Regional Research, University of Vienna, Althanstr. 14, 1090 Vienna, Austria

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ABSTRACT

Wetlands are the largest natural sources for atmospheric methane (CH_4). In wetlands with permanent shallow inundation, the seasonal variation of CH_4 exchange is mainly controlled by temperature and phenology. In addition, ecosystem CH_4 exchange varies considerably on smaller temporal scales such as days or weeks. Several single processes that control CH_4 emissions on the local soil–plant–atmosphere continuum are well investigated, but their interaction on ecosystem level is not well understood yet. We applied wavelet analysis to a quasi-continuous eddy covariance CH_4 flux time series to describe the temporal variation of ecosystem CH_4 exchange within the growing season of a permanently inundated temperate fen. Moreover, we addressed time scale-specific controls and investigated whether their impact changes during the course of the growing season.

On large time scales of two weeks to three months, temperature explained most of the variation in ecosystem CH_4 exchange. In general, the temperature in the shallow water column had the largest impact as explanatory variable, however, air temperature and soil temperature became increasingly important as explanatory variables when water level dropped slightly up to June. The diurnal variation of ecosystem CH_4 exchange shifted during the course of the growing season: During a short time period at the end of April, plant activity (expressed by canopy photosynthesis) caused a diurnal variation of ecosystem CH_4 exchange with peak time around noon. In the following weeks, the daily cycle of convective mixing within the water column (expressed by the water temperature gradient) gradually gained importance and caused high night-time CH_4 emissions, thereby levelling off the diurnal CH_4 emission pattern. Moreover, shear-induced turbulence caused short-term fluctuations of ecosystem CH_4 exchange on time scales up to two hours.

Our study highlights the need for multi-scale approaches that consider the non-stationarity of the underlying processes to adequately describe the complexity of ecosystem CH_4 exchange. Moreover, we show that CH_4 release processes such as convective mixing of the water column which have been mainly considered for aquatic ecosystems (see recent exceptions in Godwin et al., 2013; Poindexter and Variano, 2013) might also be of importance in shallowly flooded terrestrial ecosystems.

1. Introduction

Wetlands are the largest natural sources for atmospheric methane (CH_4, Forster et al., 2007), the 2nd most important greenhouse gas following carbon dioxide (Denman et al., 2007). Thus, understanding the dynamics of wetland CH_4 emissions is an important pre-requisite for deriving global greenhouse gas budgets and for the anticipation of ecosystem feedbacks to global change. Published CH_4 budgets for global wetlands cover a wide range of values (e.g. Denman et al., 2007: 100–231 Tg yr^{-1}; Khalil and Rasmussen, 1983: 150 ± 50 Tg yr^{-1}; Meng et al., 2012: 256 Tg yr^{-1}; Reeburgh, 2003: 92–232 Tg yr^{-1}; Walter et al., 2001: 156–260 Tg yr^{-1}) and large discrepancies occur when comparing bottom-up estimates based on upscaling from field inventories with budgets derived from inverse modeling (e.g. Bousquet et al., 2011; Kirschke et al., 2013; Walter et al., 2001). The high uncertainty in wetland CH_4 budget estimates is mainly due to a lack of mechanistic understanding of the controls of CH_4 emission dynamics on ecosystem scale.

* Corresponding author. Tel.: +49 3312881423.
E-mail address: franziska.koebsch@gfz-potsdam.de (F. Koebsch).

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Further, there is no agreement on how the relevant processes can be adequately implemented into models (Bridgham et al., 2013; Saarnio et al., 2009; Wania et al., 2013).

Our understanding of CH_4 dynamics in wetlands has been greatly expanded during the last decades by many studies (see Table 1 for some examples). In experimental studies single CH_4 emission drivers were identified under controlled conditions in the local soil–plant–atmosphere continuum (e.g. Garnet et al., 2005; Poindexter and Variano, 2013), whereas most of our knowledge about in situ CH_4 emission dynamics derives from closed chamber (CC) measurements (Livingston and Hutchinson, 1995). This approach is well suited to investigate within-ecosystem flux heterogeneity (e.g. Schrier-Uijl et al., 2010) but especially on shorter time scales, the spatial upscaling of CC fluxes to the ecosystem scale is usually associated with high uncertainties (Zhang and Ding, 2011). Most of the published CC studies base manual chamber measurements with intervals of only 2–4 weeks. This allows to address the seasonal variation in gas exchange but is typically not suitable to adequately cover the large variation of CH_4 emission on smaller temporal time scales. To do so, much higher, disproportionally labour intensive measurement frequencies would be necessary. Therefore, such attempts regularly cover only limited periods of time (e.g. Crill et al., 1988; Nakano et al., 2000).

The eddy covariance (EC) method (Montgomery 1948) is a non-destructive, micro-meteorological approach for gas flux measurements on ecosystem scale. Although there are some early EC applications to measure ecosystem CH_4 exchange (e.g. Edwards et al., 1994; Shurpali et al., 1993) only recent progress in measurement technique has made this approach available for a broader range of research (e.g. McDermitt et al., 2011). Since the EC approach provides a direct signal of the atmosphere–biosphere gas exchange on ecosystem scale, it has the potential to decrease the discrepancy between field-derived bottom–up estimates and budgets derived from inverse modelling (Jung et al., 2011). Moreover, due to their quasi-continuous character, EC fluxes are perfectly suited for time series analysis. The latter can be used to investigate the temporal characteristics of a variable of interest itself as well as to assign possible relationships with environmental controls on any time scale (Cazelles et al., 2008).

