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INTRODUCTION

This chapter highlights the motivation and the scientific objectives of the research conducted in this thesis. The methane emission mechanisms and three significant Arctic wetland emission sources are introduced.

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1.1. Thesis outline

The thesis compiles a series of research works and comprises of six chapters. Chapter 1 introduces the motivation of this research, the objective and approach. Chapter 2 describes the improvements to PEATLAND-VU and its performance at plot scale (Mi et al., 2014b). Chapter 3 up-scales the application of PEATLAND-VU to the northern high latitudes tundra parameters, and investigates their linkage to sea-ice cover. Chapter 4 presents a snowmelt-driven runoff and flooding model for permafrost catchments, and its evaluation at a Northern Siberia basin. \( CH_4 \) emissions from river inundation are estimated. Chapter 5 investigates the trends of thaw lake coverage by employing the THAWLAKE model, and the resulting changes in greenhouse gas exchange are discussed (Mi et al., 2014a). Chapter 6 summarises the major conclusions and suggests for future research directions.

1.2. Background

The Fifth Assessment Report of Intergovernmental Panel on Climate Change (IPCC-AR5) predicts an increasing in global mean surface air temperature of 1.0 to 3.7 °C by the end of the 21st century. The Arctic region is projected to warm the most, \( \approx 5^\circ \)C (IPCC, 2013), known as the Arctic amplification.

A considerable area of the Arctic is covered by permafrost. Most of the permafrost soil was formed during cold glacial periods; and has been accumulating carbon gradually due to slow microbial decomposition in cold climate. Recent studies estimate that the amount of organic carbon stored in the northern circumpolar soil could be up to 1672 Pg C (Tarnocai et al., 2009), which exceeds the global vegetation (\( \approx 700 \) Pg C) and atmospheric (\( \approx 750 \) Pg C) carbon pools combined.

Circumpolar warming would lead to permafrost degradation, resulting in remarkable changes in regional morphology (Chen et al., 2013, Hinkel et al., 2005, Hussey and Michelson, 1966), hydrology (Bense et al., 2012, Walvoord et al., 2012), heat balance (Hinkel et al., 2012, Matell et al., 2013), and above all, mobile permafrost carbon and alter the exchange pattern of greenhouse gases with the atmosphere.

Methane (\( CH_4 \)) is an important greenhouse gas and have over 20-times the global radiative forcing capacity of carbon dioxide (\( CO_2 \)). The atmospheric concentration of \( CH_4 \) has increased by a factor of 2.5 since preindustrial times, from 720 ppb (parts per billion) in 1750 to 1803 ppb in 2011 (IPCC, 2013). The
main drivers of this growth are still debated. However, the natural wetlands, in particular the northern wetlands, play a significant role as they produce and subsequently release CH$_4$ at a rate of 30-50 Tg yr$^{-1}$ or, roughly 40% of the global emissions from natural sources and 12% from both natural and anthropogenic sources (IPCC, 2013, Schlesinger and Bernhardt, 2013).

The feedbacks between climate and Arctic wetland CH$_4$ emissions are complex. Precisely how climate change will impact the northern high latitudes is not fully understood. Increases in air temperatures and/or precipitation may result in an increase in active layer depth, anoxic soils conditions and raised soil temperatures, leading to elevated CH$_4$ emissions. Alternatively, CH$_4$ emissions may decrease if permafrost degradation improves soil drainage (van Huissteden et al., 2011). The latter is particularly true in discontinuous permafrost regions (Smith, 2005).

Several research stations around the Arctic have, therefore, been set-up to measure CH$_4$ fluxes and associated parameters (Golubyatnikov and Kazantsev, 2013, Lupascu et al., 2012, Parmentier et al., 2011b, Strom et al., 2012, Sturtevant and Oechel, 2013, Sturtevant et al., 2012, Tagesson et al., 2012, van Huissteden et al., 2005). However, field measurements from the northern high latitudes are spatially limited due to the vast size and remoteness of this region, the extreme climate and logistical difficulties. Computer models could be powerful tools to fill in the knowledge gaps for those remote areas. Ultimately, this process enables us to make observationally justifiable projections of future climate via the up-scaling of available field data.

1.3 Introduction to methane from the biosphere

Methane (CH$_4$) emission from soil systems, including wetlands, is the net result of a balance between CH$_4$ production by methanogenic microorganisms within anaerobic soil, and CH$_4$ oxidation by methanotrophic microorganisms in aerated soil and in plants (van Huissteden et al., 2009).

