Chapter 1

Introduction

1.1 General introduction

1.1.1 Relevance of the topic

Climate change is high on the agenda of governments, and international research and assessment bodies. It attracts an increasing amount of attention in the media. The IPCC (Intergovernmental Panel on Climate Change) has established that current climate change is the result of increased atmospheric concentrations of greenhouse gases (GHG), particularly carbon dioxide (CO_2) and methane (CH_4). The major source of these gases is the burning of fossil fuels. Atmospheric methane concentration (AMC) has risen exponentially (except for a short pause between 1998 and 2007) throughout recent times. However, large variations of AMC also occurred during past Ice Ages. These periods of high AMC are known as interstadial peaks (see Figure 1.1).

The causes of these peaks and troughs are not entirely clear. Nevertheless, AMC peaks during periods of rapid climate warming are well established as shown by analysis of the GRIP ice-core data [217]. It is important to understand the processes of CH_4 generation and how these processes interact with the environment, i.e., how CH_4 feedbacks might be triggered. A number of hypotheses exist to explain CH_4 anomalies in the past; Section 1.3 offers an overview. Several possible causes have been evaluated using different modelling approaches, often pointing to enhanced wetland emissions as the main source. The current state of the global climate, i.e., with rapid climate warming, has several similarities with the climate of the last glacial (LG) period. This thesis focuses on those northern wetland CH_4 emissions from the LG.

As in the past, the present-day wetlands play a key role as atmospheric CH_4 sources. Boreal wetlands are key players in this process because of their extent and because they overlay permafrost. A critical question is how a temperature increase could affect CH_4 generation processes in these boreal environments, for example: thermokarst processes, such as the generation of lake thaws, and release of carbon, up until now frozen into the permafrost. The importance of thermokarst lakes or permafrost thaw in these regions has been questioned as thermokarst lakes might have shifted from CH_4 sources to CH_4 sinks during the Holocene[10]. If we are to understand and tackle the causes of the present warming, and the ongoing changes in climate, it is essential to know how the northern wetlands have contributed to past atmospheric changes in AMC. However a major issue for modellers is the lack of reliable data against which to compare their predictions. Such data are scarce because of the lack of exposed and preserved paleorecords. Each time a comparison is made, between the present warming and that during the LG, it is remarked that several environmental parameters have values in the same ranges and climate shifts compare well. However, this does not prove that the initiating sources and processes were also the same. The Earths climate did recover from those glacial conditions, but exactly how this occurred is still unclear what were the precise causes, what were their effects? And, importantly, what can be learned from past states and be applied to our current state? The study of wetland ecosystems is considered problematic because they are so complex and full of intricate, only partly-understood processes, with data hard to collect and to classify. This makes assessing their contribution to the global GHG budget a tricky task, because CH_4 emissions are difficult to quantify with sufficient accuracy. This lack of data constitutes a source of large uncertainty affecting the accuracy and therefore the reliability of any model output. The main aim of the present thesis is to bring much-needed data to bear in creating new understanding of wetland CH_4 emissions. Because any advance in the understanding of wetland dynamics and their regulating processes can in principle be implemented in a climate model, the overall objective is to improve climate model performance.

1.2 Background

During the LG, the composition of the atmosphere changed. One major change was a large increase in AMC. Several interstadials took place within a relatively short time span of about 45 ky. Data retrieved from Antarctica (EPICA and Vostok) and Greenland (GRIP and NGRIP) ice cores (see Figure 1.1) confirm the sharp increase in the AMC, with the sharpest rise bordering the start of the interstadial [217]. The similarities between the present situation and the environmental conditions that were in place during the LG, make it an urgent priority to measure the amount of CH_4 actively released into the atmosphere as accurately as possible, since CH_4 is a greenhouse gas with a global warming potential of some 30 times that of CO_2, [36, 250] over a life span of 100 years.

