New **E**nabling **V**isions and Tools for **E**nd-use**R**s and stakeholders thanks to a common **MO**deling app**R**oach towards a Climat**E** neutral and resilient society

D3.1 Report on the improvements of the climate module of WILIAM

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Abbreviations and acronyms

Acronym	Description
ACCMIP	Atmospheric Chemistry and Climate Model Intercomparison Project
AFOLU	Agriculture, Forestry and Other Land Use
BC	Black Carbon
CC	Climate Change
CCN	Cloud Condensation Nuclei
CESM	Community Earth System Model
CFCs	Chlorofluorocarbons
CMIP	Coupled Model Intercomparison Project
DRF	Direct Radiative Forcing
ECS	Equilibrium Climate Sensitivity
ECVs	Essential Climate Variables
EESC	Equivalent Effective Stratospheric Chlorine
ERF	Effective Radiative Forcing
GCMs	General Circulation Models // General Climate Models
GHGs	Green House Gases
GMSAT	Global Mean Surface Air Temperature
GMST	Global Mean Surface Temperature
HFCs	Hydrofluorocarbons
IAM	Integrated Assessment Model
INPs	Ice-Nucleating Particles
IPCC	Intergovernmental Panel on Climate Change
LIM	Louvain-la-Neuve Sea Ice Model
MIROC	Model for Interdisciplinary Research On Climate
MP	Montreal Protocol
NEMO	Nucleus for European Modelling of Ocean
NMVOCs	Non-Methane Volatile Organic Compounds
NorESM	Norwegian Earth System Model
NPP	Net Primary Productivity
NSGT	Near Surface Global Temperature
OA	Organic Aerosols
ODSs	Ozone Depletion Substances
OC	Organic Carbon
PBAPs	Primary Biological Aerosol Particles
PFCs	Perfluorocarbons
RC Models	Reduced Complexity Models
RCMIP	Reduced Complexity Model Intercomparison Project
RCPs	Representative Concentration Pathways
RF	Radiative Forcing

Acronym	Description
RFari	Radiative Forcing of Aerosol-Radiation Interactions
RFaci	Radiative Forcing of Aerosol-Cloud Interactions
SAOD	Stratospheric Aerosol Optical Depth
SCMs	Simple Climate Models
SSPs	Shared Socio-economic Pathways
TSI	Total Solar Irradiance
VOCs	Volatile Organic Compounds
WILIAM	Within Limits integrated Assessment Model

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Executive summary

This deliverable contains information about the analysis conducted on different existing climate models and available climate data that can be used to improve and update the climate module of WILIAM IAM, including new features in the model and upgrading some of the already modelled in order to get a more accurate representation of climate and its evolution in future years

For this purpose, the deliverable provides a section (STEP 0 - Starting point) which contains a comprehensive description of the current climate module of the IAM, as a starting point for exploring potential improvements and new features that could be integrated in this module. The main function of this part is to contextualise the different climate submodules, their key variables (names, units…) and their interlinkages. This section addresses a set of key terms focused on climate-related concepts that are necessary to understand the following parts.

Next, the document includes the climate information and models analysed: for integrating information from global complex climate models, such as General Circulation Models (GCMs), or for adding new functionalities or improvements to WILIAM from other RC Models (Reduced Complexity Climate Models). In this section (STEP 1 – Review of other existing climate models) the criteria followed to select which RCMs are analysed is explained and a summary of the main functionalities of each one is presented (both in text and in a summary table). Regarding GCMs, first of all, we discuss how their information can be exploited for the benefit of the RCMs (as exogenous inputs or for data calibration) and, after that, we present the set of analysed GCMs and what kind of information can be derived from them.

Section 5 (STEP 2 – Selection and Prioritisation) synthesises the information previously analysed from the RCMs and GCMs, selecting the features to be improved/included in WILIAM based on our own prioritization criteria. Thus, each of the chosen functionalities is presented theoretically, emphasising what the phenomenon consists of, as well as its representation in other models.

The last section of contents (STEP 3- Implementation) aims to establish a method of implementation for each of the selected features in WILIAM, considering the necessary equations, links with other submodules as well as other considerations such as possible overlaps with current WILIAM variables, the initialisation of variables, etc. Finally, this section also includes an implementation plan of how these features will be addressed in future tasks (mainly T3.2, 3.3 and 3.4).

1. Introduction

This deliverable 3.1 "Report on the improvements of the climate module of WILIAM" is part of the Work Package 3 "Climate science information", which aims to improve the representation and modelling of Earth Systems and climate processes in the WILIAM IAM. Thus, in this deliverable an exhaustive analysis of different existing climate models is carried out. This review makes it possible to define a list of functionalities that could be used to improve the WILIAM climate module, either by updating outdated functionalities or by including completely new ones.

Integrated Assessment Models (IAM) are models that cover different disciplines (energy, technology, sociology, economy, environmental sciences, etc.), thus being able to analyse the interactions between humans and the Earth systems, and to provide a deep understanding of complex systems that include large uncertainties (Wilson, et al., 2021) as the climate change problem. In particular, WILIAM is a system dynamics policy-simulation IAM in its final stage of development within the H2020 project LOCOMOTION[1] and which descents from MEDEAS (Capellán-Pérez, et al., 2020). It was designed to explore long-term decarbonization pathways.

In addition, there are several types of climate models able to project climate change, but which are not totally suitable to all the applications. On one hand, there are comprehensive and very complete climate models which needs sufficient computing power to run and also time such as complex atmosphere–ocean general circulation models (AOGCMs) or Earth system models (ESMs), while, on the contrary, there are less computationally demanding models such as the reduced-complexity climate models (RC Models /RCMs) also known as simple climate modules (SCMs) which are emulators of the complex models. In the middle, we have Earth system models of intermediate complexity (EMICs). In the table below, it is possible to compare among these types of models.

Table 1: Comparison of different climate computational models. Based on (Sarofim, Smith, Juliana, & Corinne , 2021).

Model type	AOGCMs/ESMs	EMICs	RC Models
Time needed to simulate	Thousands of hours	Tens of minutes	Seconds or less or near-instant (depending on the model)
Adjustable climate sensitivity	No	Generally	Yes
Complex, nonlinear behaviour	Yes	Yes	In some cases

In particular IAMs, due to their own complexity (they cover more disciplines that just the climatic one), and also their purpose that require iterative policy and climate fast simulations in order to produce different scenarios and also give support to policy makers, are only compatible with RC Models. These latter types of models are very aligned with the objective of producing useful tools for practical policy applications as the IAMS, as they are less computationally expensive and faster when simulating (Sarofim, Smith, Juliana, & Corinne , 2021).

WILIAM IAM has already a climate module which is precisely based on a simple climate model (SCM) called C-ROADS (Fiddaman, Siegel, Sawin, Jones, & Sterman, 2017), adapted to WILIAM requirements and with already some improvements with respect to the original RC model (explained in section 3.2 WILIAM IAM Climate Module).

On the other hand, RC Models and IAMs are calibrated against complex climate information, such as the one from GCMs (General Circulations Models). These complex climate models are used as standard

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[1] LOCOMOTION project funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 821105. https://www.locomotion-h2020.eu/

references being able to calibrate and validate the outputs of RC Models and also IAMs, or even provide exogenous information.

In this deliverable a group of chosen RC models (the selection criteria are explained in Section 4.1.1 Criteria for the selection of RC Models to review) is analysed together with information available from GCMs in order to explore improvements and new functionalities that can be included in WILIAM climate module. The ultimate purpose of the new functionalities proposed is to 1) improve the modelling of climate processes in the climate module of WILIAM, 2) support the following NEVERMORE activities by including some planetary boundaries, and 3) support the modelling of climate change impacts in WILIAM.

1.1 Purpose and structure of the deliverable

The purpose of this document is to write up the process undertaken in the Task 3.1 "Analysis of improvements and new features integration in the IAM climate module", carried out under the framework of the Work Package 3.

This task presents several goals which have led to the development of this deliverable in order to meet the established requirements. Main goals are listed below:

- Analysis and description of the current climate module of WILIAM to explore the potential of modelling improvements.
- Comprehensive analysis of open and available climate models and data and review of their related literature:
    - Simple Climate Models (SCMs), putting special focus on those included in intercomparison projects (e.g. RCMIP). The objective of this analysis is to explore additional new features to implement and/or improve in WILIAM.
    - General Circulation Models (GCMs) to explore the possible of applying more accurate and updated data for its application in WILIAM. This information could be used in various ways, from calibrating purposes to regionalisation of variables or as exogenous data.
- Prioritization of new features and potential improvements and detailed description of those selected.
- Preliminary method for the technical implementation in WILIAM climate model of the new functionalities or improvements selected (e.g. variables for coupling or integration, alignment of concepts, avoid potential overlaps, main equations, etc.).

Considering the goals listed above, the structure of this deliverable is as follows:

- Section 1 (Introduction) introduces and contextualises the addressed topic as well as the structure of the deliverable.
- Section 2 (Approach) explains the methodology followed through the deliverable to meet the objectives.
- Section 3 (STEP 0 - Starting point) establishes the starting point of this document by commenting on the current features and structure of the WILIAM climate module. It also presents the main features and common structure of climate modules including key terms to be used in the deliverable.
- Section 4 (STEP 1 – Review of other existing climate models) presents the analysis and review of different models, both RC Models and GCMs, to derive some information and features to implement/improve WILIAM.

- Section 5 (STEP 2 – Selection and Prioritisation) conducts a selection criterion of the features previously detected from the analysis of other models, determining which of them could be selected for the implementation in WILIAM. Additionally, these new features or improvements selected are explained in detailed.
- Section 6 (STEP 3- Implementation) explores how to technically integrate each new feature and/or improvement into the climate module of WILIAM, including the definition of preliminary technical methods to adapt and integrate those functionalities.
- Section 7 (Conclusions) presents the conclusions and future work to be undertaken in the following Tasks of the NEVERMORE project.

2 Approach

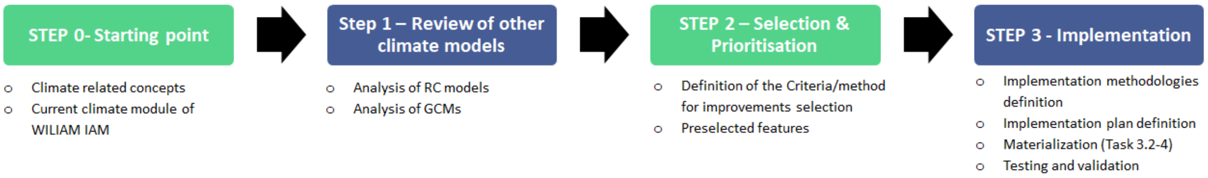

Figure 1. Step-by-step methodology followed in this document.

For the development of this deliverable (methodology shown in Figure 1) we have started with a contextualization, necessary to facilitate the reader's understanding, since certain theoretical concepts related to both climate and simulation models are used. Thus, first of all, the main climate terms have been described and then the reference model of this work, the IAM WILIAM, has been described: specifically, the climate module, which is the part that it is going to be improved.

Then, in order to meet the objectives of the task, the analysis of other existing climate models, both GCMs and RCMs, has been carried out. The selection criteria of these models have been defined (i.e., why these models have been analysed) and certain features that could be useful for WILIAM have been extracted or determined.

In a next step, a criterion for the selection and prioritization of functionalities has been established, thus defining which ones should be implemented in WILIAM´s climate module. A more in-depth description of each of these functionalities has also been carried out in order to define their theoretical framework.

Finally, the methodology for the practical implementation of the selected features has been proposed, describing step by step how they will be introduced in WILIAM and in which moment or task the modelling of these improvements will be carried out.

3 STEP 0 - Starting point

This section is two-fold: on one side the general structure and main features of climate models, and especially RC Models are presented, including key terms related to climate modelling; secondly the starting point in relation of climate modelling in NEVERMORE is explained, detailing the different parts that the climate module of WILIAM IAM already includes. This will serve as a basis for analysing potential improvements or new functionalities to be integrated in this module. It will also support the evaluation of the feasibility of integrating into WILIAM these improvements and/or functionalities.

3.1 Climate-related key concepts

For facilitating the comprehension of this deliverable, it is necessary to establish a glossary of climate-related terms that will appear throughout it. The main concepts covered are those related to the main features normally included in the Simple Climate Models (SCMs) or Reduced Complexity Climate Models (RCMs). This general structure is also aligned with the climate module already included in WILIAM (see Figure 2). Thus, the organisation of the terms used in this section is as follows:

1) Emissions, 2) GHG cycles, 3) Radiative forcing, 4) Climate sub-module (Heat Exchange), 5) Climate Responses: climate impacts and 6) Tipping points. This scheme will also be used not only in the description of WILIAM but also in the posterior analysis or RC models in the next section.

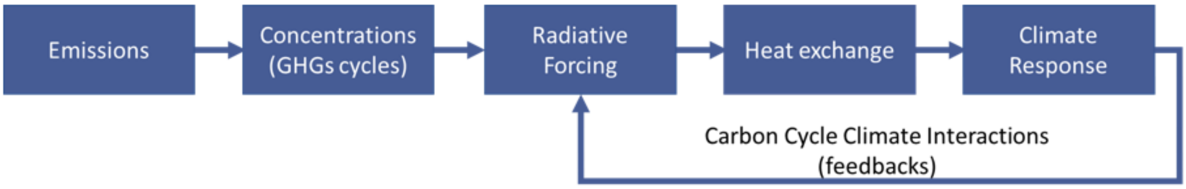

Figure 2: General structure (submodules) of RC models. Source: Own elaboration based on MAGICC RC model (Meinshausen, Raper, & Wigley, 2011).

