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Comparative paleoclimatic reconstruction of Western and Southern Europe Glacial Ecosystems using inverse modeling of loess $\delta^{13}\text{C}_{\text{org}}$

Rossella Conti

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Internship report

Comparative paleoclimatic reconstruction of Western and Southern Europe Glacial Ecosystems using inverse modeling of loess $\delta^{13}\text{C}_{\text{org}}$

Rossella Conti

Du 01/02/2025 au 30/06/2025

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Caroline Gauthier, équipe GeoTrac, LSCE

Aknowledgements

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My husband and children, for their continuous and reliable backstage support

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Abbreviations

Hz	Harletz
kBP	thousands of years Before Present, Before Present = 1950AD
LGM	Last Glacial Maximum
MCMC	Monte Carlo Markov Chain
MIS	Marine Isotopic Stage
NPP	Net Primary Production
PFT	Plant Functional Type
Sdev	standard deviation
VA	Villiers-Adam

Introduction

Context of the study

Understanding the evolution of past climates is important for reconstructing the history of human evolution and for assessing how environments have adapted to climate changes. It is also a key feature to be able to predict the potential evolution of today's climate. Access to natural archives capable of shedding light on the impacts of global climate change on ecosystems is crucial for validating modelled processes and calibrating the variables required to evaluate the system's response — including response time, magnitude, and potential threshold effects. Modern observations do not cover a sufficiently long period to capture processes that evolve over centuries or more. Paleoclimatology offers the long-term records necessary to overcome this limitation.

1.1 Climatic cycles during the Pleistocene and their influence on human evolution

The Pleistocene (from 2.6 million to 11 700 Before Present (BP)) marks the period during which the genus *Homo* emerged on earth. At the beginning of Pleistocene, global temperatures, as recorded from the Antarctica ice cores, were comparable, though slightly cooler, than pre-industrial temperatures, but what characterizes mostly this period is the advent of strong oscillations in temperature, with a periodicity of ca. 41 000 years, which later shifted to a 100 000-year cycle over the past 1 million years (Baykal, Yunus, 2023). These oscillations correlate to advances and retraction of the ice caps in the Northern and Southern Hemisphere. They are named Marine Isotopic Stages (MIS), based on oxygen isotope ratios in deep-sea sediment cores. The successive stages are numbered with even numbers corresponding to periods of lower temperatures (glacial) and odd numbers corresponding to periods of warmer temperatures (interglacial), increasing in number as we go back into the past. In this period, *Homo* developed and expanded across the African, European and Asian continents. *Homo neanderthalensis*, Denisovan and *Homo sapiens* all emerged during this period and their evolution and interactions were likely influenced by climatic fluctuations, which may have contributed to the dispersal of *Homo sapiens* out of Africa, potentially in connection with major environmental changes.

1.2 The geographical context of the study

In the Northern Hemisphere, ice cap advances during glacial periods extend into the American and Eurasian continents. The maximum extent of the ice sheets during these glacial maxima, reconstructed mostly from studies of moraines and glacial sills (Hughes et al., 2020), is shown in figure 1. The thickening and advance of the ice sheets caused major changes in the continental geomorphology, primarily due to the isostatic pressure of the ice cap on the continental crust and the global lowering of the sea levels, that reshaped the geographic distribution of submerged and emerged lands.



Figure 1 : Extent of the Eurasian ice sheet margins during glacial periods from MIS 16 to MIS 2 superimposed on a map of the actual geomorphology of Eurasia. Lower MIS numbers correspond to more recent periods, with MIS 2 corresponding to about 20 000 years BP. From Hughes PD, Gibbard PL, Ehlers J. *Quaternary Research*. 2020

Figure 2 depicts the configuration of the Northern European landscape as it is currently reconstructed for the two most recent glacial periods included in this study, MIS 6 (Late Saalian) and MIS 2 (Upper Pleniglacial Weichselian).

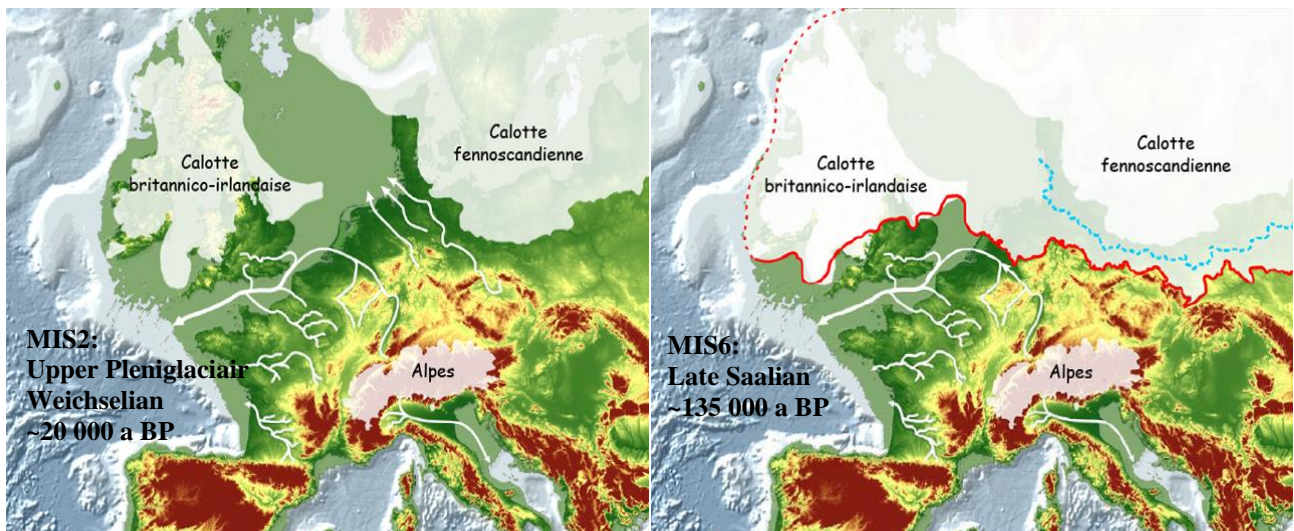


Figure 2 : Extent of the Eurasian ice cap borders during glacial periods from MIS 2 and MIS 6 and corresponding altered geomorphology of Eurasia after Hughes PD, Gibbard PL, Ehlers J. *Quaternary Research*. 2020

Evidence of human settlements in the northern part of France appears only after the end of MIS 6. While there are quite precise data for the temperature fluctuations in the Northern hemisphere for the period covering MIS 5 to present, thanks to the records of the Greenland ice cores, these data become unreliable before MIS 5, about 122 kBP (Baumgartner et al., 2014; Seierstad et al., 2014). Marine oxygen isotopic records provide insights into global climate changes but cannot give absolute temperature values for continental

regions. Pollen data, which give information about past vegetation cover, are scarce during glacial periods and most pollen deposits in Northern Europe accumulated only after the end of the MIS 6.

In this context, the data collected from loess, and in particular those of the two sites used in this study, are precious. Loess, terrestrial clastic sediments composed predominantly of silt-size particles (5 to 50 μm in diameter), accumulate mainly during glacial periods through the deposition of wind-blown dust (Pye, 1995). They often preserve traces of the local vegetation in the form of organic material within the loess (Hatté, 2000). These records, together with the pollen data from the less cold periods, give complementary means of reconstructing vegetation, biomes and hence the climate of Europe throughout the last hundreds of thousands of years.

1.3 The role of $\delta^{13}\text{C}_{\text{org}}$ measurements

During their growth, plants use nutrients from their environment to build macromolecules which constitute their structural and cellular components. Carbon is taken directly from the atmospheric CO_2 , through photosynthesis. Carbon exists naturally as two stable isotopes: ^{13}C and ^{12}C . ^{13}C has an extra neutron in its nucleus, it is thus heavier and is less abundant than ^{12}C , this last one constituting 99% of the total carbon. The ratio of $^{13}\text{C}/^{12}\text{C}$ in the atmospheric CO_2 differs from that found in organic matter. The diffusion of CO_2 from the outside air to the inner compartments of the plant and the formation of chemical bonds that leads to the production of sugars through photosynthesis, are both processes that will change the final ratio of $^{13}\text{C}/^{12}\text{C}$ in the organic products (Farquhar et al., 1989). This effect is known as isotopic discrimination. Diffusion is easier for the lighter isotopes and photosynthesis requires less energy to metabolize ^{12}C than ^{13}C , so that, plant $^{13}\text{C}/^{12}\text{C}$ ratios is smaller than the original ratio in atmospheric CO_2 . In practice, the deviation of the $^{13}\text{C}/^{12}\text{C}$ ratio of the organic matter relative to a universal sample (Vienna-PDB) is measured, expressed as $\delta^{13}\text{C}$. To facilitate reading, $\delta^{13}\text{C}$ is expressed in per mil (‰). The more negative $\delta^{13}\text{C}$, the less abundant the ^{13}C is in the sample (Hatté, 2000).

$\delta^{13}\text{C}$ in vegetation biomass depends on the type of photosynthetic process that plants use to build their organic elements (C3, C4 or CAM photosynthesis). For C3 photosynthetic plants, which are the most abundant, $\delta^{13}\text{C}$ is also influenced by atmospheric CO_2 concentration, atmospheric CO_2 $\delta^{13}\text{C}$ ($\delta^{13}\text{C}_{\text{atm}}$) and water availability. Under water stress, plants close their stomata (pores responsible for gas exchange) to prevent water loss. This limits CO_2 intake, forcing the plant to assimilate all the CO_2 available, including the heavier (^{13}C) isotope. C4 plants, on the other hand, possess a carbon-concentrating mechanism that largely eliminates the influence of atmospheric CO_2 concentration on their $\delta^{13}\text{C}$. They typically thrive in environments subject to water stress.

C3 plants typically exhibit $\delta^{13}\text{C}$ values ranging from approximately -25‰ to -30‰, while C4 plants display values closer to -12‰ to -15‰. CAM plants generally have intermediate $\delta^{13}\text{C}$ values, depending on the degree to which they rely on C3- or C4-like photosynthetic pathways (O'Leary, 1981).

In terrestrial ecosystems, measurement of the carbon composition of sedimentary organic matter ($\delta^{13}\text{C}_{\text{org}}$) can inform us about past climatic conditions, particularly on average water availability, at the time the plants lived.