This study focuses on the last part of Pleistocene, specifically the time between 60 ky to 25 ky years ago, which corresponds to Marine Isotope Stages - MIS 3 (60 ky) and MIS 2 (24 ky) of an old classification [3], or to MIS 4 (71 ky), MIS 3 (57 ky) and MIS 2 (29 ky) according to a more recent revision [162]. The MIS digits give an indication of the climate, because odd numbers are associated with warmer stages and even ones with colder stages. Interglacials are the Holocene or MIS 1, MIS 3 and the Eemian or 5e, which was the warmest of the recent past. Colder stadials were MIS 4 and MIS 2, which was the last ice age or LG.

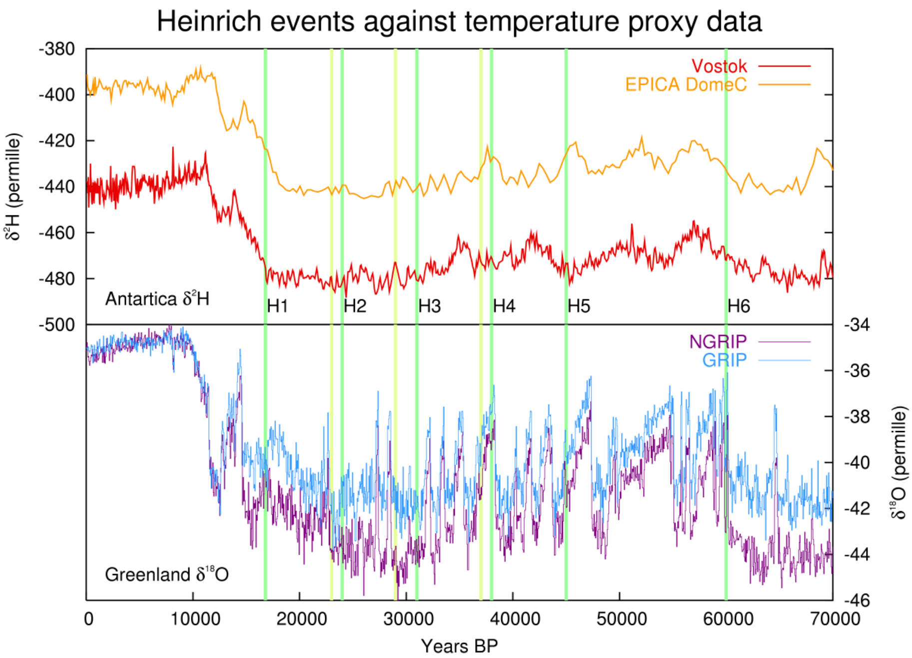

Figure 1.1: Comparison of temperature proxies for ice cores from Antarctica and Greenland for 70,000 years. Greenland ice cores use δ^{18}O, while Antarctic ice cores use δ^{2}H. Heinrich events, denoted by vertical green bars, plotted against temperature proxy data from Antarctic and Greenland ice cores. Dansgaard-Oeschger events can be seen most clearly in the Greenland δ^{18}O data. Darker green bars represent the Heinrich events from Hemming [108], while the lighter green represents alternative dates for events 2 through 4 from Bond [43], [177].

1.3 Initial Hypothesis

Although the exact processes are not completely known, the link between atmospheric CH_4 and global warming is widely understood and accepted. But from where did the large amounts of this gas come? What would be a plausible source capable of releasing such large amounts so quickly? One could argue that moving this huge volume of gas in just 5 ky during the Weichselian, 60-25 ky ago, implies the likelihood of more than a single mechanism with multiple sources contributing to the total flux reaching the atmosphere. Several theories have been formulated reflecting this diversity; they have been grouped under four main hypotheses, considered as possible explanations:

1. The "wetland methane hypothesis", which attributes the AMC variation to climate sensitivity of methane emission from northern wetlands [46];
2. The "tropical wetlands hypothesis", which identifies these areas as the main source, shifting focus towards the southern hemisphere [311]
3. The "clathrate gun hypothesis", which states that the AMC is driven by catastrophic CH_4 release from seafloor methane hydrates or clathrates [145];
4. The "deglaciation hypothesis", which considers fluxes to have originated from geological sources [88, 9].