1) <u>Emissions</u>

This sub-module includes both natural and anthropogenic emissions, well differentiated in some cases as for example CO_2, CH_4, N_2O and some halogenated gases (CF_4 and CH_3Br), due to their relevance with respect other Greenhouse Gas (GHGs). Anthropogenic emissions correspond to GHGs, GHG precursors and aerosols associated with human activities. These activities include land-use changes as for example those due to deforestation, use of fossil fuels, etc. In this review, the following features of climate models related to emissions have been examined (Field, et al., 2012):

- Land-Use Change CO_2 emissions: these emissions are mainly due to deforestation, accounting for 45% of total AFOLU (Agriculture, Forestry and Other Land Use) emissions. In addition, a part of being a major source and sink of carbon, it influences phenomena such as albedo and evapotranspiration (IPCC, 2021).
- Other anthropogenic CO_2 emissions: this category considers other human-related sources such as the burning of fossil fuels in the energy, transport and industrial sectors (Field, et al., 2012).
- Natural CO_2 emissions: although smaller in magnitude than anthropogenic sources, some models consider CO_2 fluxes from ocean outgassing, plant decomposition or fires generated by natural causes, among others (Herring, 2020).
- Fossil fuel CH_4 emissions: more than 33% of all CH_4 emissions are generated by fossil fuel processes, with similar contributions from coal, natural gas and oil (de Oliveira & Schulz, 2022).
- Agricultural CH_4 emissions: agriculture is a crucial source of human methane. Although more than the 32% of human-induced emissions come from the livestock, it is not only animals that generate releases, as paddy rice cultivation accounts for 8% of anthropogenic emissions (Climate and Clean Air Coalition (CCAC), 2021).
- Natural CH_4 emissions: these sources contribute to about 40% of total CH_4 emissions, with wetlands representing about 75% of the enduring natural releases (de Oliveira & Schulz, 2022).

- Anthropogenic N_2O emissions: agricultural soils contribute about 60% of human-induced emissions, while the rest of relevant sources are waste burning and the chemical industry, with much smaller contributions (Winiwarter, Höglund-Isaksson, & Klimont, 2018) (Del Grosso, Ogle, & Nevison, 2022).
- Natural N_2O emissions: the major natural sources include soils under natural vegetation, tundra and the oceans, which account for two thirds of total emissions (ICOS (Integrated Carbon Observation System), 2021).
- Atmospheric aerosols emissions: tiny liquid or solid particles suspended in the atmosphere, distinct from the larger particles in clouds and precipitation. Atmospheric aerosols have a lifetime of between one day and two weeks in the troposphere, and about one year in the stratosphere (mainly particles from volcanic eruptions). They range widely in shape, chemical composition and size and it is possible to distinguish between absorbing and scattering aerosols (Shindell, et al., 2014).

  Their pathways can be classified as: emission of primary particulate matter, and formation of secondary particulate matter (e.g. from NH_3, SO_2 and NOx to ammonium, sulphate and nitrate aerosols, respectively). Although there is not a consensus between models of which aerosols should be taken into account, according to several references, the most climate relevant aerosols are: sulphates, nitrates, ammoniums, black carbon (BC), organic aerosols (OA), mineral dust and primary biological aerosol particles (PBAPs) (Shindell, et al., 2014).
- Emissions of ozone precursors: this category includes Non-Methane Volatile Organic Compounds (NMVOCs), NOx and CO but not CH_4. These gases contribute to the formation of ground-level ozone and their main sources are diesel and catalytic converters in road vehicles (Shindell, et al., 2014).
- Halocarbon emissions: this group covers organic compounds with at least one halogen atom as HFCs (Hydrofluorocarbons), PFCs (Perfluorocarbons) SF_6 (although it is not a halocarbon), etc. Montreal Protocol (MP) gases, also known as ozone depleting substances, are also part of this category such halons, HCFCs or CFCs among others. Most of them are entirely of human origin, with the exception of CF_4, CH_3Br and CH_3Cl. They are widely used as solvents and refrigerants (World Meteorological Organization (WMO), 2022).

2) GHGs Cycles

This term describes the flow of a gas (mainly CO_2, CH_4 and N_2O) through different sinks and sources such as the atmosphere, ocean, terrestrial biosphere and lithosphere, including the time that it takes (residence time) in each of the systems listed. These pools and sources are presented in the models with systems of boxes and fluxes, respectively. Each model includes a different number of boxes and equations to calculate the fluxes.

- Terrestrial carbon cycle: this term describes the flow of carbon in several forms (i.e. CO_2 and sometimes CH_4) from both natural and anthropogenic sources to sinks like the atmosphere or the biosphere. In some models, the carbon cycle includes the releases of carbon gases due to the permafrost melting (Field, et al., 2012).
- Ocean carbon cycle: it is the part of the carbon cycle in which the ocean is involved, exchanging gases between the surface water and the atmosphere (CO_2, O_2, etc.). The ocean is the biggest carbon sink and models usually represent the interaction between the surface and the deep layers.

- CH_4 cycle: although some models include methane within the carbon cycle, others represent it separately with several sinks: stratospheric and tropospheric oxidation by OH; bacteria from dry soils; and oxidation in the oceanic boundary layer (Whiticar, 2020).
- N_2O cycle: it takes part in the N cycle, but in the climate models it is represented as a one-box system with the stratosphere as the sink.
- Other GHGs cycle: while less common than the previous cycles, some models also consider cycles of other GHGs such as aerosols and fluorinated compounds.
- Hydrological cycle: also known as the water cycle, it refers to the evaporation of water from the oceans and land surfaces, the atmospheric circulation over the Earth in form of water vapour, the condensation to generate clouds, the precipitation as snow or rain falling on vegetation and land surfaces, and the infiltration into soils to groundwater/rivers, ending the cycle in the oceans again (Field, et al., 2012).

3) Radiative Forcing (RF)

This phenomenon consists of a change in the net irradiance at the tropopause because of a change in an external driver of climate change (i.e. a variation in a GHG concentration), which leads to a modification in the global mean surface temperature (often an increase). It is necessary to establish a baseline year to define the relative change (the IPCC calculates the RF comparing values with 1750) (Field, et al., 2012). Greenhouse gases, aerosols, aviation contrails, tropospheric and stratospheric ozone, surface and cloud albedo, volcanic eruptions and solar variability are the main physical drivers of radiative forcing. Although RF is usually positive ($> 0\ W/m^2$), some compounds contribute negatively like sulphur dioxide or nitrogen oxides (Shindell, et al., 2014),.

- Albedo: clouds and aerosols, oceans and landforms, snow and ice, vegetation, and other naturally and artificially created surface features reflect a portion of the incident solar energy. The fraction reflected is called as bond albedo.
  - Surface albedo: some human and natural actions as deforestation and desertification raise the reflectivity while irrigating arid lands and losing artic ice lower it.
  - Cloud albedo: it is the phenomenon by which an increase in aerosol concentration generates an increase in the albedo of liquid clouds (reflectance of solar radiation). The main factors that cause the albedo enhancing are the reduction of droplet size and the increase of droplet number concentration (therefore, more total droplet surface area) (Shindell, et al., 2014).
- Aerosol radiative forcing: aerosol particles interact with solar radiation by absorption and, to a lesser extent, with terrestrial radiation by absorption, scattering and emission. Aerosols of anthropogenic origin are responsible for a RF of climate change through their interaction with radiation, and also as a result of their interaction with clouds. Thus, it is possible to distinguish two effects: Aerosol-Radiation interactions (RFari; direct effect) and Aerosol-Cloud interactions (RFaci; indirect effects). RFaci refers to the effect on cloud albedo because of the modification of concentrations in cloud condensation, as well as further changes in cloud life (Shindell, et al., 2014). Atmospheric aerosols play a major role in Earth's radiative budget, being one of the larges sources of uncertainty in modelling. Therefore, their radiative forcing may explain the difference between observed and modelled trends in average global temperature. In Figure 3 it is possible to see a schematic representation of aerosol radiative effects (Li, et al., 2022).
  - RFari: it refers to the change in radiative fluxes due to the scattering and absorption of radiation by aerosols. RFari, also known as Direct Radiative Forcing (DRF), weakens in

cloudy conditions. Rapid adjustments of RFari (semi-direct effect) are mainly generated by absorbing aerosols like BC that modify atmospheric stability in the boundary layer and free troposphere as well as reduce the downwelling radiation at the surface. This "semi-direct effect" generates changes in cloud formation as the solar radiation is absorbed by aerosols and the atmosphere suffers a local warming (decreasing cloud cover) (Shindell, et al., 2014).

- RFaci: it represents all of the interactions between aerosols and clouds and how these chemical species affect the radiative properties of cloud as well as the intensity and distribution of precipitations. RFaci accounts for aerosol-related cloud albedo modifications and also any secondary effect in clouds such as their lifetime. It also includes how clouds change aerosols properties (aqueous chemistry, mixing state of the aerosol or coalescence scavenging) (Shindell, et al., 2014).

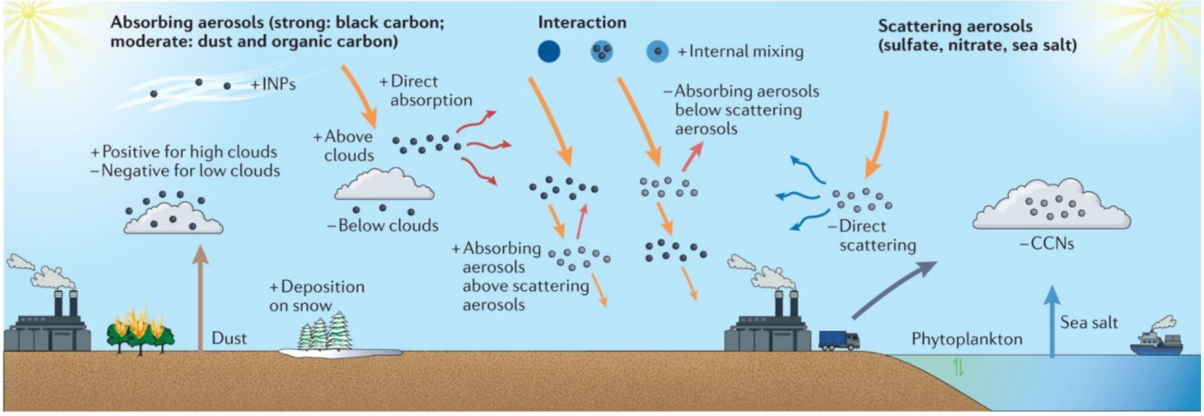

Figure 3. Schematic representation of radiative effects of aerosols. Absorbing aerosols are represented as dark dots (positive contribution) and scattering aerosols are represented as grey dots (negative contribution). CCN=cloud condensation nuclei; INPs=ice-nucleating particle. Source: (Li, et al., 2022).

4) <u>Climate Submodule (Heat Exchange)</u>

In the same way as with flows of gases such as CO_2, climate models also calculate heat flows among different systems like the atmosphere, the surface and the deep layers of the ocean. The heat flow provided by the RF drivers is included in this submodule too. Each model may implement a different kind of module such as an upwelling diffusion model or a zero-dimensional global climate model. Using this submodule, climate models are able to calculate several parameters and responses as the ocean heat uptake, temperatures at a different scale (global, ocean…) or a gradient profile of the deep ocean.

- Climate sensitivity: this is a very important parameter of this submodule. It is defined as the global temperature rise after doubling the CO_2 concentration in the atmosphere compared to pre-industrial levels, which has increased from 260 ppm to 520 ppm (Met Office, 2019). This parameter, however, has a lot of uncertainty, and for this reason, it has implicit a "likely range". In particular the high confidence interval of the "equilibrium climate sensitivity" is from 2,5°C to 4°C, being the best estimated value of 3°C (IPCC, 2021).

5) <u>Climatic Responses: climate impacts</u>

Models provide as outputs a wide range of climatic responses in which it can be highlighted the temperature (main climatic response), the sea level variation, the proliferation of extreme weather events, the ocean acidification (reduction of the pH of the ocean over a long period) and the reduction of Earth's ice cover.

- Temperature: models calculate mean temperatures, usually the Global Mean Surface Temperature (GMST). Some of them can also provide hemispheric, regional, land or ocean (mixed layer and Deep Ocean) temperatures.

6) Tipping points

Tipping points refer to the threshold limit of certain climatic parameters that, if crossed, would lead to major and irreversible changes in the planet and, therefore, in human life. These tipping points can be found in the polar zones as well as in other ecosystems and in oceanic and atmospheric circulatory phenomena. After crossing the threshold, the system reorganizes itself abruptly (Steffen, et al., 2015). Although there is not an official consensus about the list of tipping point as it is in a continuous process of renovation and updating, the currently proposed tipping elements are shown in Figure 4 and listed below (Armstrong McKay, Staal, Abrams, Winkelmann, & Sakschewski, 2022):

- Artic Winter Sea Ice: Collapse
- Boreal Forest: Northern Expansion
- Boreal Permafrost: Abrupt thaw
- Greenland Ice Sheet: Collapse
- Labrador Sea / Subpolar gyre: Collapse
- Barents Sea Ice: Abrupt loss
- Boreal Permafrost: Collapse
- Boreal Forest: Southern Dieback
- Atlantic Meridional Overturning Circulation: Collapse
- Sahel / West African Monsoon: Greening
- Low-Latitude Coral Reefs: Die-off
- Amazon Rainforest: Dieback
- Extra-Polar Mountain Glaciers: Loss
- West Antarctic Ice Sheet: Collapse
- East Antarctic Ice Sheet: Collapse
- East Antarctic Subglacial Basins: Collapse

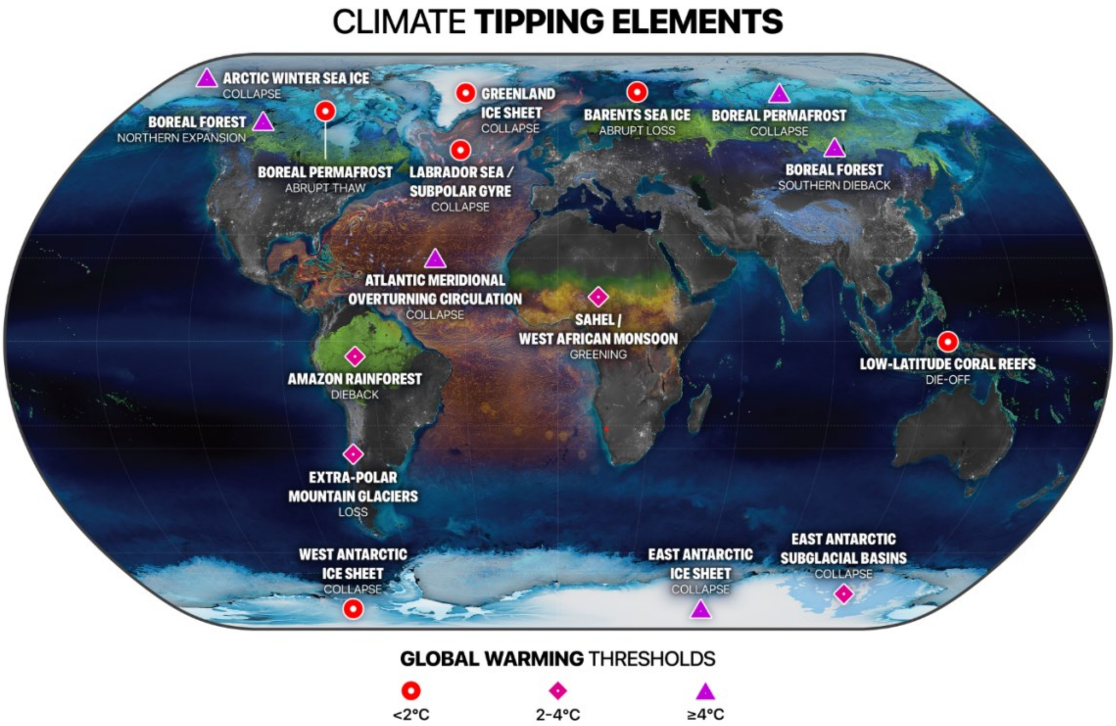

Figure 4. Location of climate tipping points in the cryosphere (blue), biosphere (green) and ocean/atmosphere (orange), and their triggering global warming levels. Source: (Armstrong McKay, Staal, Abrams, Winkelmann, & Sakschewski, 2022)

3.2 WILIAM IAM Climate Module

The climate module of WILIAM is based on the climate model C-ROADS (Fiddaman, Siegel, Sawin, Jones, & Sterman, 2017) including some improvements as the endogenization of some Greenhouse Gases (GHGs) like the land use associated emissions, the disaggregation in climate zones, or the inclusion of additional climate impacts. The last improved version of this module has been detailed in LOCOMOTION project (Pastor A. V., et al., 2021).

