REQUEST FOR A SPECIAL PROJECT 2020–2022

MEMBER STATE: Sweden……………….……………………………………………..…

Principal Investigator[1]: Wilhelm May……………………………………………………….……

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Project Title:

Land surface - climate interactions in the EC-Earth ESM: their role for climate variability and contribution to future climate change…

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** SEMAY_________________	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2020	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for 2020-2022: (To make changes to an existing project please submit an amended version of the original form.)		**2020**	**2021**	**2022**
High Performance Computing Facility	(SBU)	9,000,000	9,000,000	9,000,000
Accumulated data storage (total archive volume)[2]	(GB)	20,000	40,000	60,000

Continue overleaf

[1] The Principal Investigator will act as contact person for this Special Project and, in particular, will be asked to register the project, provide annual progress reports of the project's activities, etc.

[2] If e.g. you archive x GB in year one and y GB in year two and don't delete anything you need to request x + y GB for the second project year etc.

Principal Investigator: Wilhelm May……………………………………………………

Project Title: Land surface - climate interactions: their role for climate variability and contribution to future climate change……………

Extended abstract

Need for computer resources

The project described below incorporates numerous simulations with the EC-Earth earth system model (ESM) in various configurations (see Table 2). Given the relatively fine resolution of the global climate model as well as the high number of long simulations (typically on the order of 100 years), this creates a considerable demand for computing resources over, ideally, the three-year period of the project. Also, it is worth noting that ECMWF's HPC (cca at the moment) is one of the systems, where EC-Earth is fully supported and running smoothly.

Purpose and aims

The purpose of this project is to improve the understanding of the effects of land surface couplings and feedbacks on climate, to evaluate their role for historical climate variability and to assess their contribution to future climate change. For the land surface, I distinguish between the physical state of the land surface (i.e. soil moisture and soil temperatures) and the state of the natural and managed vegetation, in combination with anthropogenic land-use and land-cover changes (LULCC). This will be done based on targeted experiments with the EC-Earth ESM for historical and future climate conditions, where the land surface conditions are incorporated in novel ways.

In the project, I will focus on specific regional climate phenomena, climate zones and climate variables, chosen because of their strong (and at the same time variable) interactions with the land surface, but also for their potentially far-reaching socioeconomic effects in the event of future changes in their characteristics (mean state and variability) in response to the anticipated increase in the anthropogenic climate forcing. These are:

- Western Africa (West African monsoon) and South Asia (Indian summer monsoon)
- Tropics and subtropics as well as the mid-latitudes during local summer (North America, Europe, Southern Africa, Australia)
- Characteristics of precipitation (intensity, frequency, variability)
- Extreme weather and climate events (hot temperature extremes, heatwaves, droughts)

The aims of the project are twofold:

- Firstly, to evaluate the role of the land surface conditions for the realistic simulation of the aforementioned aspects of climate and their variability in the global climate model. I will do that by comparing the simulations against comprehensive observational data sets.
- Secondly, to assess the extent to which the projected changes in the land surface conditions including LULCC contribute to the future changes in the aforementioned aspects of climate in response to the projected increase in the anthropogenic climate forcing.

The project will generate new knowledge on the role of the coupling between the land surface and the atmosphere for the analysed aspects of climate. This will lead to a better understanding of the uncertainties in climate projections related to the land surface and, thus, enhance the credibility of the projected climate changes, which is important for climate mitigation. Also, the project will provide a better understanding of the role of the land surface coupling in the EC-Earth ESM and, thus, in ECMWF's Integrated Forecasting System (IFS) and the H-TESSEL land surface model (LSM; Balsamo et al. 2009).

The project is linked to the Land Surface, Snow and Soil moisture Multimodel Intercomparison Project (LS3MIP; Van den Hurk et al. 2016), which addresses the role of land processes and feedbacks in climate simulations for historical and future conditions. LS3MIP is one project on the extensive list of MIPs within the Coupled Model Intercomparison Project phase 6 (CMIP6; Eyring et al. 2016), which is the largest ever coordinated international effort on climate modelling, and will provide the climate scenarios to be utilized in the next assessment report by the Intergovernmental Panel on Climate Change (IPCC).

Project description

Model components and configurations

In the project, I will apply the EC-Earth ESM (Hazeleger et al. 2012, Döscher et al. 2019) in different configurations and specific experimental setups in order to achieve the aims presented before.

EC-Earth: In its latest version, the EC-Earth atmosphere-ocean-sea-ice coupled global climate model combines the ECMWF IFS global atmospheric general circulation model with the NEMO global ocean circulation model and the LIM dynamical sea-ice model. The individual models have been updated compared to the previous version of EC-Earth and the horizontal and vertical resolutions of some of the models have been increased (Döscher et al. 2019).