1.1 Climate parameters inferred by inverse modeling of $\delta^{13}\text{C}_{\text{org}}$ measurements

The relationship between the climatic parameters and the $\delta^{13}\text{C}$ of the local vegetation can be modeled by different vegetation models. The one used by Christine Hatté is BIOME4 (Haxeltine & Prentice, 1996; Kaplan et al., 2002), a model that integrates geophysical information (soil properties, geographical position, atmospheric CO_2 concentration and $\delta^{13}\text{C}$ ($\delta^{13}\text{C}_{\text{atm}}$)) together with the climatic parameters to calculate the best combination of plants, the corresponding biome and the $\delta^{13}\text{C}$ for the given environmental conditions. The

program is a well-developed software which integrates all known physical laws that regulate plant growth as well as the specific constraints for survival of the different plant functional types (PFT - Prentice et al., 1992, 1993). In this work, the model is used in an inverse manner. What the laboratory can measure is the $\delta^{13}\text{C}_{\text{org}}$ in the loess samples taken at different depth, which correspond to different periods of time. What we aim to reconstruct are the climatic parameters of the past, based on the effect they had onto the vegetation, which is the inverse of what BIOME4 does.

To do this, an inversion program has been developed by a colleague of Christine Hatté, Joël Guiot, that statistically explores a large range of possible climates by feeding them to the BIOME4 and records the corresponding vegetation parameters. By iteratively selecting the climates that give results that are closer to the experimental values, the program builds a subgroup distribution of climates which could have been responsible for the measured data (figure 3). This inversion process is done for each sample point in the stratigraphical sequence and this allows us to reconstruct the most probable precipitation and air temperature values for the measured ages.

1.2 Objective of the internship work

The aim of my internship work was to pose the boundaries for some of the most relevant climatic parameters during the last two glacial periods for two loess sites in Europe: Villiers-Adam (VA) in the Paris Basin, France (Rousseau et al., 2003), and Harletz (Hz), in the Danube Valley, Bulgaria (Antoine et al., 2019) (figure 4). The laboratory holds two extensive records of $\delta^{13}\text{C}_{\text{org}}$ from these loess sequences. Both records span the last part of the Late Saalian period, the Last Interglacial period (including the Eemian) and the Early Glacial and Pleniglacial Weichselian, which correspond to MIS 6, MIS 5 and MIS 4 to 2, respectively.

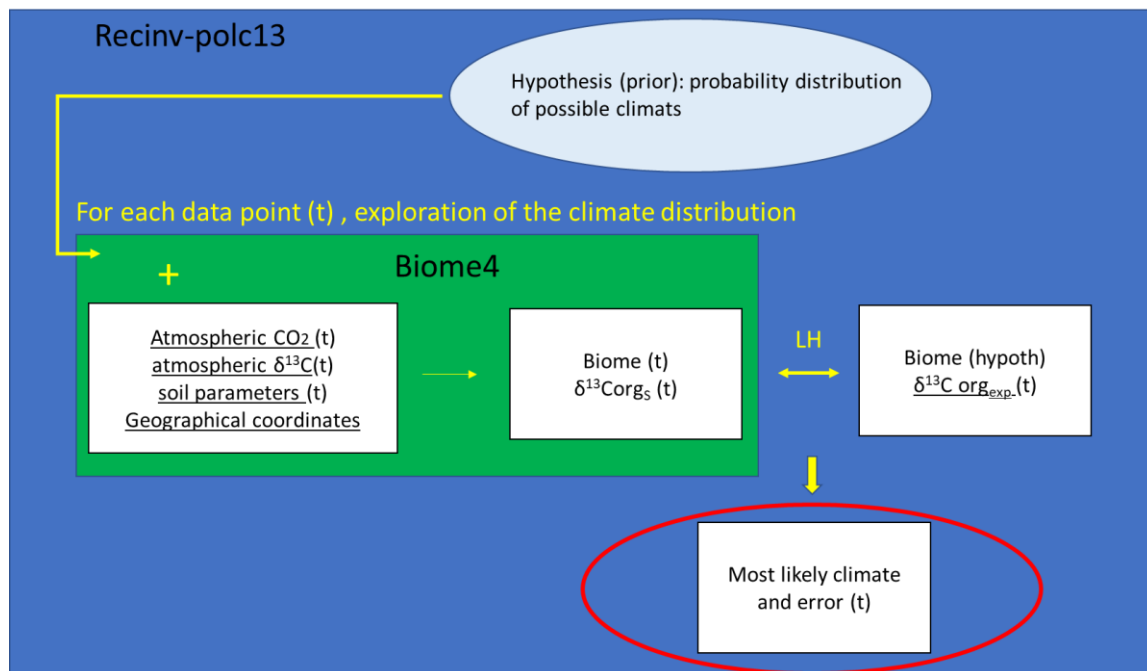


Figure 3: schematic of the inversion model structure. RecInv-polc13 is the inversion model. The model constructs a prior probability distribution of climates, then inputs the climates to BIOME4 through a MCMC sampling method and computes their likelihood (LH) based on the $\delta^{13}\text{C}_{\text{org}}$ data and the biome constraints. The likelihood determines the posterior distribution of probable climates which is the output of the program

In order to achieve this objective, the work has consisted in a first part, which took approximately one fifth of my research time, of bibliographic research to understand the context of the study and gather all possible continental information by complementary studies of other proxies in the surrounding regions that could help in setting appropriate constraints for the possible biomes during the different periods.

The second part of my work has been dedicated to understanding, testing and modifying the inverse modeling software to adapt it to the specific aim of this project. This has been the more time-consuming part, which took almost half of the internship work. The pilot version of the software had been developed to use for a particular geographic site for which both pollen data and $\delta^{13}\text{C}_{\text{org}}$ data were available. The inversion had been optimized to fit the data on pollen by testing the program on the actual climate and pollen composition. The purpose of my work was to find the best way to adapt it to the constraints of the loess measurements for the glacial periods, notably the low pluviometry and the absence of pollen data. The bibliographic work helped in adding constraints on the possible biomes in the model, that partly compensate the absence of pollen data.

Finally, after setting up a temporal sequence for the geophysical parameters of the sites needed by BIOME4, together with the $\delta^{13}\text{C}_{\text{org}}$ measurements and the acceptable biome constraints, I used the model to answer to the major question: can we reconstruct and constrain the values of the two climate parameters, temperature and precipitations, on the sites of Villiers-Adam and Harletz based on the $\delta^{13}\text{C}_{\text{org}}$ data, and does the simulation give acceptable scenarios for these glacial periods?

Material and Methods

Geographical location of the two loess sites

The $\delta^{13}\text{C}_{\text{org}}$ data used for modeling come from two European loess sequences: Villiers-Adam (lat. 49.07°, long. 2.23°), located in the Paris area in the Oise valley in France and Harletz (lat. 43.7°N, long. 23.8°E), located on the western bank of the Ogosta river, in the Danube valley in Bulgaria.

$\delta^{13}\text{C}_{\text{org}}$ data

Bulk sampling was done with a 5 cm depth resolution in Hz and a 10 cm depth resolution in Villiers-Adam. Samples are treated to eliminate all traces of mineral carbon and then burnt to transform organic carbon into CO_2 , which is analyzed by a mass spectrometer to measure the $\delta^{13}\text{C}$, which corresponds to the $\delta^{13}\text{C}_{\text{org}}$.

Modeling environment

Recinv-polC13, the inversion program, was written in the R programming language in 2020 by Joel Guiot. The program was modified and run for initial testing in the RStudio environment. The inversion program is time consuming, so for multiple time points simulations and final runs over the whole sequence of measurements, the simulations were performed on the cluster of the LSCE. I setup the working environment on the cluster with the directory containing data sets, BIOME4 and the Recinv-polC13 program and a result folder. The PBS scripts (job) containing instructions and calls to the inversion program were submitted to the cluster and the results were then transferred to a local computer for analysis in the RStudio environment. Final rendering of the data was made in the Igor Pro programming language.

BIOME4 model

BIOME4 (Kaplan et al., 2002) is an upgraded version of the BIOME3 (Haxeltine & Prentice, 1996) model, written in the Fortran programming language. The version used for these simulation is a version modified by C. Hatté and J. Guiot (Hatté & Guiot, 2005), optimized for calculation of $\delta^{13}\text{C}$ based on atmospheric parameters and external environmental forcing. The input parameters are: atmospheric CO_2 pressure and $\delta^{13}\text{C}_{\text{atm}}$, geographical latitude, 36 climate parameters (mean monthly values of temperature, precipitation and relative cloudiness), absolute minimum temperature, and soil properties. The soil water availability for plants in the model is calculated based on a two-layer model of soil, with an upper 30 cm layer and a lower 120 cm layer. The soil inputs are 4 parameters: maximal available water retention (sw1 and sw2) and percolation coefficient (K1 and K2). The different sets of climate inputs for modeling for each sample depth was generated by the inversion program. The other inputs were passed through an Excel file constructed by the experimenter which contained the parameters corresponding to each depth. Based on the inputs BIOME4 selects the best combination of PFTs based on a competition algorithm, calculates their NPPs, the $\delta^{13}\text{C}$ and finds the biome that corresponds to the combination of selected PFTs. The relevant outputs of BIOME4 (notably $\delta^{13}\text{C}$ and biome number) are stored for each climate and used by the inversion program for calculation of the likelihood.

Reclnv-polC13 program

The inversion program is written in the R programming language. The inputs to the program are the geographical area for the definition of the prior's distribution, the 36 climate parameters (mean monthly values of temperature, precipitation and relative cloudiness), the elevation data, the soil parameters of each grid point of the area, and the geographical coordinates of the studied site together with an Excel file

containing atmospheric CO₂ concentration, $\delta^{13}\text{C}_{\text{atm}}$, sw1, sw2, k1, k2 as well as the $\delta^{13}\text{C}_{\text{org}}$ and the sdev $\delta^{13}\text{C}_{\text{org}}$ and the 2 acceptable biome groups as a function of the sample depth for the studied site. The actual world-wide climate data were taken from a gridded database of 30 years span (from 1961 to 1990) provided by the Climatic Research Unit. A topography dataset was used to find the altitude corresponding to each grid point. The soil sw1 and sw2 data were obtained from available data of the Food and Agriculture Organization of the United Nations. The k1 and k2 values for each grid point were taken from the built-in BIOME4 data from (Kaplan et al., 2002). For the sequence of site data a function of depth, the CO₂ atmospheric concentration values were built by linear interpolation of the Antarctica ice core data. A constant value of -6.5‰ was attributed to the $\delta^{13}\text{C}_{\text{atm}}$. The soil parameters were chosen using the average values of actual loess sites in the world as baseline and introducing shifts from baseline as a function of depth according to the changes in soil texture reported for the sequence. The atmospheric CO₂ partial pressure was computed based on the altitude and the CO₂ atmospheric concentration. To constrain the space of possible climates by means of the acceptable biomes, we divided the 28 biomes that are integrated in BIOME4 into 8 groups (see appendix 1), and only 2 of these groups were allowed for each depth point. For the loess data of the two sequences we did not expect any biome that would correspond to tropical, temperate, or desert biomes. We thus excluded groups 1 to 4 and 8 for all data points. Mainly, group 6 and 7 (boreal grasslands and steppe tundra) were allowed during glacial maxima and group 5 and 6 (conifer or cold forests and steppe tundra) during MIS 3 and at the transition into and out of the Eemian Interglacial.