C-ROADS is a state-of-the-art model (Simple Climate model) able to run in WILIAM computational time (i.e., avoiding the complexity and long simulation times of Global Circulation Models). This C-ROADS model is based on the works of (Fiddaman T. S., 1997), (Goudriaan & Ketner, 1984), and (Oeschger, Siegenthaler, Schotterer, & Gugelmann, 1975).

The module projects the levels of climate change as a function of the GHG emissions from human activity. In particular, it includes:

- The **emissions from the different GHGs** (link with other modules). In particular, the total CO_2 emissions are endogenously calculated in the model, while the rest of GHGs are mostly exogenous, except for CH_4 and N_2O, for which the share of its emissions associated to the extraction, distribution and combustion of natural gas (in the case of CH_4), and also AFOLU emissions (CH4 and N2O) are endogenously calculated (Pastor A. , et al., 2020).

  In this regard, when using WILIAM, the user can select the level of future emissions of the rest of the GHGs (those exogenous) through the selection of their respective RCP scenario (van Vuuren, Edmonds, Kainuma, Riahi, & Thomson, 2011).
- A **carbon cycle** (the most detailed GHG cycle in WILIAM), which represents the dynamics between the carbon in the atmosphere, the biosphere (humus and biomass) and the ocean, including temperature feedbacks. The CO_2 emissions from fossil fuel combustion and land use changes are endogenously calculated in WILIAM.
- **Other GHGs cycles** (simpler structure). In particular, the cycles of CH_4, N_2O, PFCs, SF_6 and HFCs are also explicitly modelled.
- **Global mean temperature change**: **heat transfer** representation between atmosphere, ocean surface and deep ocean based considering the radiative forcing introduced by the GHGs. The ocean is divided in 4 layers.
- WILIAM global man temperature change is disaggregated **in climate zones** (Pastor A. V., et al., 2021)(based on Köppen-Geiger climate classes) for distribute better the climate impacts and improve the modelling of natural resources.
- Finally, WILIAM also includes the modelling of **specific global climate impacts** (through some specific damage functions) to capture the effect of a global temperature increase/variation and other climate-related variables, as global sea level rise.

The general structure of the complete climate module in WILIAM (just including the climate impacts regarding: 1) Global sea level rise, and 2) Global ocean acidification) can be seen in Figure 5.

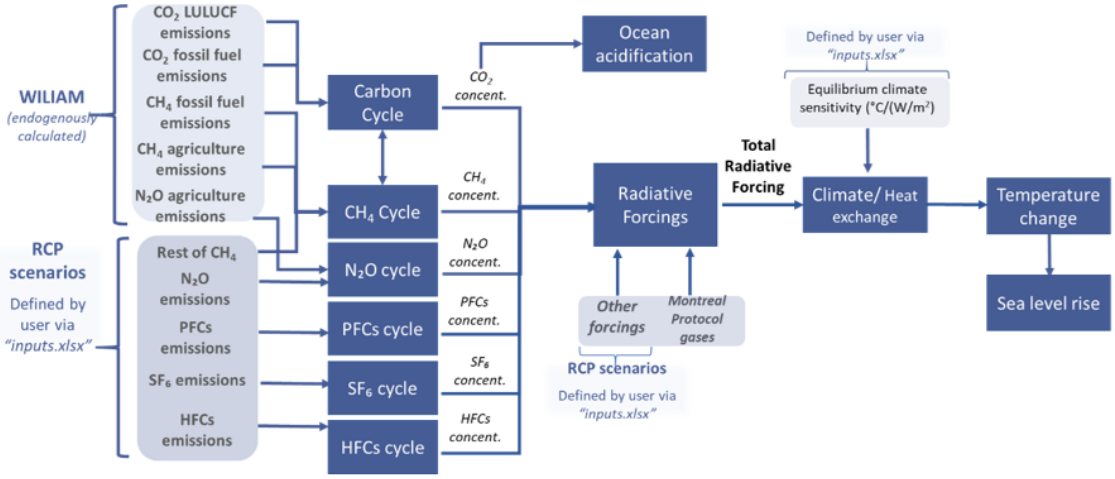

Figure 5. General structure of the climate module in WILIAM. Source: based on Deliverable 6.3 LOCOMOTION (Pastor A. , et al., 2021).

In the following subsections, each part will be more detailed explained focusing on main variables, input and output information, and some simplified diagrams to help in orienting potential future improvements.

3.2.1 Emissions

WILIAM is able to calculate some GHG emissions endogenously, while others enter into the module from exogenous sources. In addition, those GHGs emissions or other forcing (like albedo) whose GHG cycle is not specifically modelled enter also exogenously directly into the "Radiative Forcing" box (see Figure 6).

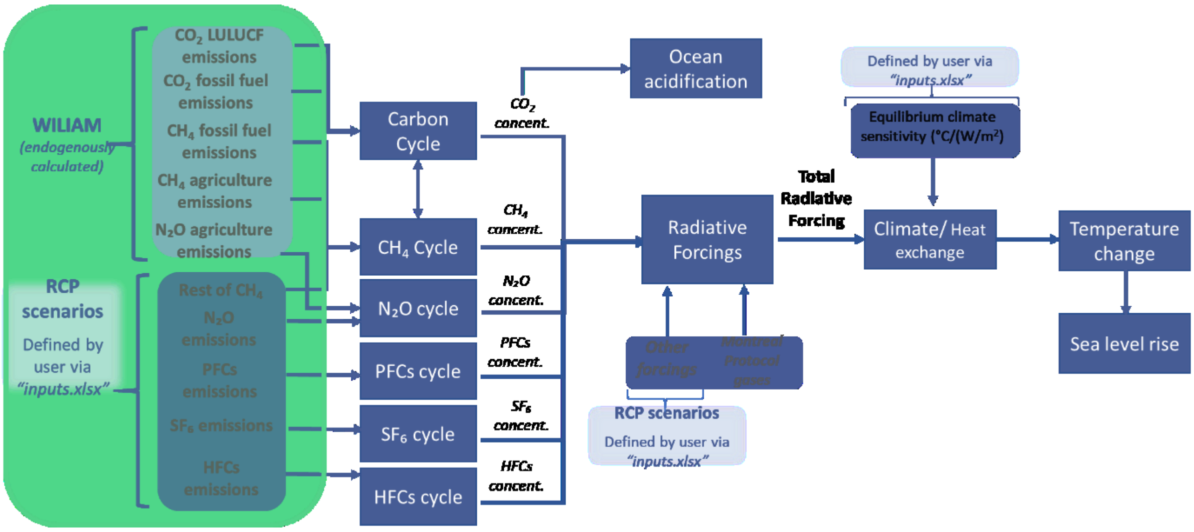

Figure 6. Inputs of the WILIAM climate model, grouped into endogenous and exogenous (green box). Adapted from LOCOMOTION project (Pastor A. , et al., 2021).

In particular, the emissions that are endogenously calculated (which are disaggregated by "political" Regions of WILIAM) are:

- The anthropogenic CO_2 emissions. These emissions enter into the carbon cycle. They are totally endogenous. They come from fossil fuel and LULUCF emissions, as shown in Figure 7. *Main variables: Total CO_2 emissions. Units: GtC/Year.*

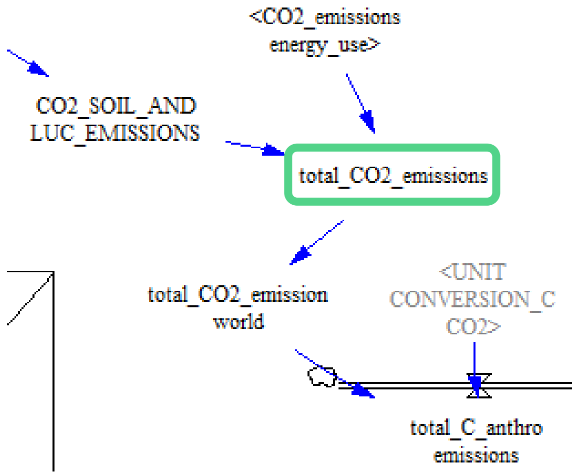

Figure 7. Anthropogenic CO_2 emissions represented in WILIAM. Based on C-ROADS SCM.

- Part of the CH_4 emissions is also endogenously calculated. These come from fossil fuel and land use activities (agriculture activities), as shown in Figure 8. To this variable, exogenous CH_4 emissions from other sectors that are not endogenous calculated are added to calculate the total emissions. These exogenous emissions depend on the RCP scenario selected. *Variable: CH_4 anthropogenic emissions. Units: $MtCH_4$/Year.*

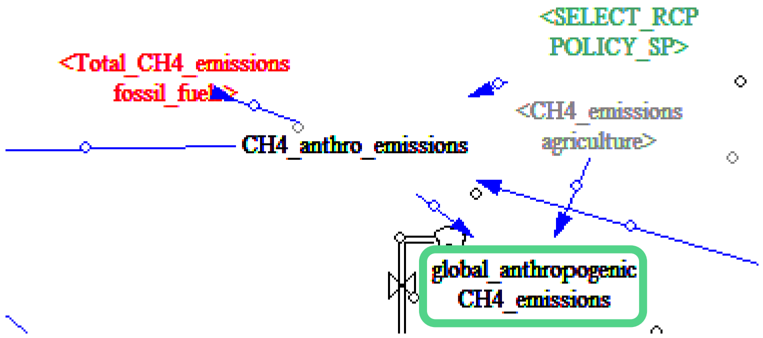

Figure 8. Endogenously calculated CH_4 emissions represented in WILIAM. Based on C-ROADS SCM.

- Part of the N_2O emissions is also endogenously calculated. These come from land use activities (agriculture activities like the application of fertilizers). To this variable, exogenous N_2O emissions from other sectors that are not endogenous calculated, as in the case of CH_4 are added to calculate the total emissions. The scheme is similar to the one from CH_4 Figure 8. Variable: N2O_antrophogenic emissions. Units: MtnN2O/Year.
- The rest of GHGs emissions for those gases with an explicit GHG cycle are exogenously introduced. The variables are:
    - *PCF_anthropogenic emissions. Units: t/Year.*
    - *HFC_anthrophogenic emissions. Units: t/Year.*
    - *SF6_anthropogenic emissions. Units: t/Year.*

3.2.2 GHGs Cycles- concentration

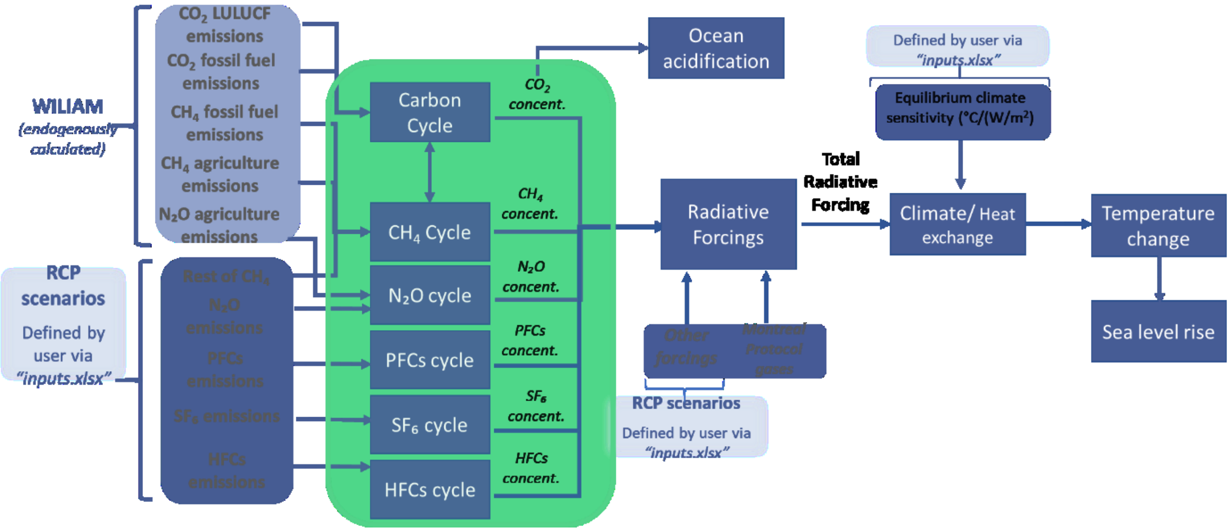

Figure 9. Module of GHGs cycles in WILIAM (green box). Adapted from LOCOMOTION project (Pastor A. , et al., 2021).