Wavelet analysis is a time series analysis tool that decomposes a signal in the time and frequency domain. In contrast to other spectral approaches like Fourier analysis, wavelet analysis can account for transitions that occur during the observation period (i.e. instationarities that occur over the course of the growing season (Daubechies 1992; Foufoula-Georgiou and Kumar, 1994)). In the time domain, wavelet analysis covers the transitional character of ecosystem processes, thereby avoiding the partitioning of time series to discrete periods with arbitrary start and end dates. In the frequency domain, wavelet analysis provides results that are unbiased from artificial time concepts (e.g. the time scale "week" does not have an equivalent in the variation of physical forces). Wavelet coherence allows to test for the correlation between 2 signals in the time and frequency domain and yields the phase shift between these signals which is a meaningful criterion for a potential cause-and-effect relationship (Grinsted et al., 2004). So far, spectral analyses yielded valuable insights regarding the temporal dynamics of net ecosystem exchange of CO_2 (NEE) and the associated controls (e.g. Baldocchi et al., 2001; Stoy et al., 2005). Although it provides large potential to promote our mechanistic understanding of ecosystem processes, time series analysis approaches have yet hardly been applied to CH_4 flux time series (but see an exception in Hatala et al., 2012).

Here, we investigate the temporal dynamics of ecosystem CH_4 exchange on multiple time scales of hours to several months during the growing season of a permanently inundated fen using wavelet analysis based on a half-hourly CH_4 flux time series derived from EC measurements. Furthermore, we describe the relationship between ecosystem CH_4 exchange and single environmental variables in the time-frequency domain using wavelet coherence. In doing so, we will also take account for the instationarity of the found patterns, i.e. we investigate whether relationships change during the course of the growing season. The included variables were selected according to the current knowledge on drivers of net CH_4 exchange across a variety of wetland ecosystems (Table 1). Furthermore, we provide a verifiable and systematic overview about which processes control the ecosystem CH_4 exchange at certain time scales and time periods by superimposing the wavelet coherence results and applying analytical filter criteria (e.g. level of significance, phase lag). Finally, we present a conceptual model to explain the shifting diurnal pattern of ecosystem CH_4 exchange during the course of the growing season.

2. Material and methods

2.1. Study site

Ecosystem CH_4 exchange was measured at the 'Rodewiese', a degraded fen, which is part of the nature reserve 'Heiligensee and Hütelmoor' in north eastern Germany (54°12′N, 12°0′E). Annual precipitation totals 645 mm and the mean annual temperature is about 9.2 °C (reference period 1982–2011, data from the German Weather Service). The fen extends 1.59 km in north–south direction and 1.38 km in east–west direction and is bordered by the Baltic Sea in the north and west. Under natural conditions, the fen was episodically flooded with brackish waters. However, since the installation of a dune dike in 1963, the fen had been almost completely cut off from the Baltic Sea leading to a relative increase in freshwater supply (Voigtländer et al., 1996). Since 2000, the maintenance of the dune dike has been stopped and the dike is now left to the natural coastal dynamics of accumulation and abrasion (Hübner and Gräff, 2013). Today, pore water in the top peat layers is slightly brackish with salinities from 0.7–1.2 ppt. Apart from that, the land use history of the fen is representative for many peatlands in Central Europe. Following the general demand to increase agricultural yields in the 1970s (Diggelen et al., 2006), the fen had been drained with water levels down to 1.60 m below surface. Mowing was conducted twice a year for hay production. In the following, peat decomposed rapidly and was identified as sapric histosol in 2010. In the 1990s, many peatlands were abandoned, which promoted the shift to a more ecological focus on peatland use across Central Europe (Diggelen et al., 2006). Correspondingly, the Rodewiese was moderately rewetted leading to mean water levels close to the surface during the growing season. Despite these measures, water levels still went down to 70 cm below the surface during summers, preventing to effectively stop peat decomposition. Therefore, a ground sill was installed in the outflow of the catchment in winter 2009/2010 causing a year-round shallow flooding of most parts of the study site. Currently, the fen vegetation is dominated by a combination of competitive species typical for species-poor fens of cool temperate regions such as Common reed (*Phragmites australis* (Cav.) Trin. ex Steud.) or Lesser Pond sedge (*Carex acutiformis* Ehrh., Timmermann et al., 2006), and relics of former brackish conditions such as sea- and grey club-rush (*Bolboschoenus maritimus* (L.) Palla, *Schoenoplectus tabernaemontani* (C.C. Gmel.) Palla, see Koebsch et al., 2013 for a more thorough description of the study site).

2.2. Eddy covariance and supporting measurements

The EC instrumentation to measure fast fluctuations of gas molar density, wind velocity and sonic temperature comprised (i) a LI-