The program uses a built-in R principal component analysis function to build the prior distribution. To get a Bayesian inference of the possible climates for each data point the program runs 4 parallel MCMC with Metropolis Hastings algorithm on the constructed prior distribution. Each chain starts with a different random climate. The climate and the other geophysical input parameters for the given depth are passed to BIOME4, that outputs the corresponding $\delta^{13}\text{C}$ and biomes. The inversion program will reject all climates for which the output biome is not within the group of acceptable biomes. It will then use the $\delta^{13}\text{C}_{\text{org}}$ to compute the likelihood of the simulated $\delta^{13}\text{C}$ for climates that have not yet been rejected, based on a normal distribution for $\delta^{13}\text{C}$ with sdev equal to twice the error of the $\delta^{13}\text{C}_{\text{org}}$. The program runs 10000 iterations for each chain. For each accepted proposition of climate, the corresponding likelihood, the set of climate parameters and the results of BIOME4 are stored. The probability distribution of the climate parameters was built from the frequency distribution of the subset of climate configuration towards which the MCMC simulation converged. A burn-in time of 5000 iterations (the first half of the data) was discarded. Of the remaining half, results for which the likelihood fell within the first quartile were discarded. A matrix thinning was used to select one out of 4 of the remaining set of results, which represent the distribution of posterior climates (the climate distribution that corresponds to the measured $\delta^{13}\text{C}_{\text{org}}$) and the corresponding vegetation parameters. The frequency distribution for the average annual temperature and precipitations and other relevant outputs of BIOME4 (mean temperature of the coldest and warmest months, NPP etc..) were normalized and then averaged over the 4 chains. The median of the distribution and the 0.05% lower and 0.95% upper limits of the distributions were stored and used to quantify the predictions of the model for each sample depth.

Results

2.1 Confining the possible biomes by analysis of other regional proxies

While there is a common understanding of the evolution of climate during the Weichselian period, and in particular the Last Glacial maximum, the Late Saalian remains a more unknown age, with few and fragmented continental data, especially in the northern part of Europe. The MIS 6 is often present only in its late part (130-150 kBP), as erosive events have deleted the sedimentation of the 190 to 150 kBP period (Antoine & Limondin-Lozouet, 2024). The Villiers-Adam sequence, in the Paris region, follows the same logic, with only the later phase of MIS6 (130-150 kBP) preserved. In contrast, the Weichselian period is well represented by a quite extended deposit with a deposit rate of up to 1cm for 100 years. The granulometry measurements show a clear transition from MIS 5 to MIS4 characterized by a change in the source of loess sediments probably due to the progressive advance of the ice cap and decrease in sea level which lead to the drying of the English Channel and availability of sand particles to be transported by the Northwesterly winds. A concomitant decrease in clay percentage probably related to a decrease in rainfall confirms a dryer climate typical of the periglacial regions. An increase in clay content and the development of a paleosol mark the advent of MIS3 that is milder and more humid, and a typical loess layer develops finally with the emergence of the last Glacial Maximum, around 20 000 years BP (Rousseau et al., 2003). A bit North-East from there, in Waziers (France, see figure 4), multi-proxy investigations – including palynology, malacology and faunal analyses – reveal that during the Late Saalian period, the climate was arctic with arctic vegetation, which later shifted to tundra-steppe during the last phase of the Late Saalian (Deschodt et al., 2023; Gauthier, 2022).



Figure 4: The sites of loess included in this study are shown in red on the geographical map of Europe during the Last Glacial Maximum. In France, Villiers-Adam (VA) is situated in the large Basin of the Paris area, while Harletz (Hz), Bulgaria is situated in the Danube valley. The other proxies' sites cited in the text are also indicated in blue. Wz: Waziers, France; Am: Amsterdam and Amersfoort, Netherlands; Oh: lake Ohrid, Macedoine/Albania; TP: Tenaghi Philippon, Greece.

Further North, in the Netherlands the ice sheet covered the sites of Amsterdam and the nearby site of Amersfoort (Cleveringa et al., 2000; Van Leeuwen et al., 2000). Here, the end of the Saalian is marked by a

period of fresh water lake due to melting of the ice cap on land, which was isolated from the sea due to the well-formed isostatic depression and a sill formed by glacier moraine. As sea level raised due to melting of ice cap, sea water invaded the region. The beginning of the Eemian in Waziers is marked by the presence of a peak in aquatic plants and algae, which argues for a very slow flow of water in the region. There is thus a rapid transition from steppe to aquatic environment, followed by the slow buildup of prairies that leaves place to an increasingly dense forest and biomass production, with the presence of peat. During this interglacial stage, many Neandertal remains of human activity and big fauna are present in the area (Deschodt et al., 2023). The Weichselian starts after the Eemian with a gradual degradation of the vegetative cover followed by a strong erosion and soil fractures due to freezing episodes. The soils are strongly ravaged and the chronology is difficult to interpret.

In the Harletz site, far south in the Danube valley, the loess records are more complete and they extend all throughout the MIS 6 and MIS7 (Antoine et al., 2019; Lomax et al., 2019). As for Villiers-Adam, the granulometry and magnetic susceptibility data shows phases of pure loess deposits during the Saalian, followed by a soil development enriched in clay and ferromagnetic components, that denotes a transition to the more humid Eemian Interglacial and a gradual return to drier conditions during the Weichselian, interrupted by a more humid phase during MIS3. Additional proxies from the region include pollen data from Lake Ohrid, at the border between Albania and Macedoine. The lake is located at 693 m altitude, and it's surrounded by mountains up to 2000 m altitude that contribute to the sedimentary pollen input. These pollen data reveal a very cold and dry period for the Late Saalian characterized by tundra to steppe vegetation, shifting to pioneer trees and conifers that indicate a progressive onset into the Eemian interglacial period (Sinopoli et al., 2019). The transition to forest is quite abrupt at the start of the Eemian. The transition to the Weichselian is marked by a return to steppe vegetation alternating to coniferous vegetation throughout the Early glacial period. Climate modeling based on this data suggests colder and dryer climates for the Late Saalian period, with intense oscillations during the very last 140 to 130 kBP period. Further south, the peatland of Tenaghi Philippon in the Drama basin (Greece) complements this picture. This site shows a marked predominantly open vegetation dominated by steppe and coniferous open lands during most of the Late Saalian, with almost no trees in the last 150-130 kBP period. An abrupt transition on a decadal time scale at the Saalian-Eemian boundary marks the development of mixed, tree-dominated forests that persist throughout the Interglacial. The Weichselian deposits contain a mixture of both type of vegetation, with less abrupt shifts but a marked steppe phase between 60 and 70 kBP (MIS4), and a frequent millennial-scale oscillation between steppe and forest environments (Koutsodendris et al., 2023). At Tenaghi Philippon, proxy measurements of relative precipitation are based on sedimentary calcium (Ca) and iron (Fe) concentrations ratio, which is proportional to karstic water input to the lake. Higher Ca contents correspond to increased precipitation, although absolute values are not established. The lowest Ca/Fe ratios, indicating drier conditions, occur during the 130 to 150 kBP, and 60-70 kBP and around 20 kBP periods, which correspond to the coldest glacial periods of the Late Saalian and Weichselian glaciations.

Overall, pollen data and other proxies indicate that, during the Late Saalian, biomes ranged from arctic tundra, tundra and steppe vegetation from North to South Europe. Despite the Mediterranean influence and lower latitude, pollen data suggest that temperature and precipitation conditions were hard even in Greece. The transition to the Eemian interglacial in northern Europe left place to cold adapted vegetation, while southern Europe experienced the development of abundant mixed forests. Climatic harshness returned during the Weichselian glaciation, particularly in the 60-70 kBP interval, and at the Last Glacial Maximum, around 20 kBP, with environmental conditions resembling those of the late Saalian. This research allowed me to set boundaries in the model for the acceptable biomes during the different ages.

2.2 Qualitative analysis of the $\delta^{13}\text{C}_{\text{org}}$ data sequences of Villiers-Adam and Harletz

The loess samples used for $\delta^{13}\text{C}_{\text{org}}$ measurements come from two European sites, Villiers-Adam (France) and Harletz (Bulgaria). The Harletz sequence lacks the most recent period from 35-40 kBP to present, due to erosion and the influence of human activity. The VA sequence is more complete for the most recent period, but is missing part of the MIS6. The $\delta^{13}\text{C}_{\text{org}}$ data from both sites overlap over the period from 140 000 BP to 35 000 BP.

In the Villiers-Adam sequence, $\delta^{13}\text{C}_{\text{org}}$ values range from -26.0‰ and -23.8‰, while the Harletz data show overall more enriched values (from -25‰ to -21.8‰) (figure 5). As a general rule, heavier ^{13}C signature could correspond to a higher proportion of C4 plants (which are more adapted to drier climates), to a drier climate as recorded by C3 plants, to C3 plant growth in a lower atmospheric CO_2 concentration and/or to C4 or C3 plant growth in a context of less depletion of atmospheric CO_2 $\delta^{13}\text{C}$. For a same period of time, heavier $\delta^{13}\text{C}_{\text{org}}$ values in Harletz compared to VA are likely due to climatic differences, which may have led to the presence of C4 plants, an isotopic response of C3 plants to a drier condition in Hz, or both. A differential level of degradation of the vegetation could also in part contribute to a shift in the fractionation. When records are aligned based on the stratigraphic correlations, despite differences in absolute values, both sequences present several common features, especially similar patterns of major and minor deflections.