Through the GHGs cycles explicitly modelled (Figure 9) it is possible to calculate the concentration of the gas (outputs) based on the emissions (inputs). The main variables are the following:

- C in atmosphere. *Units: GtC*
- CH_4 in atmosphere. *Units: Mt*CH_4
- N_2O in atmosphere. *Units: MtN*
- PFC in atmosphere. *Units: t PFC*
- SF_6 in atmosphere. *Units: t* SF_6
- HFC in atmosphere. *Unit: t HFC.* The concentration is disaggregated in different HFC types.

3.2.2.1 Carbon cycle

This is the cycle that is more detailed in WILIAM. The carbon cycle estimates the CO_2 concentration in the atmosphere based on carbon stocks and fluxes between the biosphere and the ocean and is based on C-ROADS SCM (Fiddaman, Siegel, Sawin, Jones, & Sterman, 2017). The main variables are explained below with simplified diagrams from WILIAM model (Figure 10 and Figure 11).

Carbon fluxes related to the biosphere, and from permafrost:

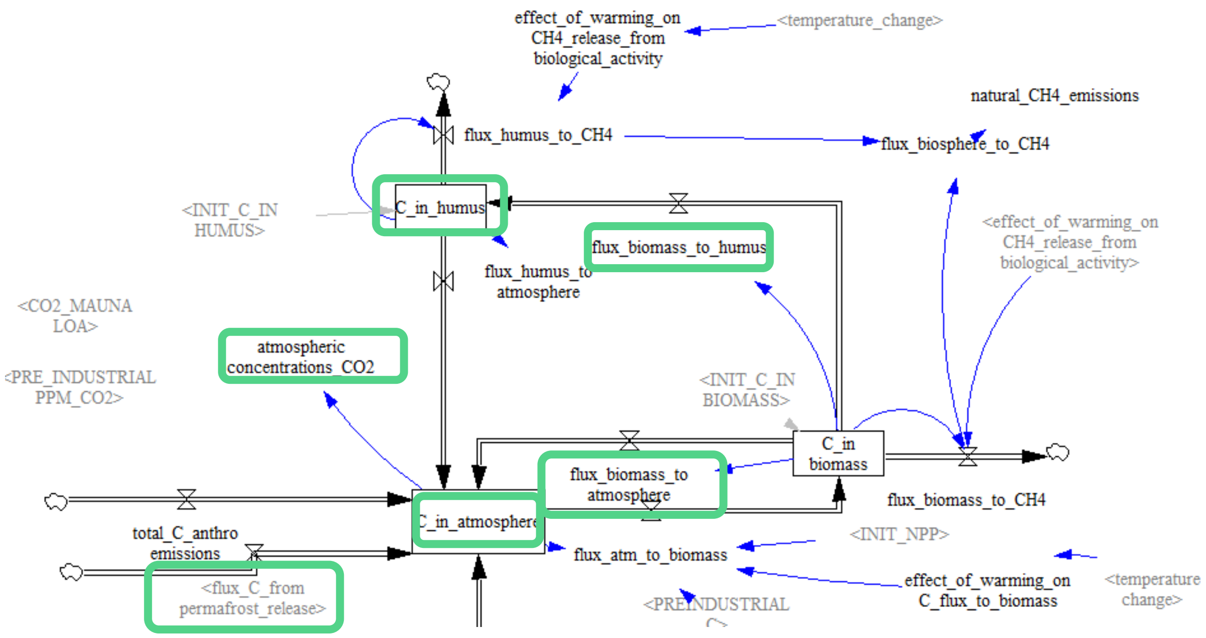

Figure 10. Schematic representation of the carbon fluxes related to the biosphere and permafrost from WILIAM model (simplified diagram). Based on C-ROADS SCM.

Ocean uptake + C from CH_4 oxidation:

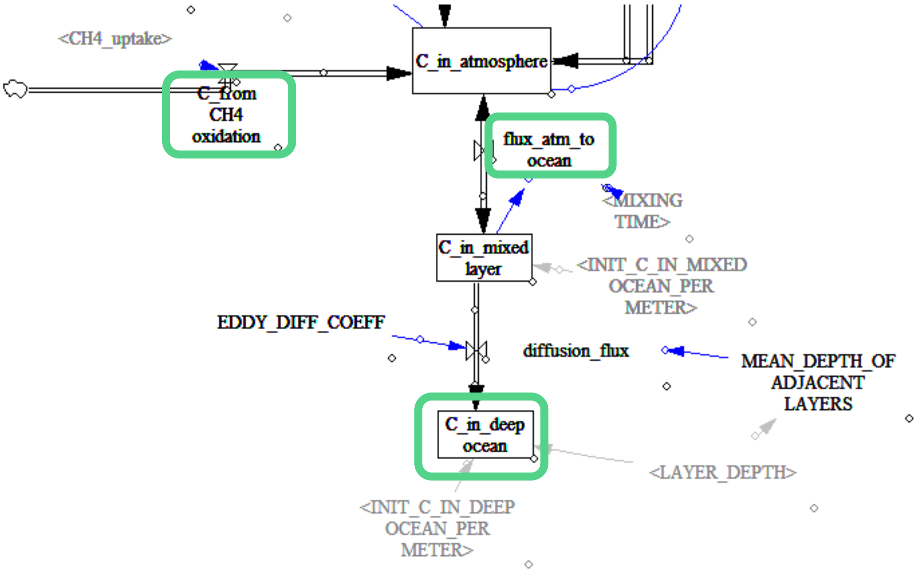

Figure 11. Schematic representation of the ocean uptake of carbon and CH_4 oxidation from WILIAM model (simplified diagram). Based on C-ROADS SCM.

The main variables and features included in the carbon cycle of WILIAM are the following:

- Concentration (global) of carbon (C) in atmosphere, in biomass, in humus, in mixed layer, in deep ocean (the “deep ocean” is divided in 4 layers of the ocean where the flux is distributed- from one layer to the other). The variables are:
    - *C_in_humus. Unit: GtC*

  - *C_in_biomass. Unit: GtC*
  - *C_in_atmosphere. Unit: GtC*
  - *C_in_mixed layer* (atmosphere-ocean interface). *Unit: GtC*
  - *C_in_deep ocean* (4 layers). *Unit: GtC*
- Flux of C from different carbon "pools". Flux of C from the atmosphere to the biomass ("*flux_biomass_to_atmosphere*"), from the atmosphere to the ocean, from biomass to humus… *Units of these flux of C are: GtC/year*
- Feedbacks due to the increase of temperature change: climate change impacts on the carbon cycle due to temperature increase.

  This relationship comes from CROADS model, and IS based on results from the C4MIP Model intercomparison (Friedlingstein, et al., 2006) from which determines the coefficients for modelling the climate-carbon cycle feedback. Its shows that "climate change will increase the fraction of anthropogenic CO_2 emissions that remain airbone" leading to an additional warming due to a positive feedback. The feedbacks included in the carbon cycle are the following:

  - *Feedback 1: effect of global mean temperature change on CH_4 release from biological activity*. A linear relationship is assumed and is applied to the "humus" and biomass stocks. Both fluxes of methane from carbon in humus and in biomass are the natural emissions of methane (Friedlingstein, et al., 2006).
  - *Feedback 2: effect of global mean temperature change on C and CH_4 release from permafrost and clathrate.* Due to uncertainties this is deactivated by default as in C-ROADS SCM. The value of reference of emissions of CH_4 from permafrost and clathrates per °C of global temperature change used is 50 Mt/year·°C, and it starts to be released when the temperature surpasses a "temperature threshold" with respect preindustrial levels.
  - *Feedback 3: effect of global mean temperature change on carbon uptake by biomass and by ocean*. First, ocean capacity to absorb carbon from the atmosphere is reduced due changes in the solubility of CO_2. This falls with rising temperatures. Second, in the case of carbon uptake by biomass, the capacity to absorb carbon from the atmosphere also decreases with rising temperatures. In both cases, the climate change impacts on carbon uptake are assumed as a linear relationship which depends on the "temperature change" variable. In the case of biomass, it directly affects NPP (Net Primary Productivity at global level), while in the case of ocean it affects the carbon equilibrium between atmosphere and ocean (solubility). These loops are shown in Figure 12 (Friedlingstein, et al., 2006).

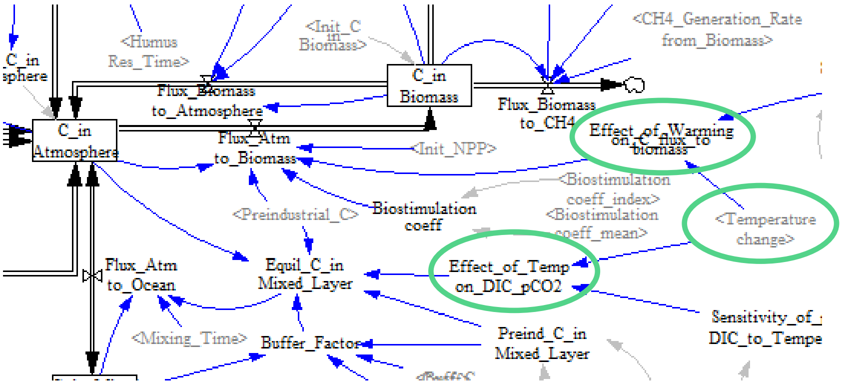

Figure 12. Schematic representation of the carbon uptake by biomass and ocean in WILIAM. Based on C-ROADS SCM.

In particular, the equation of temperature change affecting NPP is the following:

$$\mathrm{NPP} = \mathrm{NPP}_0\left(1 + \beta_b \ln\frac{C_a}{C_{a,0}}\right) * \text{Effect of Warming on } C_{\text{flux to biomass}}$$

Equation 1

where:

- NPP_0 is the reference Net Primary Production.
- β_b is the biostimulation coefficient.
- $C_{a,0}$ is the reference C in atmosphere (preindustrial).

The equation which represents the impact of temperature in carbon equilibrium between atmosphere and ocean (solubility) is the following:

$$\mathrm{Equil\_C}_{\mathrm{MixLayer}} = C_{\mathrm{pre-MixLayer}}\left(\frac{C_a}{C_{a,0}}\right) * \text{Effect of Warming on } C_{\text{flux to biomass}}$$

Equation 2

where:

- $\mathrm{Equil\_C}_{\mathrm{MixLayer}}$ is the equilibrium carbon content of mixed layer.
- $C_{\mathrm{pre-MixLayer}}$ is the preindustrial carbon content in mixed layer.
- $C_{a,0}$ is the reference C in atmosphere (preindustrial).

3.2.2.2 Other GHG cycles

The cycle of each GHG is modelled separately (simpler that in the case of the carbon cycle), in order to obtain the concentration of each GHG in the atmosphere. In particular the GHG cycles that are explicitly modelled are the cycles of CH_4, N_2O, PFCs, SF_6 and HFCs.

In the Figure 13 there is the example of methane GHG cycle.

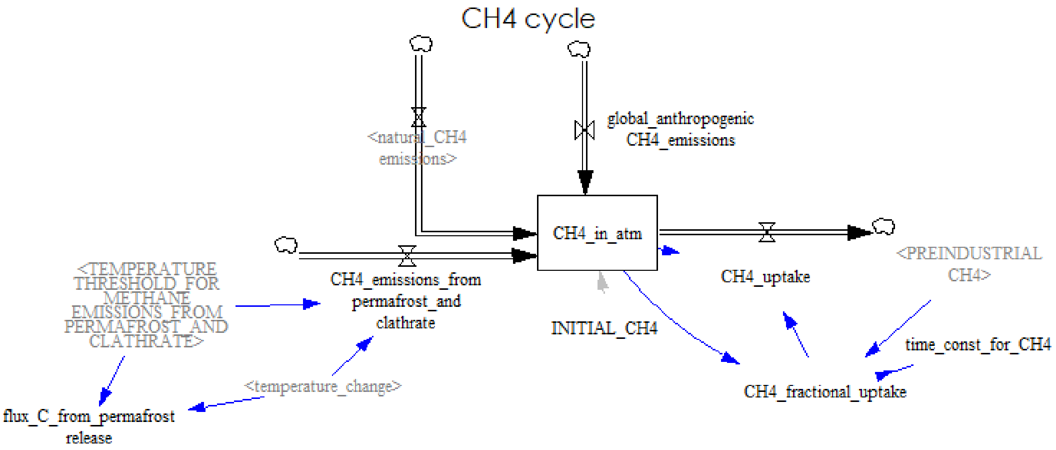

Figure 13. CH_4 cycle representation in WILIAM. Based on C-ROADS SCM.

The general structure of the GHGs cycles includes:

- Anthropogenic emissions. *Units: Mt/year*
- Natural emissions. *Units: Mt/year*
- Flux of GHG uptake (eliminated from atmosphere). *Units: Mt/year*
- Output: GHG concentration in the atmosphere. *Units: Mt*

In the case of CH_4 (and also carbon emissions) it also includes the emissions from permafrost as can be seen in the Figure 13. However, this potential tipping point is very simple and with a lot of uncertainties (by default is deactivated as in C-ROADS and in WILIAM as commented before).

3.2.3 Heat transfer-temperature

3.2.3.1 Radiative forcing

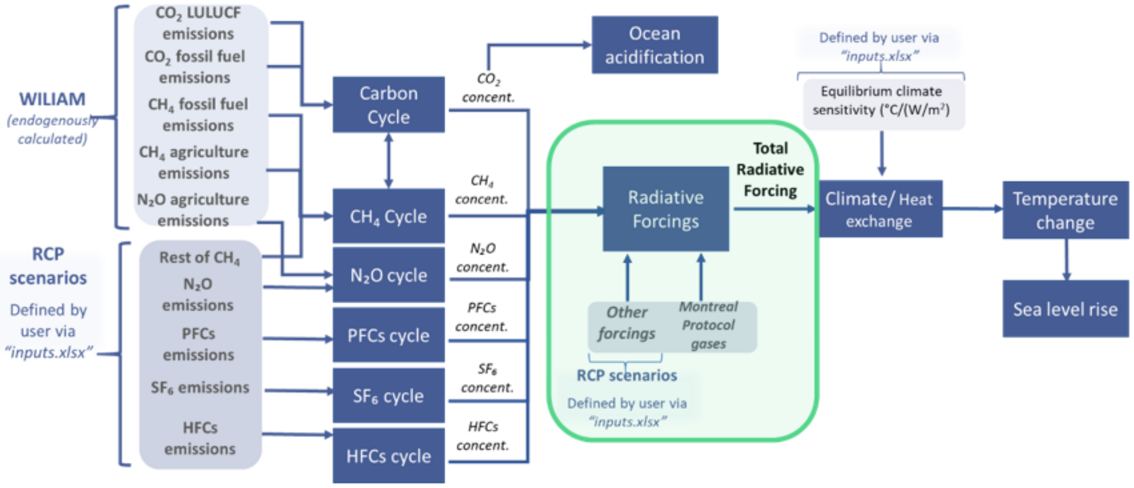

Figure 14. Radiative forcing module in WILIAM (green box). Adapted from LOCOMOTION project (Pastor A. , et al., 2021).