1.3.1 Production and consumption

The decay of organic matter in the soil sediments is part of the nutrient cycling in freshwater wetlands, which is controlled by a suite of oxidation-reduction reactions (redox). Methanogenesis, the production process of CH$_4$, is the final step in the decay of organic matter. During the decay process, electron
acceptors with higher redox potentials (such as oxygen (O$_2$), ferric iron (Fe$^{3+}$), sulfate (SO$_4^{2-}$), and nitrate (NO$_3^-$)) become depleted progressively leaving only carbon, where only methanogenesis and fermentation can occur (Schlesinger and Bernhardt, 2013).

Fermentation breaks large organic compounds into hydrogen, small organics, and carbon dioxide (CO$_2$), and provides metabolic energy. Methanogenesis occurs by splitting the acetate-type organic compounds produced from fermentation (eq. 1.1), or by CO$_2$ reduction described in eq. 1.2, in which hydrogen (H$_2$) is also a product of fermentation. Methanogenesis eventually releases CH$_4$ from the wetland sediments.

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (1.1)$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (1.2)$$

A variety of bacteria, methanotrophic bacteria, consume CH$_4$ and convert it into CO$_2$ before reaching the atmosphere (eq. 1.3). The proportion of CH$_4$ production being oxidized depends on environmental factors and the emission pathways, ranging up to more than 90% (Boon and Mitchell, 1995, Gilbert and Frenzel, 1995, King et al., 1990, 1998, Krumholz et al., 1995, Watanabe et al., 1995).

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (1.3)$$

CH$_4$ escapes into the atmosphere mainly through three pathways: diffusion through soil profile or water column, transport through aerenchyma of herbaceous plants, where the hollow stems composed of porous tissue acts as a conduit, and ebullition through pore water, referring to the sudden release of CH$_4$ bubbles built up over time.

### 1.3.2 Impacting factors

A wide array of both biotic and abiotic factors and their interactions, control CH$_4$ fluxes. The most important factors include:

**Substrate composition.** The substrate quality and availability change the nutrients available for methanogenesis, and therefore directly influences the rate of methane production. The substrate is comprised of stable soil organic matter (SOM), such as peat, humic matter, and labile SOM, including plant root exudate, dead roots, leaf litter, dead microbes. The latter is more conducive to CH$_4$ production, and is strongly linked to primary production.
1. Introduction

Water table. Methanogens are obligate anaerobes, oxygen is only sparingly soluble in the water, and therefore water table defines the anaerobic-aerated zones where CH$_4$ production or oxidation takes place. Additionally, the presence or absence of water results in different rate of CH$_4$ diffusion, in the descending order of: standing water, porous soil filled with air, and porous soil filled with water.

Temperature. Temperature, in particular soil temperature, directly affects CH$_4$ production and consumption rate by affecting the metabolic rate of methanogenic and methanotrophic microorganisms. However, temperature sensitivity of CH$_4$ production is higher than that of CH$_4$ consumption: the rate of CH$_4$ production will rise more steeply with temperature than CH$_4$ consumption. Temperature can also affect the flux indirectly by changing the active layer depth and primary production, both associated with substrate availability.

Vegetation composition. Vegetation influences CH$_4$ exchange not only by changing the transport pattern, but also by providing fresh substrate. CH$_4$ emissions are in general highest in areas with a large amount of vascular plants due to aerenchyma. Additionally, through photosynthesis and respiration, vascular plants are a significant source of fresh carbon compounds.
1.4. Introduction to Northern wetlands

Methane (CH$_4$) emissions from the Arctic wetlands are strongly linked to the atmospheric CH$_4$ concentration (IPCC, 2007, Umezawa et al., 2012, Yu et al., 2013). Arctic wetlands are believed to emit 19 Tg C yr$^{-1}$ in the form of CH$_4$ during the past decades (McGuire et al., 2012). Three important sources of these regions are: peatland, river floodplain, and thaw lake.

![Figure 1.2: Three important methane sources in the Northern high latitudes: peatland, river floodplains, and thaw lake.](image)

1.4.1 Peatland

Broadly speaking, peatlands are terrestrial environments where, over the long-term, net primary production exceeds organic matter decomposition, leading to the substantial accumulation of a deposit rich in incompletely decomposed organic matter, or peat (Wieder et al., 2006). Peat soils have unique hydraulic and thermal properties due to the high porosity rates compared with mineral soils. Northern peatlands are high latitude wetland areas with cold climate and unique biodiversity, covering 3.556×10$^6$ km$^2$, or approximately 19% of the northern circumpolar permafrost region (Tarnocai et al., 2009, van Huissteden and Dolman, 2012). In this study, we refer to the wetland areas north of 60 degrees, covering the subarctic regions of Russia, the USA, Canada, and the Fennoscandian countries.