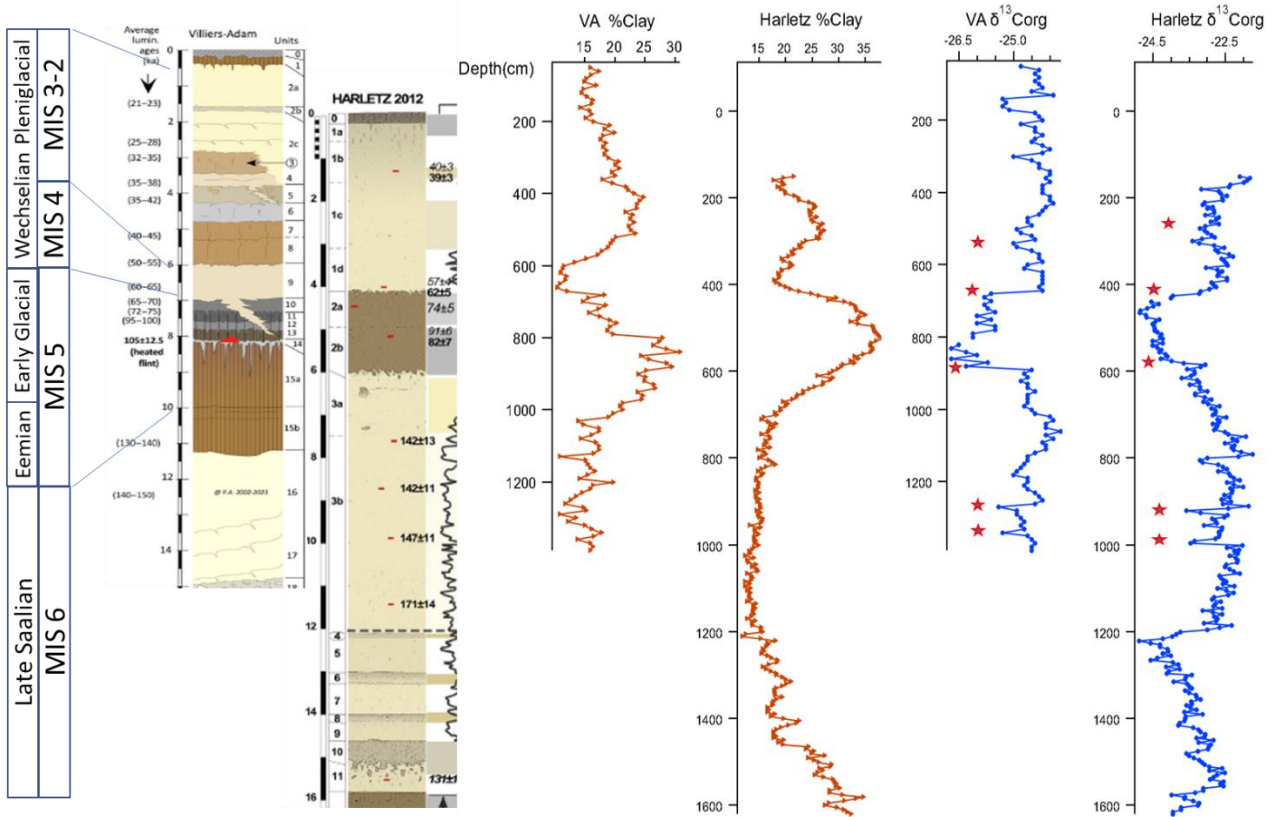


Figure 5. Loess stratigraphy and corresponding $\delta^{13}\text{C}_{\text{org}}$ and % clay measurements for the Villiers-Adam (VA) and Harletz (Hz) sites. The depth axis for the Hz data has been shifted and stretched to tentatively match the VA chronology, notably the onset of the Eemian Interglacial (123 kBP) and the 60-70 kBP glacial maxima period. The red stars on the $\delta^{13}\text{C}_{\text{org}}$ traces show common deflections (including the Eemian Interglacial and Weichselian Lower Pleniglacial transitions at 123 and 70kBP respectively), that suggest global environmental changes over the European continent. Average luminescence ages are shown on the left of the stratigraphic VA log and on the right of the Hz log. Left: MIS period match from Antoine & Limondin-Lozouet (2024).

We have to keep in mind that the deposition rate might differ depending on the site, so we do not expect an exact depth-to-depth match. If we allow for a bit of stretching and compression here and there, both profiles exhibit a very similar sequence of deflections, which should be indicators of climate changes over the European Continent, considering that the two sites are almost 2000 km apart. The most notable climatic changes are the transitions from Late Saalian glacial period to the Eemian interglacial, and then the transition to the Weichselian Lower Pleniglacial period. This is marked by a long-lasting deflection to more negative values, corresponding to relatively milder climates for the vegetation during the Eemian period. Interestingly, the Saalian-Eemian transition is smoother in Harletz, with a $\delta^{13}\text{C}_{\text{org}}$ that gradually decreases accompanied by a slow increase in the percentage of clay in the soil and of ferro manganese nodule formations and root traces, which all are signs of a slowly increasing precipitation over time. In Villiers-Adam, both Saalian-Eemian and Eemian-Weichselian transition are definitely much sharper. In the tentative alignment presented in figure 5, we also identify 2 other inflections, during the Late Saalian period. Considering the geographical distance of the two sites and the amplitude of the deflection, accompanied in VA by changes in soil composition as well, they might be the signature of a global change in climate all over Europe in this last phase of the Late Saalian period. This correlates well with the data from lake Ohrid that showed oscillations in temperature and precipitation for the same period. These absolute value of the $\delta^{13}\text{C}_{\text{org}}$ are the major constraint that I have used to infer the climate parameters.

2.3 Getting grips on the model and adapting it to the new constraints

Inverse modeling is used in science to try and reconstruct the distribution of unknown parameters based on real measurements of variables that are function of those parameters. In the case of past climate modeling, this approach is applied to environmental archives preserved in continental or oceanic sediments, or even tree rings, where mineral or organic proxies are measured to reconstruct past climatic and environmental conditions. One such proxy, the carbon isotope ratio in sediment organic matter, reflects environmental constraints on vegetation. When (or not) combined with palynological data, $\delta^{13}\text{C}$ allow us to reconstruct key past climate parameters such as temperature, precipitation and seasonality.

My work builds on previous work by Christine Hatté who applied this inverse modeling method to loess organic matter $\delta^{13}\text{C}$ of the Nußloch loess sequence (Germany) for the Weichselian period (Hatté & Guiot, 2005). At that time, the inversion was based on the predictions of the BIOME4 model, with a random exploration of the space of climates, under the assumption that any combination of climate parameters could be an acceptable climate. In contrast, the inversion approach that I used, is based on a more recent development by Joël Guiot, which includes a particular method, Bayesian inference, coupled to a Monte Carlo Markov Chain sampling, to iteratively sample and convergence towards the most probable distribution of climate parameters. This method introduces prior knowledge into the inference process and provides a more robust probabilistic framework for climate reconstruction. The core of the inversion is written in the R programming language and begins by defining a prior probability distribution over a continuous multidimensional climate parameter space (e.g. temperature, precipitation, seasonality), called "priors". A candidate climate is then sampled from this space according to a Monte Carlo Markov Chain exploration method and used as input for the external program, BIOME4, written in the Fortran programming language. BIOME4 simulates the most probable biome under the proposed climatic conditions, and an associated $\delta^{13}\text{C}$ value is inferred based on biome type and physiological response models. The simulated output of BIOME4 is then compared to the measured values of the $\delta^{13}\text{C}_{\text{org}}$ and the expected range of biomes. Based on this comparison, the candidate climate's likelihood is estimated.

There are different ways of choosing the space of climate parameters and the sampling criteria. The Bayesian inference method is based on a theorem that states that if we have an a priori knowledge of a reasonable probability distribution of all climates, and we know the probability distribution for a given value of $\delta^{13}\text{C}$ given

a climate, then we can infer the distribution probability of climates given the measured value of $\delta^{13}\text{C}_{\text{org}}$. For the Bayesian inference method, we thus need to have a knowledge of the probability distribution of all possible climates in the region we are studying. The exploration method based on Monte Carlo Markov Chains consists of picking a random climate at first, computing the likelihood, then picking a second climate, computing the likelihood, comparing the two and retain only the one that is more likely. Once the more likely is retained, the next climate is picked. In the Markov Chain method with Metropolis Hastings algorithm used in the program, the criteria for accepting or rejecting the new proposed climate is based on the likelihood of the climate, with a probability that allows from time to time a climate to be retained even if its likelihood is smaller than that of the preceding one. The probability of this digression gets smaller the more the likelihood difference is big, so that we do not end up accepting too many really improbable climates.

2.3.1 The convergence method

The calculation of the likelihood in the inversion program by Joel Guiot was mostly based on pollen measurements. Part of my internship work was to change the program at multiple levels, to adapt it to work on presumably glacial periods, when pollen data are absent. To compensate for the lack of pollen input, I made several changes: in the way convergence is achieved and how priors are defined. The definition of the priors will be addressed in the next section.

Based on palynological studies and general paleoenvironmental knowledge, we grouped the original 28 biome classes into 8 broader biome categories. For each stratigraphic level, only two biome groups were considered acceptable, depending on the presumed climatic conditions: i) for the full glacial periods (Late Saalian and Weichselian), only arctic to boreal biomes, without tree vegetation were accepted; ii) for the Eemian interglacial and the MIS3 period, with presumably milder climates, we accepted boreal to cold biomes, including conifers. All climates giving rise to desert, tropical or temperate biomes were automatically rejected.