As shown in Figure 14 and in Figure 15, from the concentration of the gases, the radiative forcing is calculated applying the correspondent radiative forcing coefficients multiplied by the concentration of each gas, being the main variables included:

- *CO_2_radiative_forcing. Units: w/m^2*
- *CH_4_and_N_2O radiative forcing*. This variable is calculated from the individual CH_4 radiative forcing and N_2O radiative forcing due to the iterations of these gases. *Units: w/m^2*
- *SF_6_radiative forcing. Units: w/m^2*
- *PFC_radiative forcing. Units: w/m^2*
- *HFC_radiative forcing. Units: w/m^2*

On the other hand, the rest of the radiative forcing not endogenously calculated from the concentration of the gas, are included exogenously in the model:

- *MP_radiative forcing. Units: w/m^2*. This variable refers to the radiative forcing of the Montreal Protocol gases. Values are exogenous from the model from the Table 8-5 of (Daniel & Velders, 2006).

- *Other_forcing. Units: w/m^2*. This includes the rest of the GHG gases and the projections depends on the RCP selected and also on values extracted from MAGICC climate model for those not included in RCP, which are the mineral and land forcing. MAGICC is one of the RC models analysed in the following section. The main forcing that are including in "other forcing" are:
    - Aerosols (black carbon, organic carbon, sulphates, biological aerosol)
    - Tropospheric ozone (ozone precursor)
    - Solar and albedo forcing

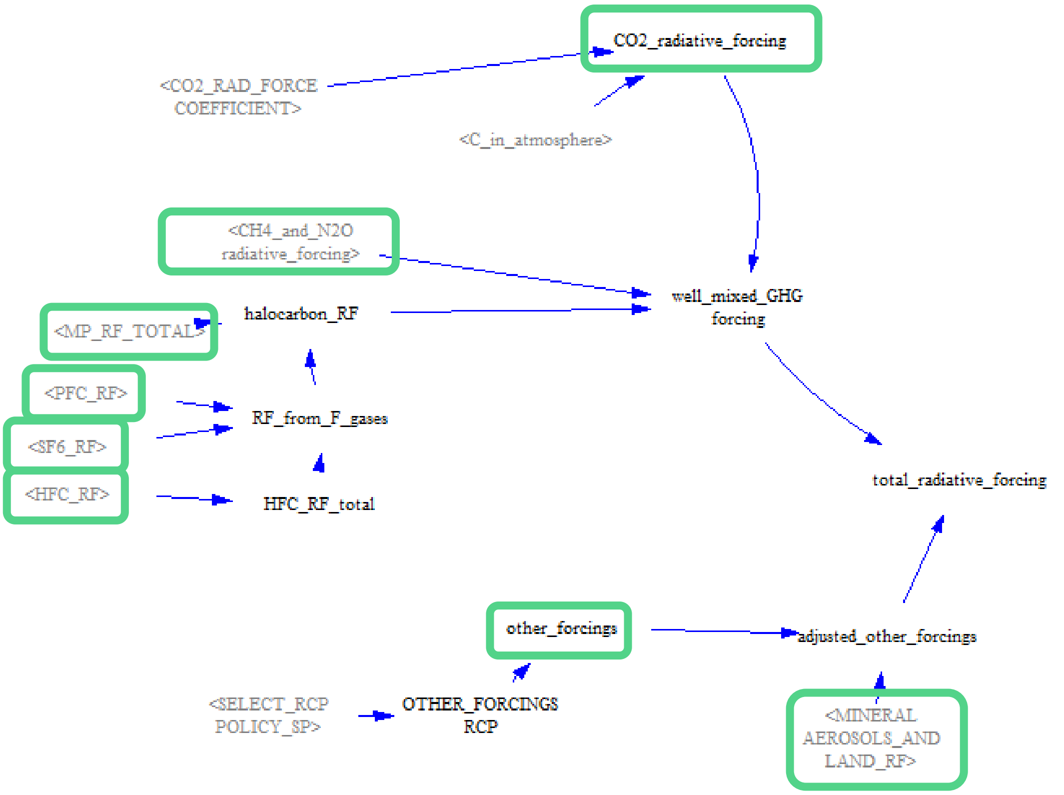

Figure 15. Schematic representation of the radiative forcing in WILIAM. Main variables highlighted with a green box. Based on C-ROADS SCM.

3.2.3.2 Mean global temperature change

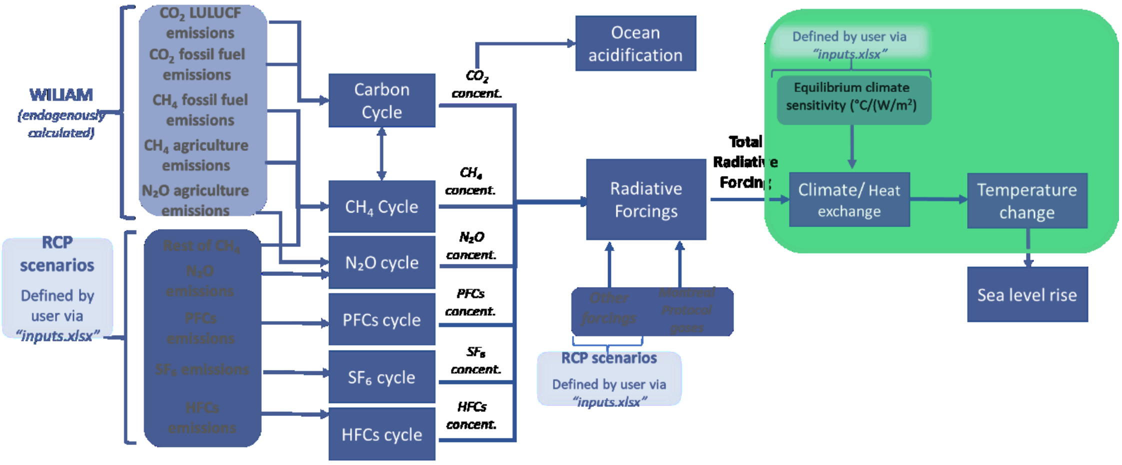

Figure 16. Mean Global Temperature Change module in WILIAM (green box). Adapted from LOCOMOTION project (Pastor A. , et al., 2021).

The calculation of the mean global temperature change (Figure 16) comes from C-ROADS SCM, which is based on the climate model from FREE model (also used in the DICE model) (Nordhaus & Yang, 1996). It includes stocks and flows of heat from the different systems, including the flow of heat (radiative forcing) from the GHG gases calculated before. It includes the transport of heat between atmosphere and surface, and the deep ocean.

The simplified diagram is the following with the main variables being:

- *Temperature_change. Units:˚C*. This temperature change is relative to preindustrial reference period, and it refers to the "global surface temperature change" (the layer between atmosphere and "upper-ocean")
- *Effective_radiative_forcing. Units: w/m*^{2}
- *Heat_transfer. Units: w/m*^{2}
- *Feedback_cooling. Units: w/m*^{2}. It is influenced by the Equilibrium Climate Sensitivity (ECS) parameter that can be modified by the user (*units:˚C*) via the variable "SELECTION ECS_INPUT METHOD". Although the ECS parameter has uncertainty as commented in the previous section, by default in WILIAM takes the value recommended in literature of 3 °C according to the most up-to-date climate reports.

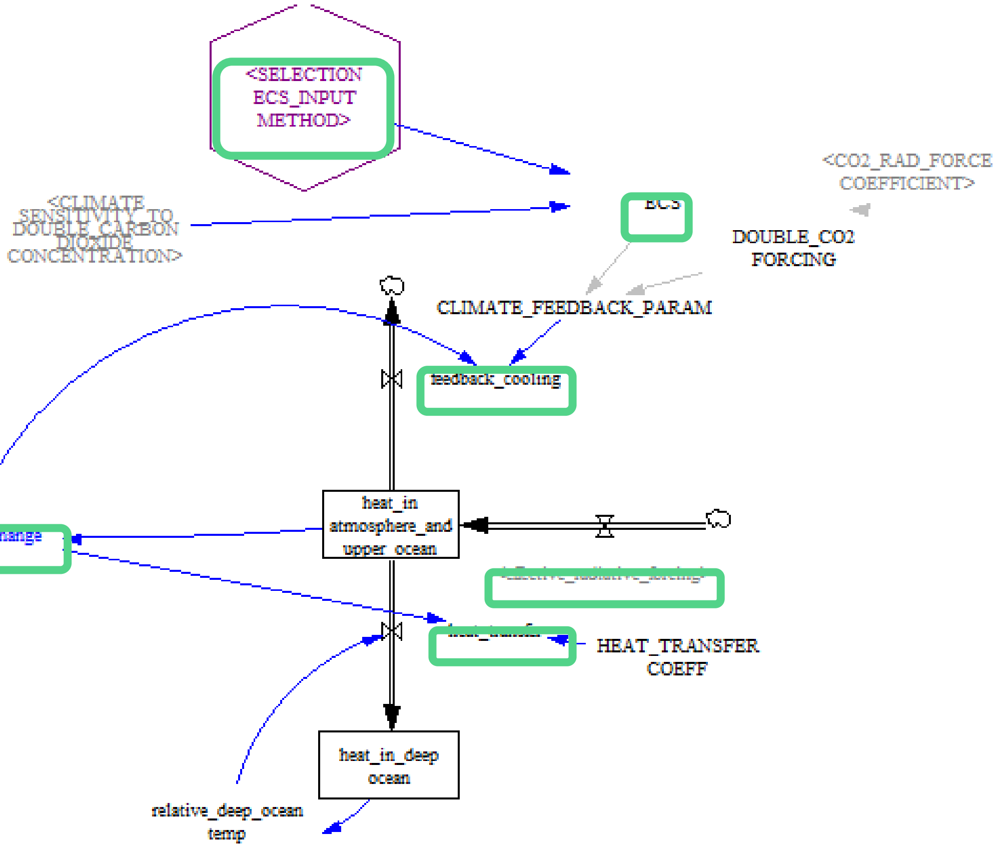

Figure 17. Schematic representation of the temperature change loop in WILIAM. Main variables highlighted with a green box. Based on C-ROADS SCM.

3.2.4 Distribution of temperature change by climate zones

In WILIAM, for the correcting computation of climate change impacts, apart from the spatial disaggregation in political world-regions[2] (which includes the disaggregation at national level in Europe - total of 35 political regions - Figure 18), it also includes a spatial disaggregation considering different climate zones. After considering different classifications, these climate zones are based in the Köppen-Geiger classification (Figure 19 from (Pastor A. V., et al., 2021)) and are the following:

1. Polar
2. Snow hot summer (or Winter snow)
3. Snow
4. Temperate
5. Warm
6. Hot arid
7. Cold arid
8. Tropical

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[2] Available online at: https://www.locomotion-h2020.eu/locomotion-models/locomotion-iams/

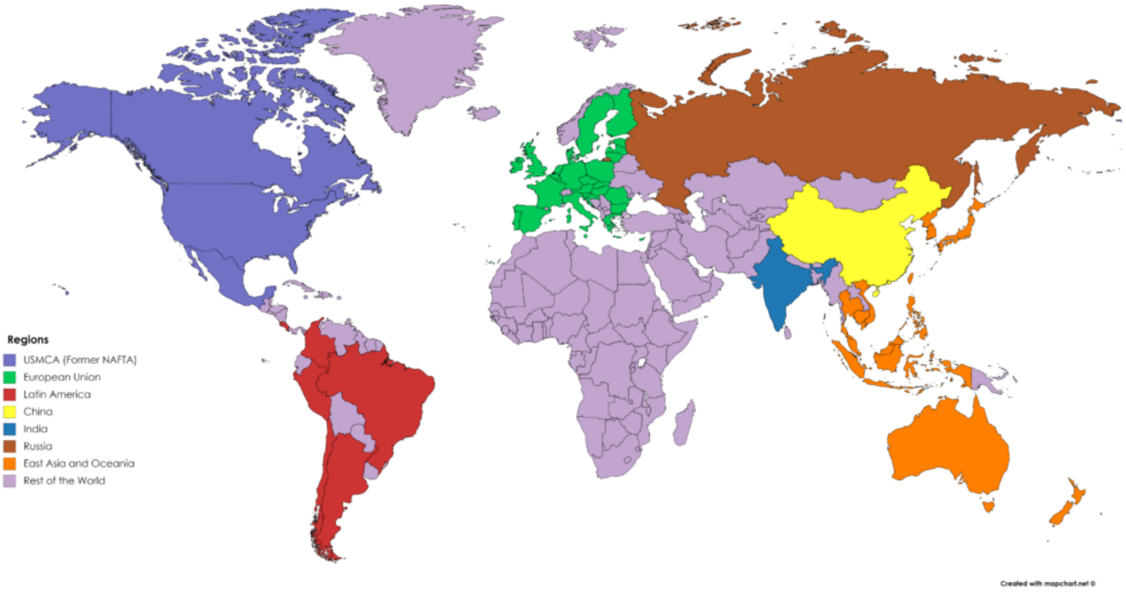

Figure 18. World map of political regions in WILIAM. Source: LOCOMOTION project[3].