IFS: EC-Earth incorporates the ECMWF IFS global atmospheric general circulation model to simulate the state of the atmosphere. IFS has a horizontal resolution of approx. 80 km and 91 vertical levels. For the purpose of this project, IFS has been extended so that the physical state of the land surface (i.e. soil moisture and soil temperatures) can be prescribed from external data by incorporating a relaxation procedure for soil moisture and soil temperatures for each of the four soil layers in IFS (May et al. 2019). Furthermore, the state of vegetation and LULCC can be prescribed to IFS.

H-TESSEL: IFS includes the H-TESSEL LSM with four soil layers (0-7, 7-28, 28-100 and 100-255 cm; Balsamo et al. 2009). It is an extension of the Tiled ECMWF Scheme for Surface Exchanges over Land (TESSEL), incorporating a revised land surface hydrology. Thus, two shortcomings of TESSEL were overcome, i.e. the lack of surface runoff and the choice of a globally uniform soil texture. The current version of H-TESSEL includes a new snow scheme and a revised description of bare soil evaporation. These changes resulted in a markedly better simulation of the land surface properties (Balsamo et al. 2015).

LPJ-GUESS: To simulate the state of the natural and managed vegetation the most recent version of the LPJ-GUESS dynamical global vegetation model (DGVM; Smith et al. 2014) is used. The model is a second-generation DGVM that explicitly represents the size and age structure properties and temporal dynamics of woody vegetation stands. It captures landscape heterogeneity in terrestrial vegetation properties resulting from land use (crops and pasture) and stochastic disturbances such as storms and wildfires. LPJ-GUESS incorporates anthropogenic LULCC (Lindeskog et al. 2013). In the project, anthropogenic LULCC will be included in LPJ-GUESS based on the Land Use Harmonization[2] (LUH2) data set (Hurtt et al. 2011), both for the historical period and the future scenario (Riahi et al. 2017).

H-TESSEL+LPJ-GUESS: To readily simulate the effects of specific atmospheric conditions on the state of the land surface and of vegetation, an offline model configuration, combining the H-TESSEL LSM and the LPJ-GUESS DGVM, has been developed. In this case, the atmospheric conditions (near-surface temperatures, humidity and winds as well as precipitation and radiation) are prescribed to the two models rather than coming directly from IFS.

IFS(+NEMO)+LPJ-GUESS: LPJ-GUESS has been interactively coupled with IFS and EC-Earth, respectively. This means that the DGVM receives the atmospheric conditions that affect vegetation (i.e. temperature, precipitation and radiation) from IFS, while IFS receives information about vegetation (i.e. leaf area index (LAI) as well as types and fractions of high and low vegetation) from LPJ-GUESS in return (Alessandri et al. 2017). Thus, the interactions between the land surface including vegetation and the atmosphere are fully incorporated in the climate model. In the simulations without coupling to the NEMO ocean model, the sea surface temperatures (SSTs) and the sea-ice extent are prescribed from observations or from simulations with the coupled version of EC-Earth.

Climate simulations

In the project, a number of simulations will be undertaken with different configurations of the EC-Earth global climate model. In these model configurations, where the concentrations of the greenhouse gases and of atmospheric aerosols will be prescribed as provided by CMIP6 (Eyring et al. 2016), only the biophysical effects of the natural vegetation and land-cover change on climate are included. The simulations cover both the historical (1850/1900/1950-2014) and the future period (2015-2085/2100). For the future period, a scenario following the Shared Socioeconomic Pathways (SSPs; O'Neill et al. 2017) will be applied in accordance with ScenarioMIP (O'Neill et al. 2016), namely the SSP1-2.6 scenario. This scenario is characterized by a weak radiative forcing (2.6 W/m^2 in 2100) but distinct LULCC over the course of the 21st century. At a global scale, the extent of forests is strongly increased and the extent of other natural land is somewhat increased. The extent of grasslands, on the other hand, is reduced, while the extent of croplands hardly changes (Riahi et al. 2017). The SSP1-2.6 scenario keeps the global warming below 2 °C with respect to pre-industrial times in accordance with the Paris Agreement. The table provides an overview of the simulations with the different model configurations for the historical and future period (simulations #1.1, 2.1 and 2.2 will be available before the start of the project through the EC-Earth consortium):