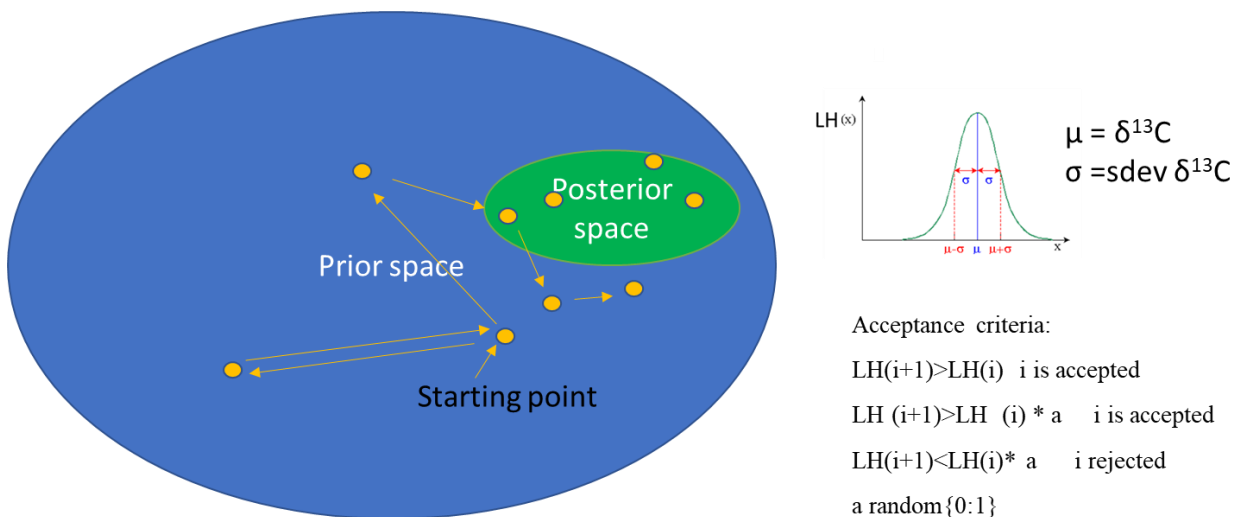


Figure 6: MCMC sampling method with Metropolis Hastings acceptance rule. Starting from an aleatory climate in the prior's space, the MCMC is constructed by proposing a new climate using the first one as reference for the climate probability distribution. The likelihood for each climate is computed as the probability density of the $\delta^{13}\text{C}_{\text{org}}$ measured, given the $\delta^{13}\text{C}$ predicted by BIOME4. A Metropolis Hastings method is used for accepting or rejecting the new proposal, based on the ratio of the two likelihoods: If the ratio of the proposed climate over the initial one is bigger than a randomly generated number between 0 and 1, the proposal is accepted and becomes the new starting point for proposal generation.

If the predicted biome was within the accepted ones, the likelihood of the climate was computed by assuming a probability distribution of the $\delta^{13}\text{C}$ with normal shape and error equal to 2 or 3 times the error in the measurement (figure 6). For the convergence method, I used the standard Monte Carlo with Markov Chain (MCMC) algorithm to sample the prior climate space (figure 6 and methods). The posterior distribution was approximated by iteratively proposing new climates, evaluating their likelihoods, and accepting or rejecting them according to the Metropolis-Hastings criterion.

2.3.2 Construction of the geophysical parameters

A key component of the inversion framework is the BIOME4 model, which predicts both the biome and its average $\delta^{13}\text{C}$ associated to each climate scenario. The model is based on the estimated of the Net Primary Production (NPP) of different plant functional types (PFT), given the climatic parameters (temperature, precipitation, seasonality, sun), atmospheric CO_2 concentration and $\delta^{13}\text{C}$ ($\delta^{13}\text{C atm}$), four soil properties parameters (water-holding capacity and permeability of the upper 30 and deeper 120 cm layers), and the geographical coordinates of the site. All of these parameters are relevant to predict the type of plant adapted to the region and the climate, their net primary production and the $\delta^{13}\text{C}$ ($\delta^{13}\text{C plant}$). The ^{13}C discrimination is computed and output based on the equation by Farquhar et al. (1989):

$$\Delta = 4.4 + (22.6) * (P \text{ CO}_2\text{int}/P \text{ CO}_2\text{atm})$$

With $P \text{ CO}_2\text{int}$: intracellular CO_2 partial pressure,

Which is then converted in the inversion model in to the $\delta^{13}\text{C}$ by the equation:

$$\delta^{13}\text{C plant} = (\delta^{13}\text{C atm} - \Delta) / (1 + \Delta)$$

$P\text{CO}_2\text{atm}$ (pressure of atmospheric CO_2) and $\delta^{13}\text{C atm}$ have varied during the past and are available in the literature from measurements of the Antarctica ice core. I used an aged matched profile for the atmospheric CO_2 and a constant value of -6.5‰ for the $\delta^{13}\text{C atm}$. The $P \text{ CO}_2\text{int}$ and hence the isotopic discrimination, depend on the stomatal conductance, which in turn is regulated by water availability. In BIOME4, water availability is estimated using variables such as latitude, pluviometry, insolation and key soil parameters: maximal available water capacity (AWC) and the percolation index. The AWC data are obtained from available data of the Food and Agriculture Organization of the United Nations all over the world, while the percolation coefficients used in BIOME4 are empirical values calibrated to optimize agreement between simulated and observed modern biome distributions at the world scale (Haxeltine & Prentice, 1996).

For this study, it was not possible to use modern soil data from the loess sites directly, since soil properties have evolved significantly over time due to pedogenesis and stratigraphic succession. To estimate paleosol characteristics for each sedimentary layer, I relied on the granulometry data to mimic the major soil properties changes (increase in clay content, increase in sand with respect to silt etc..) starting from an average value for both maximal available water capacity and percolation that I took from the average loess area properties in the world.

2.3.3 The prior space

In Bayesian inversion modeling, the prior distribution reflects our initial knowledge of the probability space of possible climates for the region of interest. The way the program was conceived to construct this distribution was by collecting all parameters (36 parameters describing the monthly precipitation, temperatures and insolation) from an extended geographical region around the site of interest. The region spanned 30 degrees latitude by 30 degrees longitude around the site. Once all climates data were collected, a principal component analysis was run to extract 4 principal coordinates that covered most of the variability in the data. The standard deviation of the distribution of the climates along each principal component were

stored and the prior distribution was constructed as the ensemble of points described by 4 coordinates with normal distribution and corresponding standard deviation along the principal axes. This approach ensures that the sampled climate scenarios are statistically representative of plausible climates observed in the geographical position, selected as prior space.

2.4 Final testing and results on reconstruction of the paleo precipitations and temperatures at the studied sites

2.4.1 Proof of principle of the new version

The first simulations were run on the site of Grand Pile (France), the site that was previously used by Joël Guiot to test the pilot program. The aim was to verify that the new version of the program could still converge in this test region. The results were satisfactory, even if without the constraint on the pollen data the predictions for temperature and rain fall were lower than those obtained with the pollen constraints. Some minor corrections during debugging might have influenced slightly the result. The important result was that the program was running and converging properly in its new form.

2.4.2 Testing and optimizing the program for the Villiers-Adam site

I then used the program on a subset of data points for the site of Villiers-Adam, which is the site with $\delta^{13}\text{C}_{\text{org}}$ values that are within a range that indicates the presence of C3 plants only. The soil and atmospheric parameters chosen for the whole data span, as well as the corresponding depth-related $\delta^{13}\text{C}_{\text{org}}$ values are shown in figure 7. The $\delta^{13}\text{C}$ output of BIOME4 used for the computation of the likelihood, was the contribution from C3 plants only. The idea was to consider only climates for which BIOME4 would predict no C4 plant components, but because of a missing call to an external routine, the program allowed for C4 plants to exist, even if we did not use their $\delta^{13}\text{C}$ contribution. I will discuss this point later (section 2.4.5).

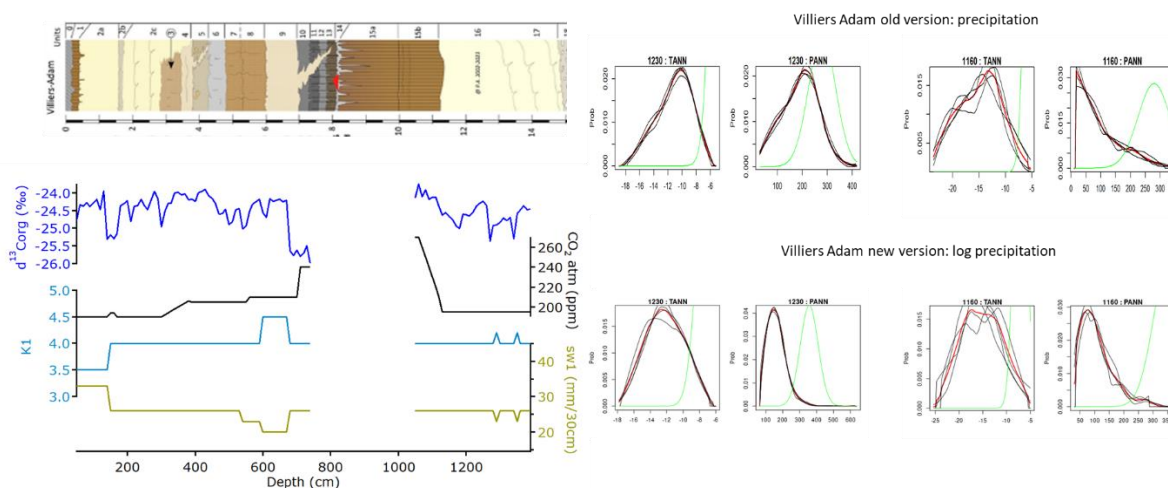


Figure 7: Left: Profile of input parameters to BIOME4. The soil parameters k1 and sw1 correspond to the percolation coefficient and the maximal water retention for the first 30 cm of soil. Right: Exemplification of the precipitation and temperature distributions before and after the change in the program prior's construction. TANN= mean annual temperature and PANN= mean annual precipitation. Black traces represent the distribution for each one of the 4 parallel chains. Red traces are the average distribution and the green trace represents the distribution of the climate parameters at the same site nowadays. Top: distribution of the two main climate parameters when precipitations were forced to a minimum uniform value for each month. Bottom: distributions of the climate parameters with no constraints on precipitation, but using the log of precipitation in the construction of priors. The simulation was run using Alaska as geographical region for priors.

2.4.3 Adjusting Total annual precipitation

By taking a close look at the probability distribution of precipitation for the tested points, I noticed that the program was artificially building a high probability peak towards the very low precipitation values, that became the preponderant result, especially during the glacial maxima. The program had indeed a built-in constraint that, once a climate was picked, would check for the total annual precipitation value and impose it to be bigger than 100 mm. If this condition was not met, it would just set the monthly value to 10 mm for each month. This condition was put thinking about milder climates, but for this set of data, especially for the Late Saalian period, low annual precipitation are an acceptable climate and the program would often tend to converge towards low values. Resetting happening in the majority of the trials, it gave a spurious peak at 120 mm annual precipitation values. I first lowered this limit to 10 mm instead of 100 mm. The results were better, but still artificially peaked at the set value (see figure 7). To obviate this problem, and avoid imposing any artificial precipitation distribution, I modified the program to use the logarithm of the rain parameters as precipitation coordinates for the principal component analysis. This way I would never get negative values for the precipitation and the total annual precipitation would be computed correctly.