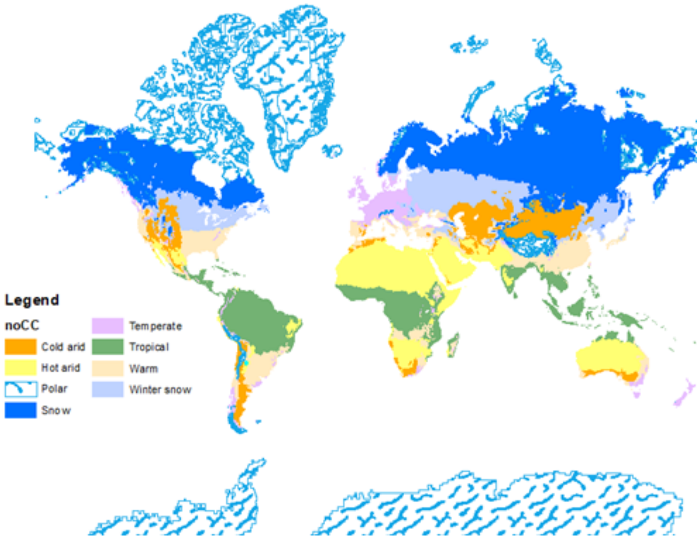

Figure 19. World map of climate zones based on the adjusted Köppen-Geiger climate classes used in WILIAM. Source: (Pastor A. V., et al., 2021).

For these climate and political zones (overlaping of the different zones) **the temperature change distribution** (from the value of global mean temperature change) is calculated, as shown in the Figure 20:

- *Temperature_change_by_region_and_climate. Units: ˚C.*

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[3] https://www.locomotion-h2020.eu/locomotion-models/locomotion-iams/

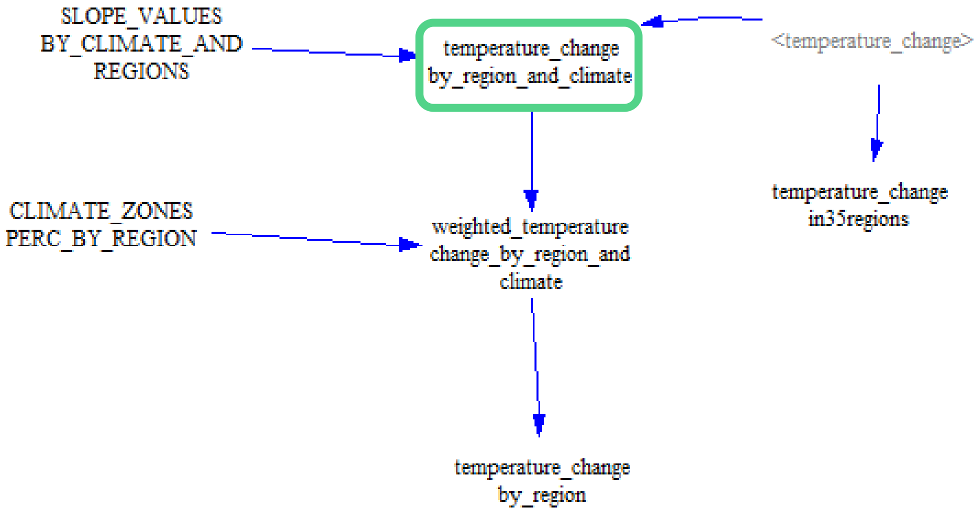

Figure 20. Schematic representation of the temperature disaggregation in WILIAM. Based on C-ROADS SCM.

3.2.5 Specific global climate impacts

Apart from the temperature change, the climate submodule in WILIAM calculates the impact of CC on two different ocean variables, also based on C-ROADS. These are:

- Ocean acidification.
- Sea level rise.

Ocean acidification

This impact depends on the CO_2 atmospheric concentration calculated in the carbon cycle as can be seen in Figure 21.

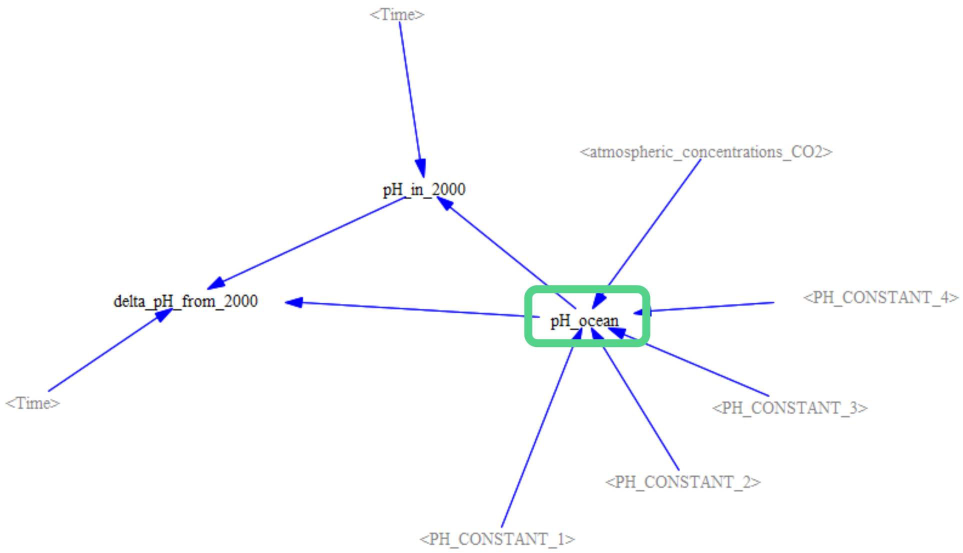

Figure 21. Schematic representation of the ocean acidification in WILIAM. Based on C-ROADS SCM.

Main variable: pH_ocean. Units: pH. The value is at global level.

The equation for calculating the global ocean pH is the following:

$$\mathrm{pH} = \mathrm{f}\,(\mathrm{CO_2 conc.}) = \alpha - \beta \cdot \mathrm{CO2_{concent}} + \gamma \cdot \mathrm{CO2^2_{concent}} - \delta \cdot \mathrm{CO2^3_{concent}}$$

Equation 3

where:

$\alpha, \beta, \gamma, \delta$ are “pH constants” for the function that estimates pH based on CO_2 concentration

Sea level rise

This impact is estimated based on global mean temperature change, as explained in the diagram below. The equation for this impact is the following:

$$\text{Sea level rise (SLR)} = \mathrm{f}\,(\Delta \mathrm{T}) = \mathrm{Equilib.\,change_{sea\,level}} + \mathrm{Sensitivity_{SRL\,to\,T}} \cdot \Delta \mathrm{T}$$

Equation 4

where:

- $\mathrm{Equilib.\,change_{sea\,level}}$ *is the equilibrium change in sea level.*
- $\mathrm{Sensitivity_{SRL\,to\,T}}$ *is the sensitivity of sea level rise rate to temperature change.*

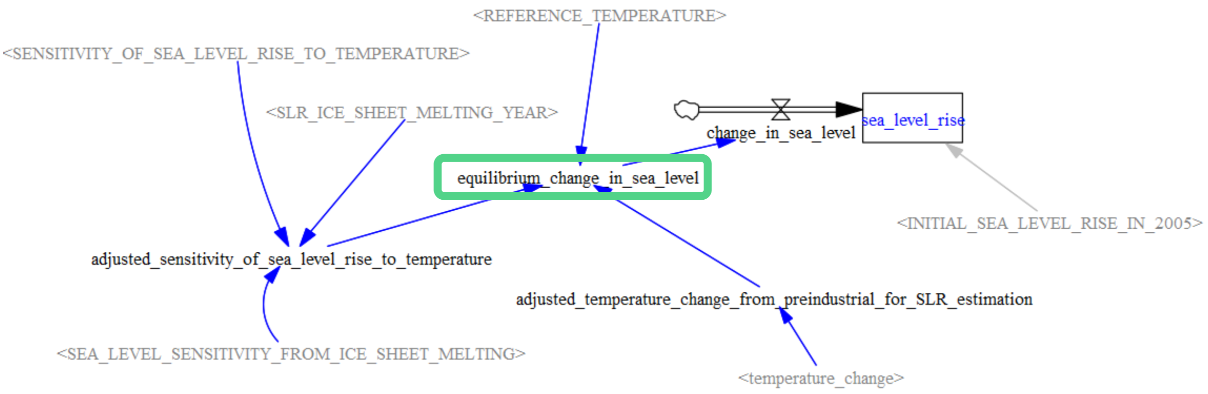

Figure 22. Schematic representation of the sea level rise in WILIAM. Based on C-ROADS SCM.

Main variable: Sea level rise. Units: mm. This value is at global level, and it is referenced to an initial value or “reference value” which indicates the accumulation of the rate of sea level rise.

4 STEP 1 – Review of other existing climate models

This review is focused on Reduced Complexity Models (RC Models) for capturing information and analysing other functionalities with respect to the climate module of WILIAM. Moreover, other complex climate models (e.g., General Circulation Models, GCMs) are reviewed with the objective of integrating/use information from them (e.g. to calibrate).

4.1 Analysis of Reduced-complexity climate models

4.1.1 Criteria for the selection of RC Models to review

The key criteria for selecting the RC Models to be reviewed and extracting information from them have been mainly the following:

- Their presence in the RCMIP: RCMIP stands for Reduced Complexity Model Intercomparison Project and it consists of a systematic evaluation of simple climate models with multiple phases. RCMIP uses scenarios and experiments from CMIP (focused on GCMs) to compare the different responses of RC Models in terms of global-mean temperature, CO_2 emissions, radiative forcing, etc. (R. J. Nicholls, et al., 2020). The presence of models in this kind of projects accounts for their relevance and, therefore, justifies their review for this document. Some examples of RC Models in RCMIP are: CICERO-SCM, FaIR, GREB, Hector, MAGICC or OSCAR.
- Their use in other IAMs: past experiences regarding the use of this RC models linked to an IAM gives evidence of applicability for the purposes we require this type of models. On this side, for example, MAGICC is the RC Model used by many IAMs[4], including the IMAGE IAM.
- System dynamics as mathematical modelling: As WILIAM is uses the system dynamics technique, it would be useful to analyse other RC Models with the same characteristics because a potential implementation of a feature from one model to another would be easier and also more aligned the approach (e.g. system dynamics is capable of modelling feedbacks loops). Thus, some models such as ESCIMO which is a simple climate model, but also ANEMI or FELIX which include a climate module as WILIAM, have been included in the review.

4.1.2 RC models review

According to the criteria explained above, multiple references related to the Reduced-Complexity Climate Models have been reviewed, ranging from papers written by the modelling teams to describe the architecture and the submodules included in the models to web pages where the code can be downloaded. Some models are not accompanied by a reference paper, but have been used and briefly described by other researchers in articles related to climate science modelling. Therefore, there are models with all features well defined whereas a few may have some characteristics not so much detailed in literature.

4.1.2.1 MAGICC

MAGICC is an open-source simple climate model, coded in Fortran and used in the climate part of some IAMs such as IMAGE. It includes various submodules: GHGs emissions, carbon cycle, atmospheric non-CO_2 concentrations, radiative forcing and climate response. The main outputs of the latter are hemispheric (land and ocean) and global mean temperatures and sea level variation. A schematic representation of the different sub-models and their interactions can be seen in the following Figure 23.

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[4] Online MAGICC Wiki: http://wiki.magicc.org/index.php?title=For_IAM_Modellers

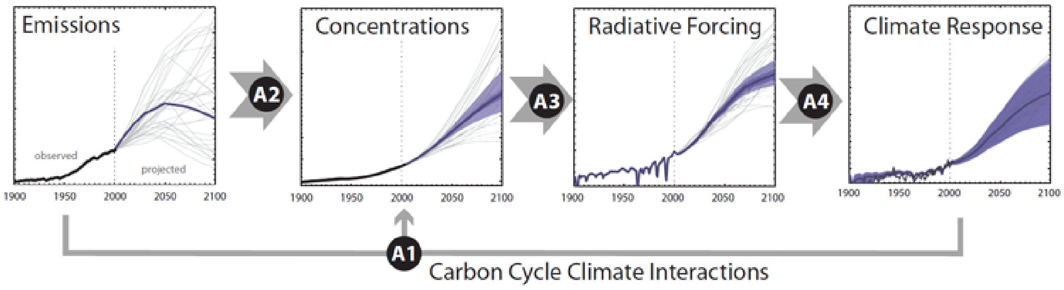

Figure 23. Climate modules included in MAGICC. Source: (Meinshausen et al., 2015).

The emissions included in MAGICC cover the most relevant GHGs (CO_2, CH_4, N_2O, tropospheric aerosols, tropospheric O_3 precursors and fluorinated gases) and they are exogenous variables mainly taken from the Shared Socio-economic Pathways (SSPs) emission data. Only natural CH_4 emissions are endogenously estimated by means of a budget. MAGICC applies these data to the GHG cycles to calculate their atmospheric concentrations which, in turn, are used to endogenously derive their radiative forcing. Notably, the SCM also calculates the RF of land albedo, cloud albedo and tropospheric and stratospheric O_3 (Meinshausen, Raper, & Wigley, 2011).

Focusing on the most developed cycle, the carbon one, as in WILIAM, the terrestrial is a globally integrated three boxes model. Temperature feedback effects on the vegetation respiration (heterotrophic respiration) and CO_2 fertilisation are also added to the cycle. Moreover, it subtracts the CO_2 emissions related to land use from the terrestrial pools, including relaxation/regrowth term for carbon sinks. Regarding the ocean carbon cycle, it uses an impulse response model to approximate the perturbation of inorganic carbon in the mixed layer. MAGICC's terrestrial carbon cycle is shown in Figure 24.

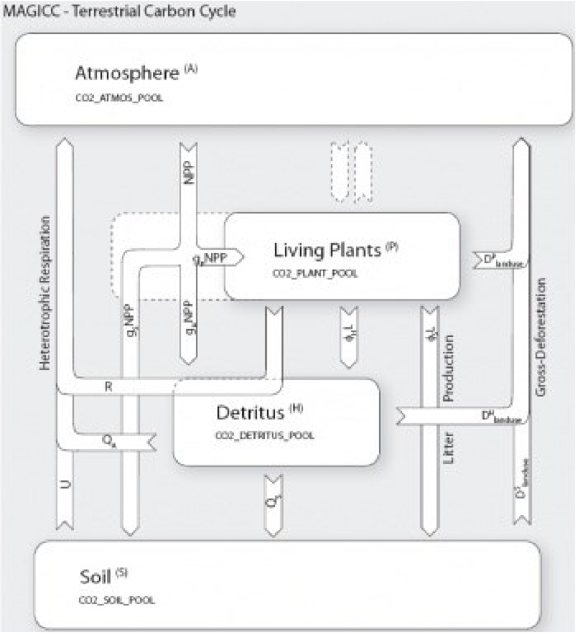

Figure 24. Terrestrial carbon cycle representation in MAGICC. Source: (Meinshausen et al., 2015).