Observations reveal that present-day climatic warming is strongest in boreal and Arctic areas [250] leading some authors to conclude that northern areas are likely be the major contributors to the LG increase in CH_4 [46]; the first hypothesis identifies these areas as the main source. However, high-latitude wetlands did not expand fast enough to explain such rapid increase in AMC levels [145], we need to consider alternative sources and hypotheses. Tropical wetlands are another candidate source contributor to CH_4 fluxes, given that these areas would also have been affected by climate change, albeit with different rates of response. Finally, gas hydrates were considered because they held the potential for the sudden, massive releases of CH_4 needed to match the rates involved in the atmospheric changes.

1.3.1 Boreal wetlands

Presently, CH_4 emissions are produced by thaw lakes and peatlands located on permafrost [304, 321] and non-permafrost wetlands at high-latitudes. Modelling experiments have confirmed boreal wetlands as the main source for CH_4 emissions in the past, with a significant contribution being made by the newly exposed area of the continental shelves [311, 187] and seasonally inundated floodplains [306, 185].

This analysis also explains the sharp rise in emissions during the interstadials [71, 22]. The northern wetlands are however considered as the major source, because as the modelling studies agree the thermohaline circulation (THC) collapsed during the Holocene [76, 128, 65, 198, 243]. The THC is part of the global ocean circulation, generated by density gradients driven by freshwater inputs and surface heat flux. It is considered as the main overturning mechanism and at present accounts for heat transport up to 1.2 ±0.3 PW (1 PW is 10^{15} watts) in the Atlantic ocean at 24°N [66]. In contrast, in the Holocene without the cooling effect of the THC, the northern hemisphere had a climate with warmer conditions than todays, therefore yielding higher CH_4 fluxes.

1.3.2 Tropical wetlands

Several papers attribute the high values of AMC over paleo-timescales to increasing emissions from the Southern Hemisphere tropics [246, 117]. This finding agrees with the results of PMIP2 (Paleoclimate Modelling Intercomparison Project Phase II) simulations of the Last Glacial Maximum (LGM) climate from coupled atmosphere-ocean and atmosphereocean-vegetation models. Model results indicate a relatively small boreal but large tropical source during the LGM, with wetlands on the exposed continental shelves being the main contributor to the tropical source [311]. The data so far collected agree about the role played by the wetlands, both boreal and tropical [22], with minor disagreements over the rates of their contribution: boreal wetlands are high emitters, with a low increase in fluxes relative to the present-day, and tropical wetlands are low emitters with a very high increase in fluxes. Continental shelves, newly exposed after the drop in global sea level, would have provided another source. Basically, during glacial periods the extensive ice cover prevents CH_4 emission from wetlands on the mainland (which corresponds to the present high-latitude wetland zone), while leaving continental shelves exposed and actively producing. Conversely, during an interstadial, more wetlands are created by both the disappearance of the snow cover and a moister climate, but the sea level rise decreases the contribution of the continental shelves. However, the total effect is almost negligible in the global picture, as their values are almost equal and opposite, and generally are not big enough to constitute the amount needed to create both the rapid climate change and to match the data from the GRIP ice cores [220]. Nevertheless, according to a recent study, the largest source of the rise in AMC today could be in the tropics [30].

1.3.3 Clathrates

One of the possible explanations of the sudden rise of AMC found in the ice-core records is that they were released from seabed sediments of methane hydrates, also known as clathrates. This idea is plausible because the amounts of CH_4 required to create the observed climate change would require continental-slope failures mobilizing up to 5000 Gt of sediments and the volumes of clathrates released would match the levels supporting the hypothesis [173]. The US Geological Survey [256] define gas hydrate as an ice-like substance formed when methane or some other gases combine with water at low temperature (up to $\sim$25°C) and moderate pressure (greater than 3-5 MPa, which corresponds to combined water and sediment depths of 300 to 500 m). These hydrates are widespread in marine and permafrost sediments [256] and are characterized by very high saturation levels; indeed they can concentrate CH_4 by $\approx$164 times on a volumetric basis compared to gas at standard pressure and temperature. The potential hazard of their release is therefore linked to the increase in deep water temperature, as any degree of warming could allow large volumes of gas to escape [230].