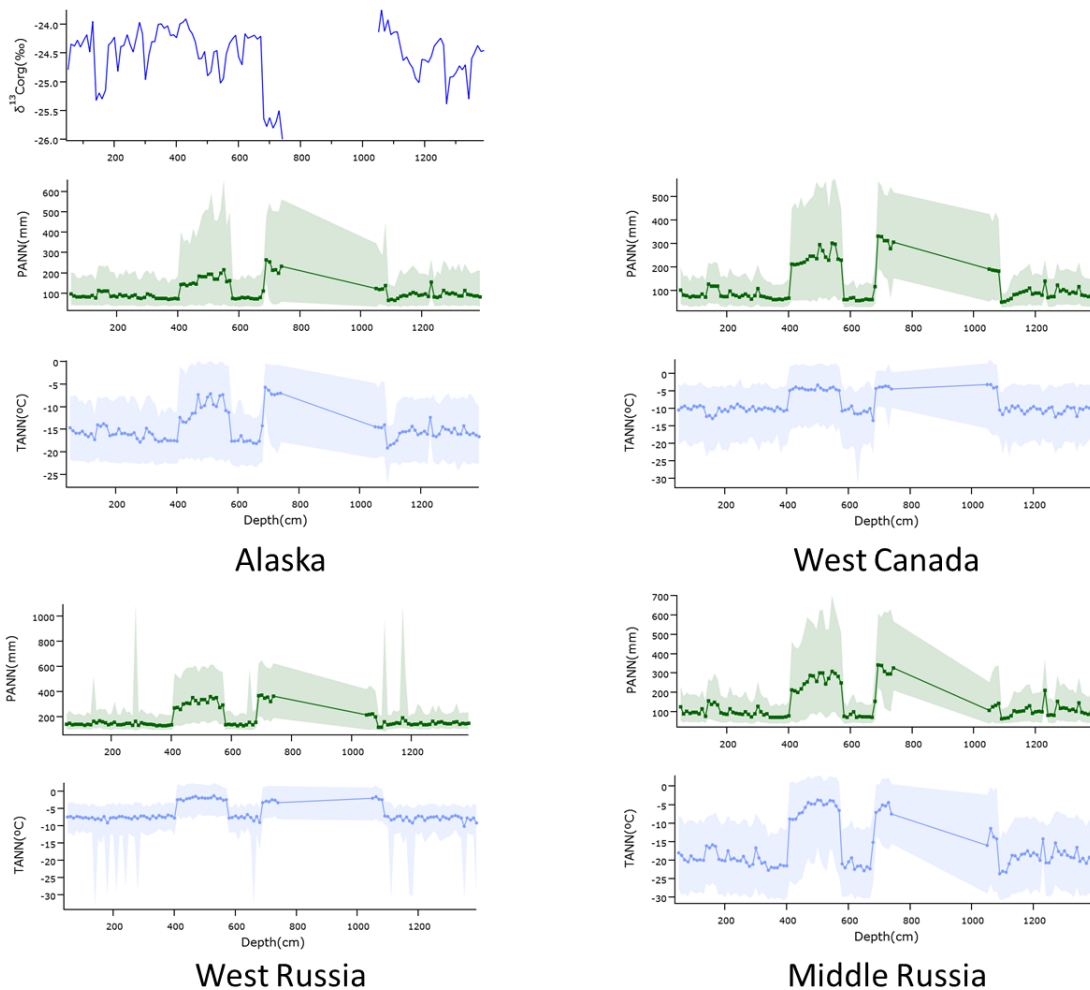


Figure 8: First series of runs to find the best priors. Results of the simulation with the new algorithm for precipitation using different regions of the northern hemisphere as basis for prior's construction. Left, top: $\delta^{13}\text{C}_{\text{org}}$ records for the depth/time over which the simulation was run. The remaining traces represent median values of the distributions for PANN and TANN. Shaded areas define the limits between 0.05% and 0.95% of the data in the probability distributions (confidence interval). Geographical coordinates corresponding to the different areas: Alaska (168° to 108° long W, 63° to 73° lat N), West Canada (125° to 95° long W, 48° to 74° lat N), West Russia (60° to 90° long E, 48° to 74° lat N), Middle Russia (90° to 120° long E, 48° to 75° lat N)

The new version of the program nicely converged and gave low but nicely distributed values for the total annual precipitation (figure 7). I could now proceed to performing the simulations over the whole sequence (with the exception of the Eemian Interglacial).

2.4.4 The choice of priors

The first series of runs were made to test the best geographical area for prior construction. I tested multiple areas, trying to find the best match between existing climates and the range of possible paleoclimates in Villiers-Adam during glacial periods. The European region around the site of VA was the first basic choice. Considering that we expected quite hard climates, possibly arctic, another set of simulations was run in Alaska, as a region that could, due to the influence of Oceanic climate, best resemble Northern Europe during glacial periods. The possible downside of Alaska is the big difference in latitude (15 ° on average). Latitude is relevant in BIOME4 to calculate the water balance and sunlight for plant growth. Three other regions, with latitudes that included the VA one's, but actual colder climates, were also selected for parallel testing and construction of the priors: Western Canada, and Middle and Western Russia. The trials over the default North-European region around VA gave negative results: the inversion program did not converge over most of the data points. In particular, for some data points the program would output a single value, corresponding to the initial random choice. This means that BIOME4 cannot find within the prior distribution any climate that gives an acceptable biome and $\delta^{13}\text{C}$. Supplementary tests with different values of the soil parameters (lower and higher range values) did not help in obtaining convergence. The inversion program could instead easily converge with priors corresponding to the region of Alaska. The resulting values of temperature and precipitation were compatible with Siberian ones (figure 8). The Eastern part of Canada gave results that were similar to those of Alaska, with slightly higher precipitation values and warmer temperatures. The region of middle of Russia also gave nicely converging results, but in this case the temperatures were on average lower by 7 degrees. Western Russia's priors were not adapted for all the points, and for some of them the distributions constructed through the 4 parallel chains did not overlap, giving an average very wide final distribution. For all selected prior regions, even though the program converged, the annual temperature and precipitation distributions were often bimodal, with a resulting wide interval of values especially for precipitations, as shown in figure 8 (shaded areas correspond to [0.05, 0.95] confidence interval). This seemed to indicate that the only constraints of $\delta^{13}\text{C}_{\text{org}}$ and large biome groups were not sufficient to give precise enough results for the predictions of possible posterior's values.

2.4.5 Last modifications and final results

A deeper analysis of the way BIOME4 calculated the $\delta^{13}\text{C}$ based on the inputs made me realize that it was calculated only on the basis of C3 plant NPP, but that the presence of C4 plants was allowed in the simulation, even though the input file contained imposed NA values for the %C4 NPP. This introduced an error in the calculation of the likelihood during the inversion process. I thus added the restriction for the presence of only C3 plants in the discrimination step at the output of BIOME4, before the likelihood is calculated. After this final modification, I ran the simulation over the entire lapse of time, using only prior regions located at a compatible latitude, but chosen amongst the colder ones today on the northern globe: the Western Russia region, the region in the middle of Russia and the one in West Canada. Alaska and Europe were abandoned, as the first was a bit too high in latitude and might not be compatible with our site, and the second because the first trials gave no convergence. Of the three regions, only the prior distribution of middle Russia gave converging distributions for all data points. To my surprise, with the last improvements in the program, the confidence intervals of the posteriors distributions were narrower and the plots of the predicted precipitation and temperatures over time nicely captured the observable fluctuations in the $\delta^{13}\text{C}_{\text{org}}$ data, which are likely to represent real long-range changes in climate. I could manage to obtain converging results over a large range of the dataset using the prior's region of West Canada, but only by increasing the sdev of

the $\delta^{13}\text{C}$ distribution for the computation of the likelihood. Increasing the sdev from 2 times to 3 times the experimental error resulted in a wider distribution of reconstructed precipitations. The temperature distribution had less negative values, but a clear shift between the measured $\delta^{13}\text{C}_{\text{Org}}$ the $\delta^{13}\text{C}$ predicted by the model (average shift= 0.2 ± 0.1 ‰) shows that these milder temperatures are less compatible with the experimental data. The results with the middle Russia priors are thus the more pertinent ones. They restrain the annual average temperature and precipitation in Villiers-Adam during the glacial maxima of the Late phase of the Late Saalian and of the Weichselian to quite low negative values (between -26 and -8°C for the temperatures and 75 to 300 mm for the precipitations), even lower than the ones of Greenland and Siberian today.

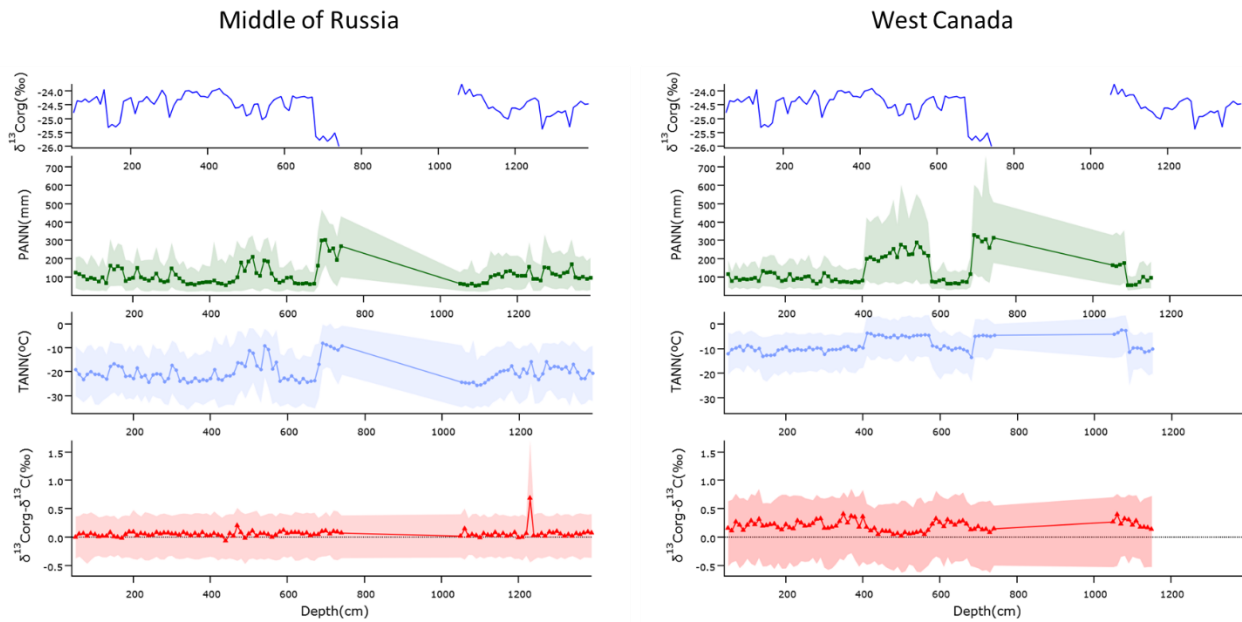


Figure 9: Reconstruction of climate parameters (PANN: mean annual precipitation and TANN: mean annual temperature) as a function of depth with the final version of the inversion program ReInv-polC13 with two different prior regions: Middle of Russia (90° to 120° long E, 48° to 75° lat N, left) and West Canada (125° to 95° long W, 48° to 74° lat N, right). For the Middle of Russia prior's region, the profiles of temperature and precipitation values as a function of depth well capture the $\delta^{13}\text{C}_{\text{Org}}$ data inflections described in section 2.2. The difference between the measured value of $\delta^{13}\text{C}_{\text{Org}}$ and the $\delta^{13}\text{C}$ predicted by the model shows a very good agreement between the simulation and real data (the $[0.05, 0.95]$ confidence interval (shaded area) is within $[-0.47, 0.52]$ for all points except one). Convergence using West Canada as prior's region could be obtained only by allowing a wider probability distribution of $\delta^{13}\text{C}$ during likelihood computation. The milder temperatures predicted do not agree with the experimental $\delta^{13}\text{C}_{\text{Org}}$ data, as shown by the systematic shift towards positive values (average shift= 0.2 ± 0.1 ‰) of the resulting $\delta^{13}\text{C}_{\text{Org}} - \delta^{13}\text{C}$ and the wider $[0.05, 0.95]$ confidence interval (within $[-0.62, 0.85]$).