As mentioned above, the two major outcomes of this model are global-mean temperature change and sea level variation, the latter being calculated following an upwelling-diffusion climate model (4 boxes) whose main variable is climate sensitivity to obtain an ocean temperature profile as a function of depth (Meinshausen, Raper, & Wigley, 2011).

4.1.2.2 FaIR

FaIR is an open-source model coded in Python, included in a combined IAM called FaIR-DICE. As a broad description, this model contains a carbon cycle with temperature feedbacks, calculates atmospheric GHGs and aerosols concentrations and effective radiative forcing (ERF) and produces future projections under RCP scenarios based on temperature changes, taking into account the different thermal response of the ocean mixed layer and deep ocean (Smith, Forster, Allen, & Nicholas, 2018).

All of the emissions are exogenous variables taken from RCP datasets (CO_2, CH_4, N_2O, tropospheric aerosols, tropospheric O_3 precursors and Kyoto and Montreal Protocol gases). Non-CO_2 gases concentrations are calculated by a one-box exponential decay model, while carbon concentration is obtained taken into account fossil fuels and land uses CO_2 emissions as well as CH_4 from fossil sources as input for a 4 boxes carbon cycle model.

In addition to the ERFs of the gases mentioned above, FaIR endogenously calculates the contribution of indirect effects from aerosols, methane oxidation to water vapour, albedo from land use, aircraft contrails and black carbon on snow. Exogenously, volcanic eruptions and solar radiation fluctuations are introduced (Smith, Forster, Allen, & Nicholas, 2018).

The calculated total ERF is used to determine the global mean surface temperature change, which is used as feedback for the carbon cycle, ozone depletion and CH_4 lifetime. Furthermore, the surface temperature allows the calculation of ocean heat content. The Figure 25 shows the submodules of the SCM and their feedbacks.

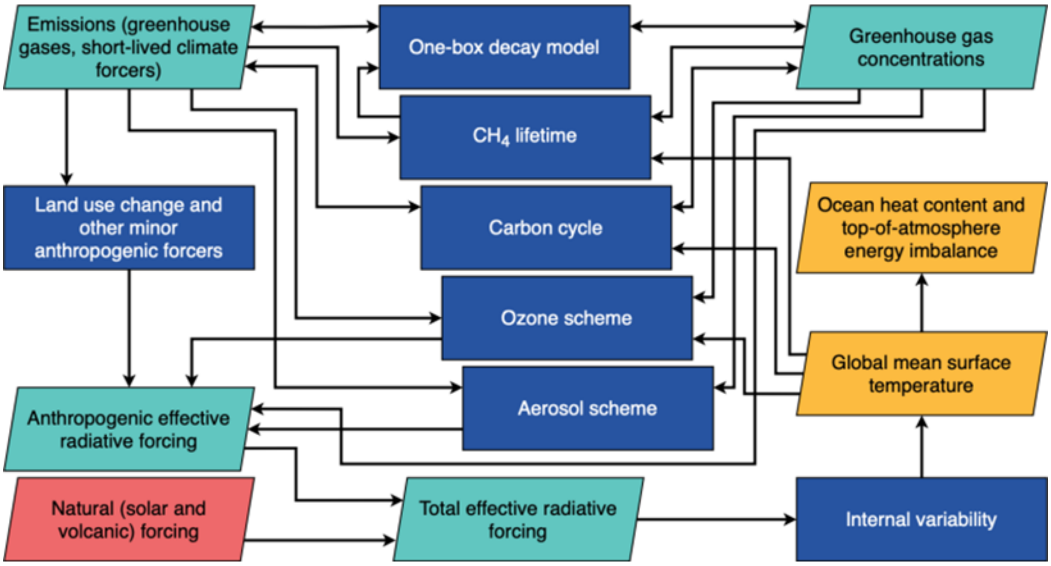

Figure 25. Climate sub-modules included in FaIR and their feedbacks. Source: (FaIR Development Team, 2022).

4.1.2.3 ESCIMO

ESCIMO is an open-source integrated model based on system dynamics which tracks global carbon fluxes, global energy flows and global albedo change in order to recreate scenarios for global-mean surface temperature, ice cover, ocean acidification, heat flow to the deep ocean, ERFs and carbon heat uptake by biomass. The Figure 26 shows and describes the functioning of the three major sectors of ESCIMO.

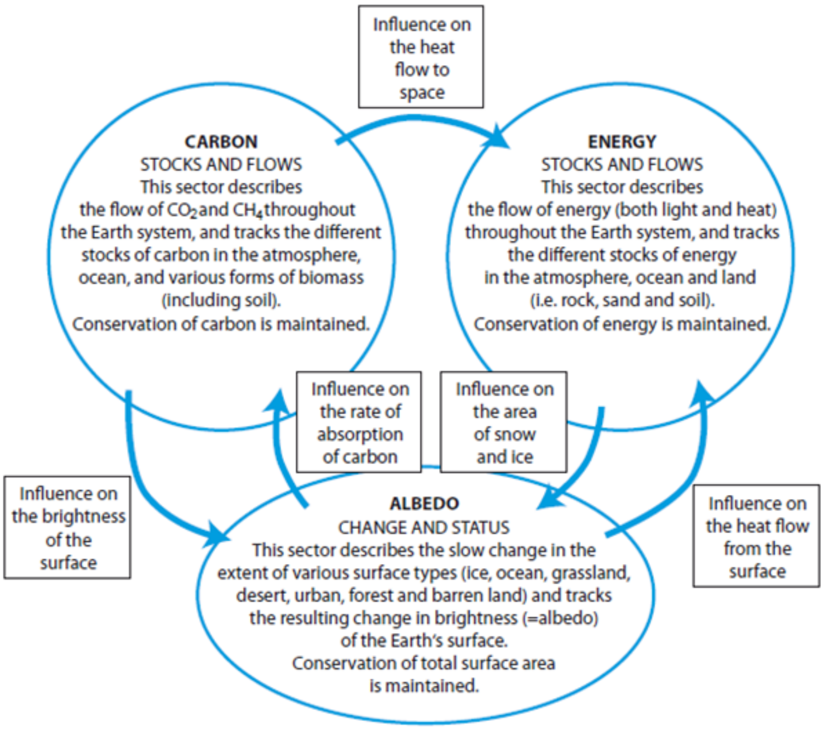

Figure 26. The three sectors included in ESCIMO. Source: (Randers, Golüke, & Wenstop, 2016).

It uses exogenous emissions of GHGs (except from CO_2 which are endogenously calculated), tropospheric aerosols and Kyoto Protocol gases to calculate their corresponding concentrations and, consequently, their ERFs. In addition, it includes ERFs from ozone-depleting substances, aerosol indirect effects, and land use albedo (endogenous) and from volcanic eruption and solar variability (exogenous). It must be remarked that ESCIMO tracks water vapour ERF and emissions (not included in most of the SCMs) (Randers, Golüke, & Wenstop, 2016).

The model takes into consideration anthropogenic and natural CO_2 and CH_4 as well as gas leakage from melting permafrost. The carbon cycle also presents the influence of temperature on biomass growth and CO_2 fertilisation. The model presents the important parts of the water cycle in atmosphere, clouds and on land-ice.

4.1.2.4 HECTOR

HECTOR is an open-source model written in C++, included in Integrated Assessment Models (IAMs) such as CGEM-IAM. It is mainly based on the carbon cycle which contains three different pools: atmospheric, oceanic and terrestrial. It reproduces the atmospheric concentration of CO_2, carbon-fluxes, radiative forcing, near surface global temperature (NSGT) and oceanic pH (acidification), as primary responses (Dorheim, Link, Hartin, & Kravitz, 2020).

To calculate radiative forcing, HECTOR uses exogenous emissions and concentrations of CO_2, halocarbons, CH_4, tropospheric ozone precursors, tropospheric aerosols (direct and indirect effect), N_2O and stratospheric H_2O from CH_4 oxidation. Radiative forcing of solar variability is introduced exogenously (Hartin, Schwarber, Patel, & Bond-Lamberty, 2015).

Regarding the carbon cycle, the atmospheric submodule is a one-box system while the oceanic one is a four-box system and the terrestrial involves a three-box system, linking detritus, soil and vegetation, taken into account temperature feedbacks on heterotrophic respiration and NPP. The carbon cycle is shown in Figure 27.

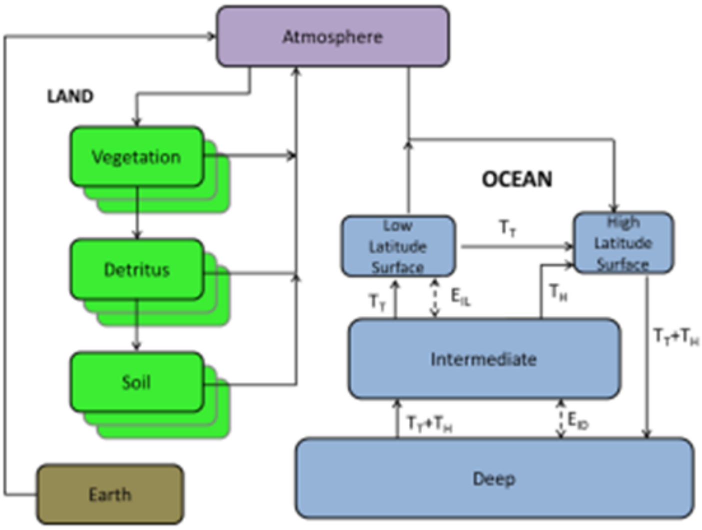

Figure 27. Representation of HECTOR's carbon cycle, land, atmosphere and ocean. Source: (Hartin, Schwarber, Patel, & Bond-Lamberty, 2015).

Other climate variables derived from HECTOR are: Global mean temperature change, NPP (net primary production), RH (heterotrophic respiration), oceanic heat flux and surface ocean temperature.

4.1.2.5 OSCAR

It is an open-source model developed in Python whose terrestrial carbon cycle is subdivided into 10 broad world regions and 5 biomes. As inputs, this model takes emissions of CO_2, anthropogenic GHGs and other environmental active species as aerosols, as well as land use and land cover change drivers. As output, it generates global temperature changes, GHGs concentrations and ocean heat content, among others (Gasser, Ciais, Boucher, Quilacaille, & Tortora, 2017). In the Figure 28, it is possible to observe a nodal diagram with all the modules included in OSCAR.

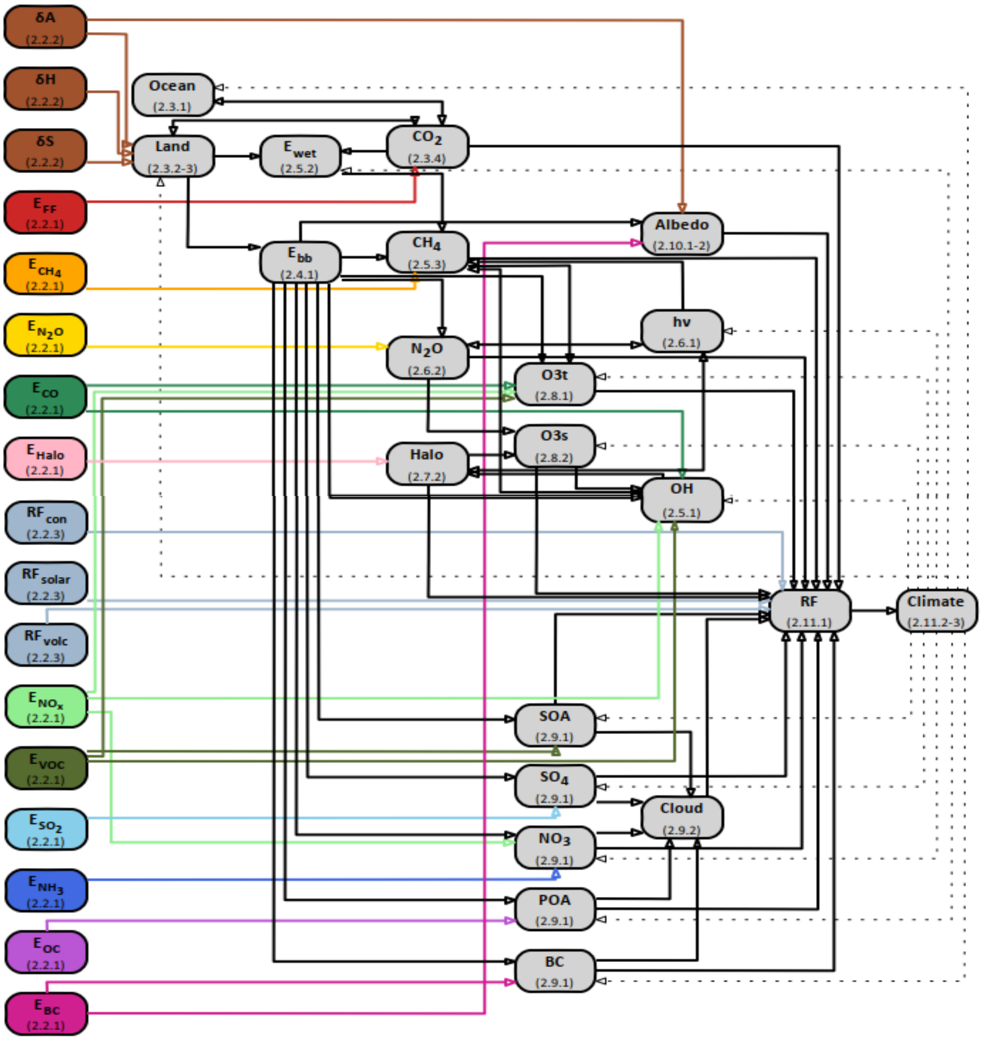

Figure 28. Simplified causal chain of OSCAR v2.2. Each node of the graph corresponds to a module. Coloured lines show the forcing of the model, black lines show the natural cause effect chain, and dashed lines show the climate feedbacks. Source: (Gasser, Ciais, Boucher, Quilacaille, & Tortora, 2017).