The only other way these deposits could be destabilized would be through a sudden drop in sea level [173], but this is unlikely to be triggered by climate warming at recent decadal rates (0.2°C per decade, IPCC 2007 [204]; 0.5°C, IPCC 2013 [250]), during the last 100 years. Furthermore, even when CH_4 is liberated from gas hydrates, oxidative and physical processes may greatly reduce the amount that reaches the atmosphere. The CO_2 produced by oxidation of CH_4 released from dissociating gas hydrates will likely have a greater impact on the Earth system (e.g., on ocean chemistry and atmospheric CO_2 concentration [13] than will the CH_4 that remains after passing through various sinks [230].

The general agreement about the wetlands role and the unlikely possibility that the conditions destabilizing these compounds would have occurred during the past glacial mean that this third hypothesis has been ruled out as highly improbable [174, 249, 38, 187]. Furthermore, the data only support the clathrate gun hypothesis for glacial-interglacial transitions, not for the millennial scale interstadial changes [173]. Nevertheless clathrates are presently considered one of the factors that should be taken into account when balancing the global carbon budget [174].

1.3.4 Geological sources

The data from polar ice [46] present very distinct isotopic values of C and H, therefore additional CH_4 sources (i.e., sedimentary environments) may be required in order to balance the isotope mass. Geological sources have received little attention in modelling AMC changes over glacial-interglacial cycles, mostly due to the isotopic values typically assigned to them, namely δ^{13}C of $\sim -44‰$and δD of $\sim -185‰$[211]. Ice-core CH_4 registered during deglaciation has values (δ^{13}C ranging from $\sim -50.7‰$to $\sim -53.6‰$and δD $> -200‰$) that do not match a release of marine clathrates, nor an increase in deuterium-enriched geological sources. They have been explained by inputs from Henriched sources such as tropical wetlands [249, 232], which could mask a contribution from a different source. Indeed, in glaciated sedimentary basins and shale formations, subsurface methanogenesis may generate substantial amounts of CH_4 as result of ice coverage and increased hydrostatic pressure. The gas produced in such a way is accumulated in the shale under the ice cap, i.e., in the North-American Antrim Shale at a rate of 1 Tg CH_4 per 1000 years [88] and it could be responsible for $<1\%$ of the 140$-$200 Tg yr^{-1} global CH_4 emissions inferred during glacial-interglacial transition [46, 232].

The carbon stored overall in the Arctic is estimated to be over 1200 Pg [9] and the amount of gas escaping from it could add substantially to the AMC. Another recent study has indeed documented this release to the atmosphere from gas seepage concentrated along boundaries of permafrost thaw and receding glaciers in Alaska and Greenland gas which was previously trapped by the ice cap. CH_4 radiocarbon age and stable isotope signature of this gas matched those of coal bed and thermogenic accumulations [9]. This geologic CH_4 has an average δ^{13}C ratio of $\sim -51‰$and δD of $\sim -230‰$[171], but because these values are within the same range as from tropical wetlands, they appear invisible to current isotope mass balance models of atmospheric CH_4 variability. The cumulative effect of such geological CH_4 reserves may have summed up to large emissions to the atmosphere, as glacial retreat from each basin resulted in releases of CH_4 extending through much of the late Pleistocene. However the final contribution is of a smaller scale than the wetlands, and this hypothesis thus has a minor role in explaining the AMC increase.