2.4.6 The site of Harletz

When running the simulation on the Harletz site, with the condition of no C4 plant production imposed, I could not find any region for the priors, within the appropriate latitude range, that would make the data converge. The values of $\delta^{13}\text{C}_{\text{Org}}$ are probably too high to be compatible with the absence of C4 plants. The BIOME4 model can be modified to calculate the $\delta^{13}\text{C}_{\text{Org}}$ in the case of both C3 and C4 plants contribution to the total NPP, but modifications and full testing of the program was not possible within the internship time.

Discussion

The bibliographic research on pollen and proxies conducted during my internship has allowed to give a clear picture of possible biomes present in Northern and Southern Europe throughout the period that goes from the glaciation of the end of the Late Saalian to the Weichselian Upper Pleniglacial. The ice sheet during the Saalian extended further South than during the LGM, covering part of the Netherlands. Arctic to boreal tundra or steppe biomes (going from North to South) during the glacial maxima alternated with steppe and open conifer woodlands or cold mixed forests during the Middle Pleniglacial Weichselian and the beginning and end of the Eemian interglacial. Periods of dry and extremely cold climates thus alternated with more humid and cold climates. The stratigraphical and $\delta^{13}\text{C}_{\text{org}}$ data of the two sites of VA and Hz also show signatures of these climatic transitions, giving a consensus scenario for these periods. The aim of the project was to try and give constraints for the absolute values of temperature and precipitations by inverse modeling using the direct measurements of loess $\delta^{13}\text{C}_{\text{org}}$. The existing ReInv-polC13 inversion program was optimized for using pollen data and not adapted to work in the low precipitations range. I modified different steps in the inversion process in order to adapt the program to our needs. At the level of the prior's definition I substituted the values for the 12 months precipitations with their logarithm, to avoid imposing artificial lower limit values to these parameters that ended up biasing the distribution of predicted posterior climates. This was a major improvement in the program that allowed us to explore arctic temperatures and precipitation values. I changed the way the likelihood was computed by rejecting all climates for which BIOME4 predicted biomes not compatible with those documented. For the remaining climates, the likelihood was computed based on the probability of getting the measured $\delta^{13}\text{C}_{\text{org}}$, given the $\delta^{13}\text{C}$ predicted by BIOME4 for that climate. Given that the climatic scenarios were possibly very different from the actual ones in Europe, I also had to conceive using different geographical areas as basis for the definition of possible climate distributions (priors). Testing the program over different geographical areas confirmed the necessity to use regions like Alaska, Russia or Western Canada for the program to converge.

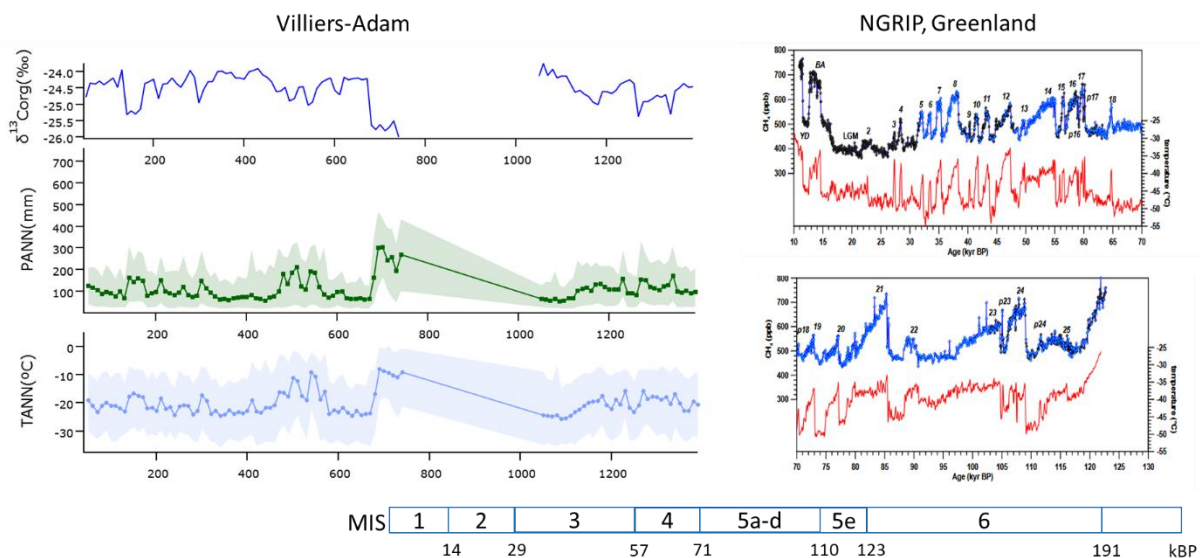


Figure 10: Comparison of the reconstructed temperatures for VA with the ice core data from Greenland. Left. Final retained results for the reconstruction of climate parameters in VA with prior distribution corresponding to the region of middle Russia (90° to 120°E long, 48° to 75°N lat). PANN: mean annual precipitation, TANN: mean annual temperature. Right. The NGRIP ice core data for temperature (red, in °C), derived from $\delta^{18}\text{O}$ measurements from Baumgartner et al. (2014) are shown for comparison. Bottom: Chronology of the MIS periods of this study. MIS 2-4: Pleniglacial Weichselien, MIS 5a-d: Early Glacial, MIS 5e: Eemian, MIS 6: Late Saalian

After a last debugging step, the final version of the program gave very nice and constrained results for both average annual precipitations and temperatures for the site of Villiers-Adam using Middle Russia as the

geographical region for prior definition (figure 9). The results nicely retraced the fluctuations observed on the $\delta^{13}\text{C}_{\text{org}}$ data. The temperature and precipitation values predicted were far lower than the actual ones (between -26 and -8°C for the temperatures and 75 to 300 mm for the precipitations). Given the results for pollen data and other proxies in this part of Europe, which indicated glacial climate with arctic vegetation during the Late Saalian, the result might be correct. Moreover, as shown in figure 10, the results are consistent with the NGRIP data for $\delta^{18}\text{O}$ derived temperatures in Greenland during those ages, which vary between -50 and -35°C (Baumgartner et al., 2014). The simulation was run with an imposed absence of plants with C4 photosynthetic pathway, because the new version of the BIOME4 model had been tested only for its predictions on C3 plants. With this constraint the model will predict higher $\delta^{13}\text{C}$ only for extreme climate conditions that would force C3 plants to fractionate less the ^{13}C isotope. An alternative reason for a higher $\delta^{13}\text{C}_{\text{org}}$ value could be the establishment of a fraction of C4 plants. It would be interesting to be able to allow a small percentage of C4 plants in the model to see by which degree this would change the average predicted temperature and precipitation. The inversion program could not find ranges of possible climates for the site of Harletz. Here the $\delta^{13}\text{C}_{\text{org}}$ values are less negative than in Villiers-Adam and the presence of C4 plants seems to be quite likely, justifying even more the necessity to develop and test the $\delta^{13}\text{C}$ calculation in BIOME4 in the presence of C4 plants.

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Organization of research and activities of the hosting institution

3.1 Role of the internship work in the context of climate and environmental research

The Climate and Environmental Science Laboratory (LSCE), located in the CEA-Orme des Merisiers campus of Saclay, is a mixed CEA (Commissariat à l'Énergie Atomique et aux Énergies Alternatives)-CNRS (Centre National de la Recherche Scientifique)-UVSQ (Université de Versailles Saint-Quentin-en-Yvelines) research unit. This laboratory has a pivot role in the domain of research at the interface between climate science, biogeochemical cycles and environmental archives. Research is structured into 3 main topics: Climates and Cycles, dedicated to modeling of climatic cycles at different spatio-temporal scales; Biogeochemical Cycles and transfers into the environment, centered on the study of greenhouse gases and other compounds and their transfer between the different environmental compartments; Archives and Tracers, that focuses on the study of past climatic cycles and the analysis of the ecosystem's response to natural and anthropogenic forcing. The Geochronology, Tracers and Archaeometry (GeoTrAc) team, where I did my internship, is part of this third axes of research. The team develops advanced analytical approaches in elementary and isotopic geochemistry to reconstruct environmental and climatic changes and human adaptation at different spatio-temporal scales. Understanding past and present climatic cycles and their effect on the ecosystems, is essential to be able to predict future climatic scenarios that will in turn determine changes in the environment and necessary adaptations that human societies have to face. My work in the laboratory has contributed to develop the means, through a computer program, to reconstruct paleoclimates based on the stable carbon isotope data held by the laboratory and thus add a small piece to the puzzle of the relationship between climatic changes, ecosystems and human adaptation.