The development of the northern peatlands is highly affected by the climate
conditions; the colder and more continential the climate, the slower the peat accumulates. The occurrence of ground ice is another unique characteristic of the Arctic besides the climatic factors driving net ecosystem exchange. Northern peatlands may contain high amounts of ground ice, for example palsas, which are peaty permafrost mounds containing a core of alternating layers of segregated ice and peat or mineral soil materia (French, 2007). These occur even in discontinuous permafrost areas. In continuous permafrost areas, the mineral subsoil may also contain high amounts of ice over large areas.

1.4.2 Floodplain

A floodplain is the strip of relatively smooth land bordering a stream and overflowed at a time of high water. Arctic river floodplains are an important source of soil CH$_4$ fluxes due to seasonal inundation. For example, van Huissteden et al. (2005) reports a considerably high efflux from a northeastern Siberian river plain backswamp. Additionally, they also play a role in carbon sequestration via sedimentation (Vonk et al., 2013). However, Arctic river floodplains are currently underrepresented in studies on wetlands CH$_4$ fluxes, and usually excluded from wetlands CH$_4$ emission calculations altogether due to limited data of sufficient spatial and temporal resolution (Melton et al., 2013).

1.4.3 Thaw lake

A thaw lake is a body of fresh water formed due to the melt-out of ground ice and subsequent ground subsidence in permafrost. Thaw lakes and drained lake basins are dominant features of the northern high latitudes, in particular in the lowlands along the coast and continental interior of Siberia and Alaska (Arp and Jones, 2008, Grosse et al., 2013). Permafrost degradation could lead to either an expansion of total lake area due to formation of new ponds or thermal erosion along already existing lake shorelines (Osterkamp et al., 2000, Smith et al., 2005, Walter et al., 2006), or lake drainage, as ground thaw may create vertical or lateral conduits, which facilitating more efficient outflow of lake water (Riordan et al., 2006, Smith et al., 2005, van Huissteden et al., 2011, Yoshikawa and Hinzman, 2003).
Key uncertainties and research goals

Controls on CH$_4$ production and consumption are generally well understood, however, how these controlling factors themselves, such as ground water level, are going to change under future climate is not clear. Additionally, little is known on the effects of these changing factors and their interactions on CH$_4$ emissions. Furthermore, across a broad scale, the potential relationships between wetland CH$_4$ emissions and Arctic climate, and its resulting changes in regional landscapes, such as sea-ice coverage and thaw lakes, are poorly known. Likewise, potential Arctic CH$_4$ source regions, such as river floodplains, are currently poorly identified and are underrepresented in studies on CH$_4$ fluxes.

This research aims to increase understandings of the above mentioned uncertainties by designing and applying computer models, with particular emphasis on quantifying the size and spatio-temporal variability of CH$_4$ efflux from the northern wetlands. In particular, this study will try to improve the modeling of the controls on CH$_4$ fluxes, and summarize the achievements and restrictions.

The study starts by investigating the CH$_4$ emission mechanisms. Factors controlling those biogeochemical processes are analysed. The above analysis results in several mechanistic improvements to an existing wetland CH$_4$ emission model, PEATLAND-VU, whose performance is tested against a longer Arctic dataset than any other model in a Siberia tundra site.

The improved model is up-scaled and applied across the northern high latitudes to compute the CH$_4$ emissions from peatlands in these regions, and also their linkage with sea-ice cover and climatic variables.

A further study on river floodplains is conducted. A process-based, spatially distributed permafrost hydrological model is designed which, for the first time, focuses on the dynamics of river flooding extent at a high spatial and temporal resolution, as hydrology strongly controls the high CH$_4$ fluxes from those areas. The model is calibrated and validated at Malaya Kuonapka basin, North Siberian Lowland. Effluxes from river inundations are estimated.

Finally, a stochastic thaw lake dynamic model, THAWLAKE, is applied to four Arctic sites where thaw lakes and drained lake basins feature prominently. The evolution of thaw lake coverage along a climatic gradient during the last 50 years are quantified; the future trends over the coming decades under various anticipated climate scenarios are projected. The implications for the future greenhouse gas exchange are discussed.