Number of simulation	Model configuration	Period	Details
1.1*	H-TESSEL+LPJ-GUESS	1850-2014	Historical simulation, forced with meteorological data from the Global Soil Wetness Project Phase 3 (GSWP3)[a]
1.2	IFS+LPJ-GUESS	1900-2014	Historical simulation; ocean state from observations
1.3	IFS+LPJ-GUESS	1900-2014	Land surface from #1.1, ocean state from observations
1.4	IFS	1900-2014	Vegetation from #1.1, ocean state from observations
1.5	IFS	1900-2014	Land surface and vegetation from #1.1, ocean state from observations
2.1*	IFS+NEMO+LPJ-GUESS	1850-2014	Historical simulation
2.2*	IFS+NEMO+LPJ-GUESS	2015-2100	Scenario simulation SSP1-2.6
3.1	IFS+LPJ-GUESS	1950-2014	Land surface from #2.1 (perpetual), ocean state from #2.1
3.2	IFS	1950-2014	Vegetation from #2.1 (perpetual), ocean state from #2.1
3.3	IFS	1950-2014	Land surface and vegetation from #2.1 (perpetual), ocean state from #2.1
4.1	IFS+LPJ-GUESS	1950-2014	Land surface from #2.1 (transient), ocean state from #2.1
4.2	IFS	1950-2014	Vegetation from #2.1 (transient), ocean state from #2.1
4.3	IFS	1950-2014	Land surface and vegetation from #2.1 (transient), ocean state from #2.1
5.1	IFS+LPJ-GUESS	2015-2085	Land surface from #2.1 (perpetual), ocean state from #2.2
5.2	IFS	2015-2085	Vegetation from #2.1 (perpetual), ocean state from #2.2
5.3	IFS	2015-2085	Land surface and vegetation from #2.1 (perpetual), ocean state from #2.2
6.1	IFS+LPJ-GUESS	2015-2085	Land surface from #2.2 (transient), ocean state from #2.2
6.2	IFS	2015-2085	Vegetation from #2.2 (transient), ocean state from #2.2
6.3	IFS	2015-2085	Land surface and vegetation from #2.2 (transient), ocean state from #2.2

Table 1: Climate simulations, the model configuration, the treatment of the land surface conditions and of vegetation in the simulations and the prescribed ocean conditions. Marked by the light (dark) shading are simulations for the historical (future) period. The asterisk indicates simulations that are available within the EC-Earth consortium. [a]http://hydro.iis.u-tokyo.ac.jp/GSWP3

Research Themes

In order to achieve the two main aims of the project, the work in the project will be organized into four research themes (RTs) with several tasks. In each RT, each of the specific climate phenomena, climate zones and climate variables defined above will be studied. The 3-year timeframe of the project will allow for covering most of the RTs.

1. Historical climate and its variability

In the first part of the project, the role of the land surface conditions for the realistic simulation of the aforementioned aspects of climate and their variability in EC-Earth will be evaluated. This will be done on the basis of several simulations with EC-Earth under historical climate conditions, where the states of the land surface and/or vegetation are prescribed to the climate model, consistent with historical meteorological data.

RT1 Simulations with land surface conditions constrained by observational data (#1.2, 1.3, 1.4 and 1.5)

To begin with, the physical state of the land surface (i.e. soil moisture and soil temperatures) and the state of vegetation including LULCC (i.e. the types of low/high vegetation, the fractions of low/high vegetation and the LAI) will be obtained from the offline simulation with H-TESSEL and LPJ-GUESS (#1.1; Table 1) for the historical period 1900-2014. These data will then be used to prescribe the state of the land surface and/or vegetation in simulations with IFS and IFS+LPJ-GUESS, respectively, for the period 1900-2014 (#1.3, 1.4, 1.5; Table 1). In addition, a historical simulation without any constrains on the land surface conditions will be performed with IFS+LPJ-GUESS (#1.2). In all simulations, the state of the ocean (i.e. SSTs and sea-ice extent) will be prescribed from observations.

RT2 Model evaluation and scientific analysis

The historical simulation (#1.2) represents the climate simulated by EC-Earth only constrained by the observed ocean state. Given the differences in the simulated climate compared to observations, in particular the GSWP3 data set, the land surface conditions from the historical simulation will be different from the offline simulation forced with the GSWP3 meteorological data (#1.1). Thus, comparing this and the three other simulations (#1.3, 1.4, 1.5) with available observations, indicates the extent to which the realistic land surface conditions are important for the state of the climate simulated by EC-Earth. In particular, this comparison for the historical period illustrates the role of the realistic land surface conditions for the observed climate variability. Comparing the land surface conditions from the offline simulation with observations will reveal potential deficiencies in H-TESSEL+LPJ-GUESS.