3.2 Reflections on the role of the LSCE and its working environment

The LSCE is part of the Pierre-Simon Laplace Institute (IPSL). Founded in 1991 by Gérard Mégie, the IPSL is an interdisciplinary research institute composed of eight laboratories and 2 research units in the Ile-de-France region, which are devoted to the study of climate and environmental dynamics. Its objective is to reinforce scientific knowledge about climate and environment of the past, present and future. The LSCE contributes to the goal of the IPSL by producing fundamental means to establish a chronological framework and the knowledge about the geochemical processes governing the interaction between climate, environment and human evolution. GeoTrAc is an interesting multidisciplinary team that counts members specialized in sciences at the interface between geochemistry, paleoclimatology and archaeometry. The GeoTrAc team is composed of about 30 members, belonging to the three different organisms (CEA, CNRS, UVSQ). The team counts about 15 permanent members that cover different positions. The GeoTrAc head, Jérémy Jacob, has a position of CNRS Research Director. My supervisors, Christine Hatté and Caroline Gauthier, are respectively CEA Research Director and CNRS Technical Engineer. The rest of the team is composed of two UVSQ Professors (Valerie Daux and Edwige Pons-Branchu), two CEA Research Directors (Ulrich von Grafenstein and Eric Douville), four CEA Research Engineers (Nadine Tisnérat-Laborde, Emmanuelle Casanova, Arnaud Dapoigny), a CNRS Research Engineer (Francois Thil), an UVSQ Assistant Engineer (Brian Phouybanhdyt), and a CNRS Assistant Engineer (Edouard Regnier), and an equivalent number of PhD students, post Docs and internship Master and BTS students and temporary technical and research engineers. The age range of the permanent members goes from 32 to retirement age. The team members are organized around the type of measurements and instrument used to perform them, while the topics are usually transverse. I was in the group "isotopic geochemistry". Working on tracers from continental and oceanic origin, many members of

the team are often out for missions to collect data from different parts of the world. It is a job that requires good organizational and dynamic skills to plan, prepare, pack up for a mission and then come back, unpack, stock, analyze. And if you are on top of it responsible of a research group and of internship students, the task is not easy. This feeling of action and a taste for traveling and exploration is palpable in the GeoTrAc team. It contributes probably in part also to the open-mindedness I felt all along. Doors are open for any question, any help needed, be it scientific, technical or logistic and you're always welcome with a smile. From the logistics point of view, there is a canteen close to the site, where most team members go and sit at the same table. It's a nice occasion to meet. I rapidly got to exchange with every member of the team. A cup of coffee after lunch in Caroline's office completes the lunch break in a relaxed atmosphere. The CEA runs buses that connect its sites to the periphery of Paris, where the dependents can get on public transportation. I find this a nice and environmentally friendly initiative, that also helps in setting a healthy framework of working hours. Environmental issues are the subject of research. Some researchers also organize a weekly weather forecast meeting that discusses local and global present evolution of the weather and climatic changes. Research work on climate and environment is not the same as taking actions towards the environmental transition, but this research is fundamental to show the direction in which actions should be taken and some of the members of the LSCE are also actively engaged in communicating outside of the scientific community.

3.3 Personal considerations

My aim when I subscribed for the AReCO training year, was to acquire the tools to better understand the problematics and the constraints, both from the legal, economical and physical point of view of working in research projects for the ecological transition. The 6 months courses I followed gave me an interesting multidisciplinary perspective of the social and fundamental sciences for the ecological transition. Integrating the GeoTrAc team has been a nice follow up of my training. I could immediately appreciate the instruction received in the fundamental science courses which allowed me to dive into the scientific literature and understand the basic principles required for the task I had to perform. At the same time, I was again like a fish in the water, in a fundamental research environment. In my research career I have always worked on experimental projects, on microscopy and electrophysiology techniques that I applied to the field of biophysical neuroscience. This internship made me discover another type of research. Modeling is quite different from experimental research, which is marked by long times of preparation of the samples, especially when biology comes into the equation. I appreciated having time to think instead of fighting with the instrument or the preparation. I learnt how to run a simulation on a local cluster, Christine allowed me to please myself with bibliographic research and engaged me in scientific discussions from the very start. I have to say that taking a script written by somebody else and find the way to modify it has not been the easiest task. But at the same time it was quite challenging, a bit like playing the role of a detective trying to trace back things by pieces of evidence here and there. Little by little I also got to discovered the downsides of this type of work: I could spend 4 hours sitting in the same position without even realizing it. I had to learn to take breaks, move around. And I missed touching the sample with my own hands. Fortunately, Christine made me visit two loess sites, even if my role in the lab was purely theoretical, which satisfied my thirst for hands-in work. All in all, this internship has been a very positive experience, that gave me the opportunity to take a deep dive into climate and environmental research.

Annex 1

Biome groups as defined in the Reclnv-polC13 program

Group	biome	code	w/c	h/d	long name	w= warm	c=cold	h=humid	d=dry
1	1	TrEgFo	w	h	Tropical evergreen forest				
1	2	TrSeDeFo	w	h	Tropical semi-deciduous forest				
1	3	TrDeFo	w	h	Tropical deciduous forest/woodland				
4	4	TeDeFo	w	h	Temperate deciduous forest				
4	5	TeCoFo	w	h	Temperate conifer forest				
4	6	WaMxFo	w		Warm mixed forest				
4	7	CoMxFo		h	Cool mixed forest				
4	8	CoCoFo		h	Cool conifer forest				
5	9	ClMxFo	c	h	Cold mixed forest				
5	10	EgTaig	c		Evergreen taiga/montane forest				
5	11	DeTaig	c		Deciduous taiga/montane forest				
2	12	TrSav	w	d	Tropical savanna				
2	13	TrXeShl	w	d	Tropical xerophytic shrubland				
3	14	TeXsShl	w	d	Temperate xerophytic shrubland				
3	15	TeXsWol	w	d	Temperate sclerophyll woodland				
3	16	TeBlSa	w		Temperate broadleaved savanna				
5	17	OpCoWol	c		Open conifer woodland				
6	18	BoPrkl	c		Boreal parkland				
2	19	TrGrL	w	d	Tropical grassland				
3	20	TeGrL		d	Temperate grassland				
8	21	Desert		d	Desert				
6	22	StTund	c		Steppe tundra				
7	23	ShTund	c		Shrub tundra				
7	24	DShTund	c		Dwarf shrub tundra				
7	25	PsShTund	c		Prostrate shrub tundra				
7	26	CuTund	c		Cushion forb lichen moss tundra				
8	27	Barren	c		Barren				
8	28	Lice	c		Land ice				

Abstract

The Pleistocene marks the period during which the genus *Homo* emerged on earth. This period is characterized by the advent of strong oscillations in temperature, with a periodicity of ca. 100 000 years over the past 1 million years. Major environmental changes associated with these climatic cycles likely determined the history of *Homo sapiens* migration and evolution. Understanding the evolution of past climate and how the environment and mankind have adapted to it is a key feature to be able to predict the potential evolution of today's climate and its possible consequences on our environment. Paleoclimatology offers the long-term records necessary to reconstruct climatic and environmental conditions on a thousand of years' time scale. The aim of this project was to reconstruct the values of temperature and precipitations during the two last glacial-interglacial cycles in Europe based on loess archives at the sites of Villiers-Adam (France) and Harletz (Bulgaria). The reconstruction was done by inverse modeling of loess stable carbon isotope measurements. An existing Bayesian inference program was modified to optimize it for use with loess $\delta^{13}\text{C}_{\text{org}}$ data and hard climate conditions during the glacial stages. The inversion algorithm is based on the BIOME4 vegetation model predictions for the $\delta^{13}\text{C}$ and biome, given the climate and the geophysical properties of the site. The modified version of the program could reconstruct temperature and precipitation values for the site of Villiers-Adam during the period from Late Saalian to Weichselian Upper Pleniglacial, with yearly temperatures ranging between -26 and -8°C and yearly precipitations ranging between 75 to 300 mm. The reconstructed parameter's time course nicely retraced the major inflections of the $\delta^{13}\text{C}_{\text{org}}$ data which seemingly correspond to climatic changes all over Europe. The program could not converge for the site of Harletz. A probable reason is the exclusion of the presence of C4 plants in the simulation, which might bring to an incompatibility between the $\delta^{13}\text{C}_{\text{org}}$ values and the range of possible climates at that latitude. The inclusion of $\delta^{13}\text{C}_{\text{org}}$ of C4 plants in the program may be needed to reconstruct the parameters of this site.

Résumé

Le Pléistocène marque la période pendant laquelle le genre *Homo* a émergé sur terre. Elle est caractérisée par la mise en place de fortes oscillations en température, avec de cycles de ca. 100 000 ans pendant le dernier million d'années. Des changements environnementaux majeurs associés à ces cycles climatiques ont probablement déterminé l'histoire de la migration et évolution d'*Homo sapiens*. Comprendre l'évolution des climats du passés et l'adaptation de l'environnement et des êtres humains est essentiel pour pouvoir prédire l'évolution potentielle du climat actuel et les conséquences possibles sur notre environnement. La Paléoclimatologie offre les enregistrements nécessaires à la reconstruction des conditions climatiques et environnementales à des échelles de temps des milliers d'années. Le but de ce projet a été de reconstruire les valeurs de température et précipitations pendant les deux dernières périodes glaciaires en Europe, sur la base des archives des sites de loess de Villiers-Adam (France) et Harletz (Bulgarie). La reconstruction a été faite avec modélisation inverse des données des isotopes stable du carbone. J'ai optimisé une version existante d'un programme d'inférence Bayésienne pour l'adapter aux mesures de $\delta^{13}\text{C}_{\text{org}}$ dans les loess et aux conditions climatiques extrêmes attendues pendant les périodes glaciaires. L'algorithme d'inversion se base sur les prévisions du modèle de végétation BIOME4 pour les valeurs de $\delta^{13}\text{C}$ et biome pour chaque climat, étant données les conditions géophysique du site. La nouvelle version du programme a pu reconstruire les valeurs de température et précipitation sur le site de Villiers-Adam pendant la période du Saalien Supérieur au Pléniglaciaire Supérieur Weichselien, avec des intervalles de température allant de -26 à -8°C et des précipitations allant de 75 à 300 mm par an. Le décours temporel des paramètres suit de manière précise les inflexions des données de $\delta^{13}\text{C}_{\text{org}}$ qui semblent correspondre à des changements climatiques à l'échelle de l'Europe. Je n'ai pas obtenu de convergence sur le site d'Harletz. Une raison probable est l'exclusion de la présence de plantes en C4 dans la simulation, qui crée une incompatibilité entre les données de $\delta^{13}\text{C}_{\text{org}}$ et les climats possibles à cette latitude. L'inclusion du calcul de $\delta^{13}\text{C}_{\text{org}}$ pour les plantes en C4 dans le programme pourrait être nécessaire pour reconstruire les paramètres sur ce site.