1.4 Current state of research

1.4.1 Paleo-enviroments

Several high-resolution climate records have confirmed that millennial-scale oscillations and rapid climate changes are our planets response to extraterrestrial forcing (e.g., orbital parameters, insolation, etc.) and internal mechanisms (such as changes in deep-ocean circulation, climate system variability) [42, 4, 175, 76, 218, 308], as noted by Aranbarri [12]. High-resolution oxygen isotope records provided the first evidence, independent of changes in the vegetation, for the occurrence of short-lived cold events during the interstadials [2, 199, 77]. The cold oscillations are thought to originate from meltwater pulses into the Atlantic Ocean [65, 198], which led to changes in the North Atlantic THC. As noted by Van Asch [267], climatic changes during the LG include rapid warming at the beginning of the interstadials, cooling during the Younger Dryas and warming at the transition to the Holocene [301, 300, 35, 48, 49, 166]. During the last deglaciation, the climate oscillations of the Younger Dryas cold period are attributed to a reorganization of the North Atlantic THC [122]. This circulation, coupled to the wind strength, also triggered other synchronous events, such as surface-ocean biological productivity changes related to the duration of upwelling rates that supply nutrients to the surface layer. This idea of a North Atlantic circulation as one of the global forcing mechanisms [122] is also supported by some extreme climate alterations associated with the Heinrich events [41], during which the meridional circulation seemed to have collapsed in the Atlantic [243]. Sharp changes in the North Atlantic circulation may justify some of the spatiotemporal heterogeneities documented during MIS 5 (and Eemian) marine and terrestrial records of the North Atlantic. Regional changes in the input of freshwater into the ocean caused surface waters of the East Greenland Current to be 3 to 5°C warmer than today [128]. These climatic shifts associated with changes in ocean circulation are expected to be clearly registered in lake sediment records. The general sequence of climatic events during the Late Glacial, a warm interstadial followed by the Younger Dryas cold phase, has been well documented in Ireland [2, 199, 77, 310, 7]. Similarly, cold events such as the Aegelsee and Gerzensee oscillations, which are comparable to the interstadial Events 1b and 1d in the Greenland ice core records [35, 166], have been recorded in lacustrine oxygen isotope records from Switzerland [82]. Another study also confirms that the influence of these oceanic perturbations extended as far as the Mediterranean Sea, and slowly triggered a response in the continental vegetation during the Last Interglacial complex (MIS-5). Mediterranean vegetation was gradually replaced by Eurosiberian-type vegetation indicating a change from Mediterranean to oceanic climates [231]. This is shown by pollen records, which reveal the persistence of a steppe-type landscape with Cupressaceae associated with the development of Ericaceae. At the same time, arboreal taxa, mainly *Betula*, and deciduous and evergreen *Quercus* developed, reflecting an increase in temperature and precipitation [231]. Recent modelling experiments simulate conditions that are consistent with these vegetation conditions [125]. Forest did not extend across Europe north of the main mountain chains at any time during MIS stages 2 to 4 [172] although during interstadials woodland or wooded steppe with temperate tree taxa extended across areas of southern Europe, especially during MIS stage 3. Even during the warmer and/or longer interstadials, however, only boreal tree populations expanded in central Europe, forming open or patchy woodlands rather than extensive forest cover, whilst in northern Europe herbaceous and dwarf-shrub vegetation prevailed during these intervals [125].

1.4.2 Modelling CH_4

The different representation of wetlands in models, as well as their different structures and resolutions leads to large variability in their simulations of present-day wetland CH_4 emissions. Petrescu et al. [**?**] found a more than four-fold difference in the maps of northern wetland CH_4 emission produced by different models. An intercomparison project (WETCHIMP) also showed substantial disagreement between their simulations of wetland areal extent and CH_4 emissions, in both space and time [179]. Importantly, these authors also note that there is as yet insufficient observational data at typical climate grid-cell scale to validate global scale models. Bohn et al. [39] repeated this experiment for a smaller area, the West Siberian Lowlands, for which more observational data are available, but again considerable discrepancies among the various approaches were found. If modelling present-day wetland CH_4 emissions provides highly uncertain results, the difficulty of modelling past glacial wetland areas can only be greater the only validation data are those based on global scale modelling of ice-core data [46]. Kaplan [138] worked on wetland CH_4 emissions from the LG maximum, based on present topography, paleoclimate and BIOME4 vegetation modelling, together with the assumption that CH_4 emission is a fixed fraction of heterotrophic soil respiration. Van Huissteden [276] also used present-day topography as a proxy for past glacial wetlands during MIS 3, and combined this with paleoclimate output and a process-based model, PEATLAND-VU. Valdes et al. [265] used an Earth-system model to study glacial CH_4 emissions. They concluded that the atmospheric sink of CH_4 (i.e., the oxidation of CH_4 in the atmosphere) varied, as a result of lower emissions of volatile organic carbon from forests, which compete with CH_4 for atmospheric oxidants.