Employing various analysis methodologies, I will investigate the majority of the aspects of climate that are considered in the project. I will focus on the processes that govern the interactions between the land surface conditions and the atmosphere and, thus, contribute to the historical climate variability. To begin with, I will inspect how the various components of the energy budget at the land surface are affected by the land surface conditions. Then, I will relate these effects on the distribution of energy to variations in local climate and potentially in the regional climate and the monsoon systems. The same processes may also regulate the contributions of the projected changes in the land surface conditions to future climate change. Since different aspects of the land surface conditions have been prescribed separately, I will be able to distinguish between the role of the physical state of the land surface, the role of vegetation including LULCC and the role of both land surface conditions combined.

<u>2. Future climate change</u>

In the second part of the project, the contributions of the projected changes in the land surface conditions to the future changes in climate will be assessed. This will be done on the basis of several scenario simulations with EC-Earth, where the states of the land surface and/or vegetation are prescribed to the model, either in accordance with present-day or in accordance with future conditions.

RT3 Simulations with land surface conditions from EC-Earth for the historical (#3 and 4) and future period (#5 and 6)

Initially, the state of the land surface and the state of vegetation including LULCC will be obtained from the historical and the scenario simulation with EC-Earth (#2.1, 2.2; Table 1) for the overall period 1900-2100. These data will be used to prescribe the state of the land surface and/or vegetation in simulations with IFS and IFS+LPJ-GUESS, respectively. These simulations fall into two categories. In one category, the land surface conditions are prescribed according to present-day conditions (i.e. the mean annual cycle for 1985-2014 from #2.1; referred to as '<u>perpetual</u>' in Table 1) originating from #2.1 through the entire period of simulation (1950-2014 for #3.1, 3.2, 3.3 and 2015-2085 for #5.1, 5.2, 5.3). In the other category, the land surface conditions will change with time, as 30-year running means of the annual cycle from #2.1 and #2.2 (referred to as '<u>transient</u>' in Table 1) will be prescribed through the entire period of simulation (#4.1, 4.2, 4.3 for 1950-2014 and #6.1, 6.2, 6.3 for 2015-2085). In the simulations for the historical period, the state of the ocean is prescribed from #2.1, and for the future from #2.2, respectively. Here, the procedure to prescribe the land surface conditions is somewhat different than in RT1. In particular, the variability of the land surface conditions ranging from intra-seasonal to interannual time scales will be suppressed.

RT4 Scientific analysis

I will employ the same analysis methodologies as in the evaluation of the role of the land surface conditions for the realistic simulation of climate and its variability (see RT2). In this case, to investigate the processes that control the contributions of the projected future changes in the land surface conditions to future climate change. Different combinations of the scenario simulations will be related to each other in order to address specific aspects of climate change.

The differences between corresponding simulations with transient and perpetual land surface conditions show the impacts of the projected changes in the land surface conditions on future climate change. The impacts of the changes in the physical state of the land surface will be given by the differences between #6.1 and #5.1 (#4.1 and #3.1) for the future (historical period). The impacts of the changes in vegetation including LULCC will be given by the differences between #6.2 and #5.2 (#4.2 and #3.2) for the future (historical period) and the impacts of both aspects combined by the differences between #6.3 and #5.3 (#4.3 and #3.3), respectively. The magnitude of the contribution of the projected changes in the land surface conditions to future climate changes will be quantified by the ratio between these differences and the difference between the future and present-day period (1985-2014) from the simulations where the changes in both aspects of the land surface conditions are prescribed (#6.3 and #4.3).

The role of the suppressed variability of the land surface conditions for climate will be determined by the differences between the fully coupled simulations with EC-Earth (#2.1, 2.2) and the simulations where the changes in both aspects of the land surface conditions are prescribed (#4.3 for the historical period and #6.3

for the future). The deviations between these differences for the future and the historical period will then give the contribution of the changes in the variability of the land surface conditions to future climate change.

References

Alessandri A, et al (2017) Multi-scale enhancement of climate prediction over land by increasing the model sensitivity to vegetation variability in EC-Earth. Clim Dyn 49: 1215-1237.

Balsamo G, Viterbo P, Beljaars A, van den Hurk B, Hirschi M, Betts AK, Scipal K (2009) A revised hydrology for the ECMWF model: Verification from field site to terrestrial water storage and impact in the Integrated Forecast System. J Hydrometeorol 10: 623-643.

Balsamo G, et al (2015) ERA-Interim/Land: a global land surface reanalysis data set. Hydrol Earth Syst Sci 19: 389-407.

