ÉCOLE DOCTORALE
SCIENCES DE LA TERRE ET DE L'ENVIRONNEMENT ET PHYSIQUE DE L'UNIVERS, PARIS

Subject title: Study of the role of permafrost in climate - carbon feedbacks using coupled simulations, surface - atmosphere - ocean.

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The role of feedbacks between the carbon cycle and the climate has been known for several decades (Hansen et al., 1984). The projections, in the twenty-first century, the terrestrial biosphere and ocean response to climate change based on the use of carbon cycle models. Many studies have highlighted the impact that climate change could potentially have on the biophysical and biogeochemical functioning of the terrestrial biosphere and the ocean, but its integration into climate models is more recent. Cox et al., (2000) and Friedlingstein et al (2001) have shown that if, at the first order, the increase in atmospheric CO2 should generate an increase in carbon sinks by terrestrial and oceanic ecosystems, all climate - carbon feedbacks probably lead to a decrease , on global average , of these sinks in the future. The additional CO2 thus accumulated in the atmosphere would be responsible for an amplification of the initial warming. Today, many models take into account the interactions between climate and the carbon cycle (Eyring et al., 2016, Jones et al., 2016). However, there remains a great deal of uncertainty about the amount of additional CO2 that will be emitted in the atmosphere during the 21st century, and also on the additional warming simulated by 2100. In this context, a number of challenges remain, in particular on the importance of high latitude zones in the climate-carbon feedback. Indeed, these zones are characterized by the presence of ecosystems with very important stocks of organic matter, and therefore carbon, especially in soils (Schädel et al., 2014). Among these biomes, permafrost soils are soils that are frozen for a large period of the year. The low temperatures have the effect of very strongly slowing down the activity of decomposing microorganisms responsible for heterotrophic respiration flows and nitrogen mineralization flows (Jackson et al., 2017). Faced with future global warming, many questions are being asked about the fate of these permafrost and their potential greenhouse gas emissions (Knoblauch et al., 2018). Permafrost is still very little or poorly represented in climate models despite their large carbon stocks and their potential large greenhouse gas flows (Guimberteau et al., 2018; Koven et al., 2017; Wieder et al. , 2019), especially since all climate models agree that the warming to come during the twenty-first century will be more important in the emerged lands, and in particular at the high latitudes of the northern hemisphere (Stocker et al. . 2014). Finally, the physical and in particular thermal properties of these ecosystems (insulation of permafrost via the carbon content of soils or surface vegetation (mosses)) play a crucial role in the evolution of the climate in boreal zones.

In this thesis we propose to study the feedbacks between the climate and the carbon cycle, within the Earth System model (ESM) developed at the Pierre and Simon Laplace Institute (IPSL), focusing on high latitudes and the role of permafrost. To do this we will use the latest version of the

ORCHIDEE surface model coupled with the LMDZ climate model and the NEMO ocean model, in an ESM configuration. This new version of ORCHIDEE integrates a set of processes relating to the functioning of boreal ecosystems not yet valued in coupled mode. This is not only a vertically discretized representation of freezing in the soil and the dynamics of organic matter, but also of the nitrogen cycle, and a better representation of the thermal properties of soils (insulation via organic in particular).

First, we will do a set of factorial simulations with two different configurations: i) without permafrost and with dynamic nitrogen cycle, ii) with permafrost and with dynamic nitrogen cycle. These simulations will be made with these two configurations over the historical period to evaluate the performance of the model thanks to the observations. In addition, idealized simulations, with an increase in atmospheric CO_2 of 1% per year, will also be carried out. These experiments with a 1% increase per year of CO_2 will be performed with different coupling a) Full carbon-climate, b) radiation only (only the radiative scheme sees the increase in CO_2) and c) only biogeochemical (only the biogeochemistry diagram sees the increase in CO_2). We will analyze the sensitivity of the climate and the carbon cycle to the increase in CO_2 (factors α, β and γ) for each of the two configurations and thus will be able to determine the role of the nitrogen cycle and permafrost on the sensitivity of the climate (TCRE) and the carbon cycle to the increase in CO_2 (compatible emissions).
Secondly, we will carry out simulations still using configurations i) and ii) but this time using trajectories of emissions and / or concentrations of CO_2 according to IPCC scenarios. With these simulations we will quantify the importance of permafrost on i) the global carbon footprint and its potential to amplify climate change and ii) on the evolution of temperatures and precipitation in a context of climate change.
Finally, the last part of the thesis will focus on the insulating role of organic matter on the surface of soils (including mosses / lichens) and its control on the future dynamics of permafrost (spatial extension in particular). To do this, we will carry out test simulations by modifying the thermal properties of the surface of soils which could be induced by an increase in boreal fires, losses of organic matter, etc. The objective will be to determine in a coupled model the importance of soil isolation processes on the intensity of climate - carbon feedbacks for boreal ecosystems.

This thesis will address the following questions: i) What is the impact of the nitrogen cycle and permafrost on climate-carbon feedbacks? ii) How permafrost thaw will alter climate-carbon feedbacks? iii) How could the insulating effect of organic matter on energy flows compensate for the biogeochemical effects linked to greenhouse gas emissions in permafrost zones?
It is important to note that all of these options are currently available within the IPSL model but have not yet been explored.

This thesis will be done within IPSL, and more particularly within the surfaces and reservoirs team of the ENS geology laboratory and the IPSL Climate Modeling Center (ICMC), with strong interactions with the climate and environmental sciences laboratory. IPSL coordinates the development and use of the Earth system model, ESM allows IPSL to participate every 6 to 7 years in international coupled model intercomparison exercises (CMIP), in order to provide the necessary information to the preparation of the reports of the Intergovernmental Panel on Climate Change (IPCC). This thesis is part of the development dynamic of the next configuration of the IPSL ESM , which will be used to perform simulations for the next CMIP phase (CMIP7).

This thesis will be co- supervised by Bertrand Guenet (advisor, LG-ENS), Patricia Cadule (supervisor, member of the IPSL federation and the ICMC) and Philippe Peylin (Second advisor, MOSAIC team, LSCE- IPSL)