Harder et al. [101] took a top-down approach to evaluate paleo CH_4 emissions during the Holocene and Last Glacial Termination, by combining a climate model with a tropospheric chemistry model constrained by ice-core data. They also concluded that both the atmospheric sink and source varied. Rosen et al [225] studied rapid climate transitions during Dansgaard-Oeschger events in relationship with AMC. They reached similar conclusions: high-resolution data are biased by uncertainties preventing reliable interpretation for narrower time-scales and CH_4 emissions diffuse globally over large spatial ranges, regardless of the area of origin. This further complicates the effort to find the cause of abrupt climate change. Based on these results it will be impossible to give a precise number for the wetlands CH_4 source during various parts of the LG. However, it is possible to explore other factors that may have contributed to past variations of CH_4 emissions, and to explore the role of wetlands therein.

1.5 Aims and objectives

The original project aimed to create a globally applicable model of CH_4 fluxes originating from northern wetlands. The PEATLAND-VU model was to be used as a starting point. However, the lack of reliable data and the huge biases affecting the climate models that were to be used, all suggested that achieving this goal was not feasible. As the research proceeded, many gaps were found in the understanding of the main processes governing wetland dynamics, as well as approximations in the general modelling approach. These factors result in poor accuracy and systematic overestimation of the calculated fluxes. However, one clear priority did emerge, namely: the peatland research community [315] needs to shift its focus on to developing models that represent peatlands as complex systems adapting to a constantly evolving environment [28]. Models need to include the internal feedbacks that allow peatland ecosystems to adjust to changing conditions [91]. Application of such models would shed light on threshold behaviours and nonlinear dynamics of peatlands [315], and when included in coupled climate/carbon-cycle models, produce new insight into the role of peatlands in global climate change [160, 150]. The key to further achievements in this field is addressing the dynamics of the peatland carbon balance and their response to climatic disturbance. Given the existing gaps in the records of present and past environments and climates, the best path to follow is an investigation of peatland dynamics based on new data. Therefore, the concept this thesis has adopted was to rely on past analogues when studying climate change and to use them as guidelines to understand the processes currently ongoing in wetland environments, in order to better assess their CH_4 contribution during present-day climate warming. According to this strategy, any knowledge derived from the current Siberian permafrost ecosystem will be used to explain evidence of past glacial sedimentation. In parallel, the past climate will be compared with the actual situation today. The similarities, but also the differences, will be highlighted. As the details are put together, they should reveal much-needed clues on how to unravel the mechanisms that triggered the rapid shifts of this planets climate in the past. This aim is addressed with a combination of data collection from modern and past cold wetland environments and of spatial modelling, based on observed natural processes. The starting point of this study was a thorough sensitivity analysis of the parameters of PEATLAND-VU, a model which predicts CH_4 fluxes. The output of this model, run with past climate data, was then validated using actual fluxes. New input came with a field trip to Siberia, one of those neglected remote areas which could provide the much-needed clues about the carbon storage of wetland environments [315]. Direct observations on the vegetation cover triggered the impulse to investigate more about the behaviour of some of the most widespread plants, namely *Carex* ssp. and the ubiquitous *sphagnum* mosses. The findings showed that the GHG (particularly CH_4 response of coexisting species can be in opposite directions. The next step, the lake thaw model, required a profound shift in the focus of the main drivers and a thorough re-evaluation of what, up until now, have been considered the major parameters. With the importance of the vegetation being recognized, the volume of water in the lake needed to be quantified. The thermodynamics of lakes are important because they will remain at a constant temperature of 4 C while the surrounding environment drops to temperatures that range between -30^o to -50^o C. However, a full thermal model could not have been applied at the necessary landscape scale needed to appreciate the effects of the main processes. The summer air temperature was therefore used as a proxy thermal indicator of lake temperature. The final piece to add to the picture was to study the Ice Age cores sampled in the periglacial sediments of The Netherlands and to investigate the evidence for repeated thermokarst and lake thaw expansion during the Middle Weichselian. The goal here was to match these data to possible paleo-ecosystem scenarios and then to compare them with the knowledge gathered about current wetland environments. The next paragraph presents a more detailed description of how this thesis addressed such research issues, chapter by chapter.