Döscher R, et al (2019). Geosci Model Dev, in preparation.

Eyring V, Bony S, Meehl GA, Senior CA, Stevens B, Stouffer RJ, Taylor KE (2016) Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geosci Model Dev 9: 1937-1958.

Hazeleger W, et al (2012) EC-Earth V2.2: description and validation of a new seamless earth system prediction model. Clim Dyn 39: 2611-2629.

Hurtt GC, et al (2011) Harmonization of land-use scenarios for the period 1500-2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. Clim Change 109: 117-161.

Lindeskog M, et al (2013) Implications of accounting for land use in simulations of ecosystem carbon cycling in Africa. Earth Syst Dynam 4: 385-407.

May W, et al (2019). Clim Dyn, in preparation.

O'Neill BC, et al (2016) The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. Geosci Model Dev 9: 3461-3482.

O'Neill BC, et al (2017) The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob Environ Change 42: 169-180.

Riahi K, et al (2017) The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Glob Environ Change 42: 153-168.

Smith B, Wårlind D, Arneth A, Hickler T, Leadley P, Siltberg J, Zaehle S (2014) Implications of incorporating N cycling and N limitations on primary production in an individual-based dynamic vegetation model. Biogeosciences 11: 2027-2054.

Van den Hurk B, et al (2016) LS3MIP (v1.0) contribution to CMIP6: the Land Surface, Snow and Soil moisture Model Intercomparison Project - aims, setup and expected outcome. Geosci Model Dev 9: 2809-2832.

Computing costs for the simulations

Number of simulation	Model configuration	Period	Details	Estimated costs (SBUs)
1.1*	H-TESSEL+LPJ-GUESS	1850-2014	Historical simulation, forced with meteorological data from the Global Soil Wetness Project Phase 3 (GSWP3)[a]	
1.2	IFS+LPJ-GUESS	1900-2014	Historical simulation; ocean state from observations	2,300,000
1.3	IFS+LPJ-GUESS	1900-2014	Land surface from #1.1, ocean state from observations	2,300.000
1.4	IFS	1900-2014	Vegetation from #1.1, ocean state from observations	2,000,000
1.5	IFS	1900-2014	Land surface and vegetation from #1.1, ocean state from observations	2,000,000
2.1*	IFS+NEMO+LPJ-GUESS	1850-2014	Historical simulation	
2.2*	IFS+NEMO+LPJ-GUESS	2015-2100	Scenario simulation SSP1-2.6	
3.1	IFS+LPJ-GUESS	1950-2014	Land surface from #2.1 (perpetual), ocean state from #2.1	1,600,000
3.2	IFS	1950-2014	Vegetation from #2.1 (perpetual), ocean state from #2.1	1,400,000
3.3	IFS	1950-2014	Land surface and vegetation from #2.1 (perpetual), ocean state from #2.1	1,400,000
4.1	IFS+LPJ-GUESS	1950-2014	Land surface from #2.1 (transient), ocean state from #2.1	1,600,000

4.2	IFS	1950-2014	Vegetation from #2.1 (transient), ocean state from #2.1	1,400,000
4.3	IFS	1950-2014	Land surface and vegetation from #2.1 (transient), ocean state from #2.1	1,400,000
5.1	IFS+LPJ-GUESS	2015-2085	Land surface from #2.1 (perpetual), ocean state from #2.2	1,800,000
5.2	IFS	2015-2085	Vegetation from #2.1 (perpetual), ocean state from #2.2	1,600,000
5.3	IFS	2015-2085	Land surface and vegetation from #2.1 (perpetual), ocean state from #2.2	1,600,000
6.1	IFS+LPJ-GUESS	2015-2085	Land surface from #2.2 (transient), ocean state from #2.2	1,800,000
6.2	IFS	2015-2085	Vegetation from #2.2 (transient), ocean state from #2.2	1,600,000
6.3	IFS	2015-2085	Land surface and vegetation from #2.2 (transient), ocean state from #2.2	1,600,000

Table 2: Climate simulations, the model configuration, the treatment of the land surface conditions and of vegetation in the simulations and the prescribed ocean conditions. Marked by the light (dark) shading are simulations for the historical (future) period. In contrast to Table 1, here the computing costs for the simulations (in SBUs) are added. The asterisk indicates simulations that are available within the EC-Earth consortium. [a]http://hydro.iis.u-tokyo.ac.jp/GSWP3

The overall estimated computing costs are 27,400,000 SBUs, roughly corresponding to 9,000,000 SBUs per year. Accordingly, the simulations will be spread over the three years of the proposed project.