1.6 Thesis approach and outline

This first chapter provides an overview of the thesis. The background, the importance of the topic, the current state of knowledge, the objectives and the key questions to be addressed. The second chapter reports how the PEATLAND model was deconstructed and studied in terms of structure and approach, with a sensitivity study that highlights the role and the importance of each parameter used. The aim was to find the correlation between the different factors and to see how the structure of a model influences its output. The sensitivity of the PEATLAND model was therefore tested for the recommended variations of the model parameters. Extreme values were then selected to evaluate the response under extreme conditions. At the end of this phase the results of this extensive sensitivity test were ready to be published as two articles presented here as Chapters 2 and 3. Chapter 3 goes deeper into the details of PEATLAND, analysing the effect of varying the previously found most sensitive parameters. The vegetation was identified as the main driver. It also quantifies CH_4 emissions, while validating the output with field data from across Europe.

The results revealed that PEATLAND would benefit from some parameter tuning, particularly when considering the importance of some factors. Vegetation cover needed more attention and better understanding: glacial, boreal and tundra wetland covers were modelled as being composed of a greater proportion of grasses than is seen currently in similar environments; they were also entirely lacking *sphagnum* mosses. Some other parameters, like the R_o factor, made almost no impact on the final output, buffered by background conditions. Re-evaluating how these factors were used in the model led to the development of a new lake model and a subsequent publication, presented here as Chapter 4. The paper successfully simulates how thaw lakes develop or may drain, depending on the climate as well as the surrounding conditions. This article presents a new approach to modelling thermokarst effects and lake formation in permafrost areas. It takes into account the newly found relevance of vegetation and other previously considered minor factors, such as the effects of wind, and ice content in the soil. Downscaling the model to a landscape scale and using time-steps of one year, to include relevant processes, was a decision taken after a thorough system analysis performed on a number of variables. The benefit of this approach, rather than a detailed process modelling based on a single lake, is that landscape scale corresponds to the scale at which these processes affect the climate and might be later included in Earth system models. Such analysis highlights the importance of linking climate factors to specific environmental parameters, and obtaining a linear correlation between climate and changes in lake thaw areas. The style of the text for Chapter 4 differs from the rest of the thesis; the presentation is less discursive and more pragmatic, due to the schematic structure of the modelling work and to the guidelines set by the editor. The model demonstrates that drainage in thawing lakes effectively reduces their CH_4 emissions.

In 2007, data from a number of sources was collected during a field trip to Siberia. Although fragmented, each dataset gave some new insight and when all the pieces were put together, the result was a picture consistent with the model output. The data collected made it possible to explain the different sizes of the fluxes from different vegetation covers, because different species provide different outputs. This partitioning of fluxes has so far been overlooked in CH_4 emissions. It was also confirmed that temperature is the main driver in this environment, although the drainage system is a key factor driving the evolution of the area. All these results are presented in Chapter 5 of this thesis, where close attention is given to investigating the role played by sphagnum mosses and their peculiar interaction with methanotrophic bacteria. While this work proceeded, TNO made two drill cores available. These sampled a complete succession of lakes from the Weichselian in The Netherlands. These samples provided the opportunity to make the comparison needed to validate my hypothesis. Chapter 6 is based on the analysis of paleo-thaw lake successions found in Europe and the Arctic. It is used to compare the evolution of the lake thaw environment in the last interglacial to the present conditions found in Kytalyk, Siberia. The aim was to present sedimentological evidence from the relevant locations of widespread permafrost thaw during the interstadials of the last glacial and to compare them to the present environment, to identify similarities and differences. Finally, Chapter 7 gives a short synthesis of the full thesis, and summarizes how the initial questions were answered by highlighting the key contributions and findings. It also offers suggestions for further studies.