OSCAR has an exogenous emissions module (carbon dioxide, methane, fluorinated gases, ozone precursors, etc.) with the exception of land use change CO_2 emissions and natural CH_4 from wetlands. Emissions are used to calculate atmospheric concentration which in turn is used to calculate the radiative forcing of each emission. Additionally, OSCAR includes forcing from CH_4 oxidation to H_2O, volcanic aerosols, solar irradiance and aviation contrails. In order to model surface albedo, OSCAR presents two first-order model perturbations: black carbon on snow and land-cover change.

Land carbon cycle includes the dependence of NPP, wildfires and heterotrophic respiration on changes in atmospheric CO_2 concentration and temperature feedbacks as main characteristics. Ocean carbon cycle is based on the mixed-layer impulse response with one carbon pool that corresponds to the surface oceanic. Not explicitly but it takes account of changes in tropospheric water vapour, in ice cover, in cloud cover and in precipitation.

The climate estimates global temperature change through an equilibrium climate sensitivity (both the global surface temperature and the temperature of the deep ocean) as well as global yearly precipitation.

4.1.2.6 CICERO-SCM

This SCM is an open-source energy balance model, written in Jupyter Notebook and Python, used in IPCC climate-assessment Python package, mainly characterised by the implementation of a deterministic energy balance/upwelling diffusion model that calculates the annual change in near-surface hemispheric temperature, global mean surface temperature and changes in global ocean heat content (separately for the two hemispheres) from radiative forcing. Other climate responses provided by CICERO are sea level change and extreme weather events (Figure 29) (Skeie, Fuglestvedt, Berntsen, Peters, & Andrew, 2017).

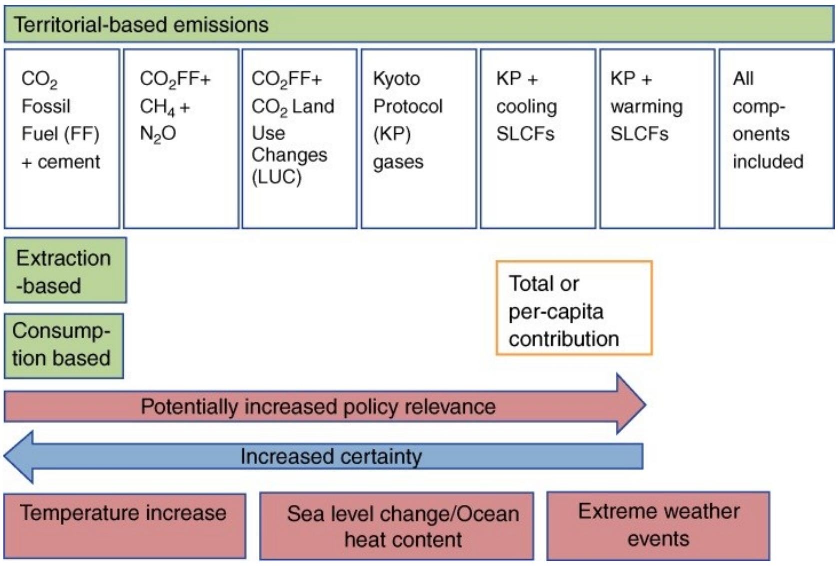

Figure 29. Schematic overview of the climate modules included in CICERO-SCM. Source: (Skeie, Fuglestvedt, Berntsen, Peters, & Andrew, 2017)

Exogenous emissions are used to calculate radiative forcing. The list of compounds utilized in the model is: CO_2 (from fossil fuel, cement, changes in albedo and land use sources), CH_4 and N_2O (natural and anthropogenic emissions), tropospheric and stratospheric ozone precursors and fluorinated gases. In addition, tropospheric aerosols, contrails, BC on snow, solar irradiation, methane oxidation to H_2O and CH_4-N_2O overlap bands are considered as exogenous forcing. In CICERO, direct effects of all type of aerosols (sulphate, BC, OC…) are considered but only indirect effect of sulphate is included.

In terms of ocean heat, vertical resolution of the ocean is 40 layers down to 4000 m and it is parameterized with variables such as climate sensitivity (2,5 °C), upwelling velocity or vertical diffusivity in the ocean, among others (Skeie, Berntsen, Aldrin, & Holden, 2018).

4.1.2.7 BERN-SCM

Coded in Fortran, BERN-SCM is an open-source, zero-dimensional global carbon cycle-climate model that uses impulse response functions in three different modules, land, ocean and heat. This can be observed in the Figure 30 (Strassmann & Joos, 2018).

BernSCM only needs CO_2 exogenous emissions to work correctly (both land use- and fuel-sourced), because radiative forcing from the rest of GHGs, tropospheric aerosols, halogenated gases, ozone precursors, volcanic eruptions and solar variability are exogenous inputs. This climate model takes neither surface albedo nor aerosol-cloud interaction into account.

Terrestrial carbon cycle is a 4-boxes model and incorporates NPP and a decay of terrestrial carbon, including heterotrophic respiration, fire and other natural disturbances. Ocean carbon cycle is based on the uptake of carbon through the air-sea interface flux and its subsequent distribution to the mixed surface layer and deep ocean.

Discussed model provides the GMST, the Global Mean Surface Air Temperature (GMSAT) and heat uptake by the planet (mainly dominated by surface ocean heat uptake) as climatic responses.

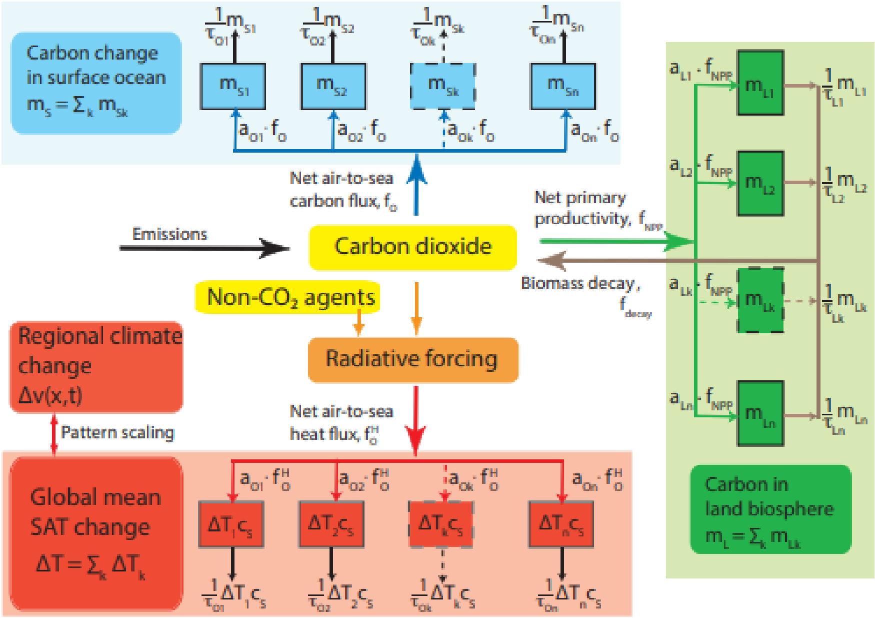

Figure 30. Schematic overview of BERN-SCM's modules. Source: (Strassmann & Joos, 2018).

4.1.2.8 FUND

It is an open-source model coded in Jupyter Notebook + Julia defined for 16 regions and based on a set of exogenous scenarios and endogenous perturbations. FUND introduces parameters such as rate of population, economic growth and GHG emissions through scenarios and establishes feedbacks among all those sectors (climate, economy, population…) (Tol, 2008).

In climatic terms, the endogenous parameters calculated by FUND are the CO_2 emissions from fossil fuels, the atmospheric concentrations of methane, nitrous oxide and carbon dioxide, the sea level change and the global mean temperature. The atmospheric concentration of CO_2 is a five-box model while CH_4 and N_2O are geometrically depleted from the atmosphere. Radiative forcing of CO_2, CH_4, N_2O and SF_6 are calculated according to their atmospheric concentration. In addition, the model includes the indirect effect of CH_4 on tropospheric O_3, as well as the exogenous forcing of SO_2 (MimiFUND.jl, 2022).

4.1.2.9 DICE

Dice is an open-source, globally aggregated model available in GAMS which combines both economic (labour, capital, etc.) and climatic (RFs, emissions, etc.) factors. A diagram of the DICE model is shown in the Figure 31 (Schneider, 2018).

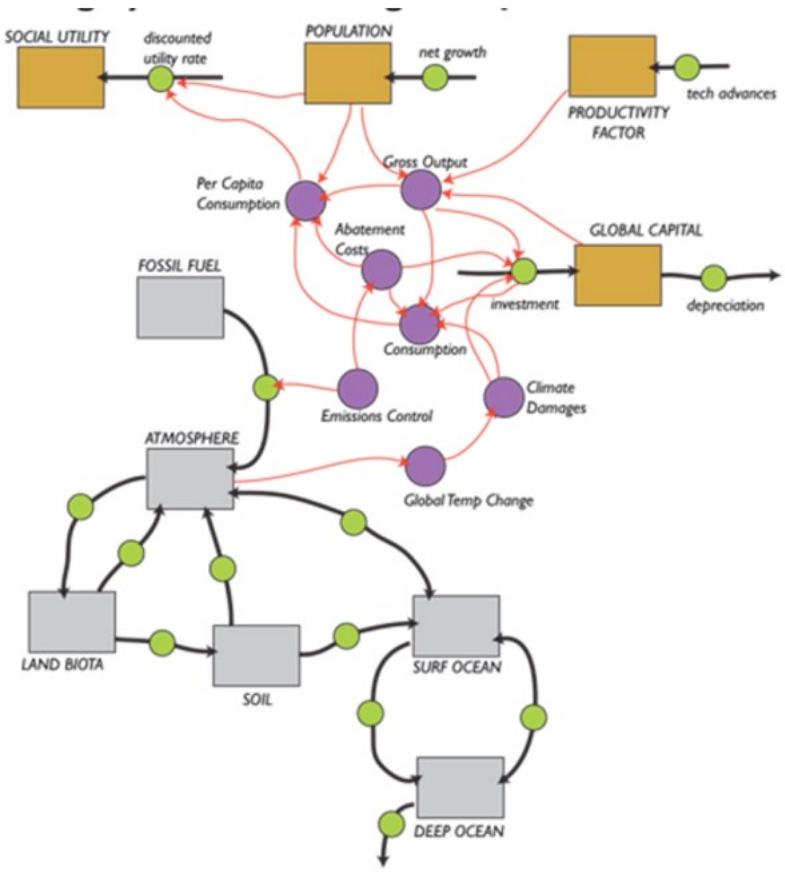

Figure 31. Highly schematic diagram of the DICE model. Source: (Penn State University, 2014).

Fossil fuel and industrial CO_2 emissions are endogenous while the permafrost and land-use ones are exogenous variables. The rest of compound emissions are not included but they are aggregated as exogenous radiative forcing (from projections prepared for the IPCC Fifth Assessment) to calculate temperature changes.

The carbon cycle consists of a three-box model with full ocean chemistry and the size of the intermediate reservoir (biosphere and upper level of the oceans) as the main parameter. Additionally, lower oceans and the atmosphere are reservoirs too.

4.1.2.10 GREB

Globally Resolved Energy Balance, or GREB, is a Fortran-coded model based on the surface energy balance through representations of solar and thermal radiation, the atmospheric hydrological cycle, sensible turbulent heat flux, transport by the mean atmospheric circulation and heat exchange with the deeper ocean (Dommenget, 2022).

This model presents several energetic processes such as oceanic heat uptake, surface albedo and cloud-albedo (without aerosol-cloud interactions). The albedo of the earth surface varies according to the region: open ocean waters, snow, ice cover, trees, desert, etc.

Contrary to other SCMs, GREB just uses CO_2 radiative forcing (endogenous) in order to calculate the global mean surface temperature. A simplified representation of the GREB processes can be seen in the Figure 32.

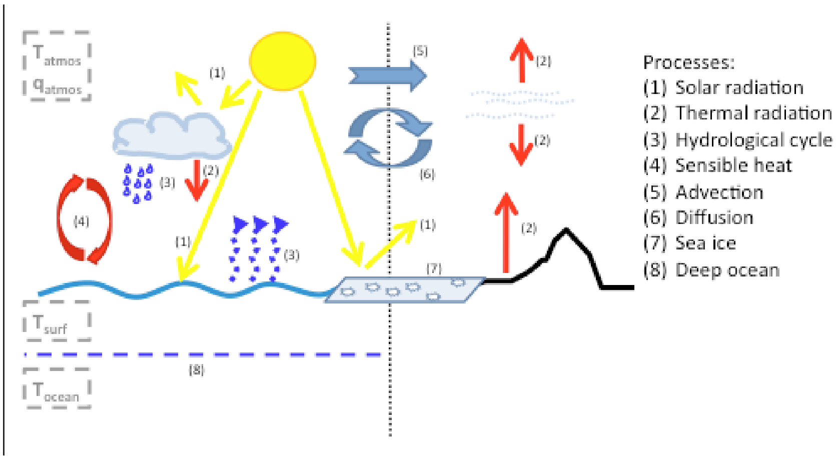

Figure 32. Processes represented in the GREB model. Source: (Dommenget, 2022).

4.1.2.11 EM-GC

EM-GC stands for Empirical Model of Global Climate and it provides a multiple linear regression energy balance simulation of GMST and ocean heat uptake. Temperature changes are calculated considering several anthropogenic and natural factors: radiative forcing due to GHGs, anthropogenic aerosols, land-use change (albedo surface), the export of heat from the atmosphere to the world's oceans [anthropogenic] and solar irradiance, aerosols from volcanic eruptions and climatic phenomenon such as El Niño-Southern Oscillation [natural] (McBride, Hope, & Canty, 2021).

EM-GC calculates the change in RF due to CO_2, CH_4 (including its oxidation to stratospheric H_2O vapour), N_2O, ozone-depleting substances, HFCs, PFCs and SF_6. In addition, tropospheric O_3 is also considered as a GHG in radiative forcing terms. Aerosol forcing (direct and indirect effect) and solar irradiance are exogenous variables (Hope, McBride, & Canty, 2021).

4.1.2.12 FeliX

The Functional Enviro-economic Linkages Integrated Nexus (FeliX) model is developed based on system dynamics methodology and composed of different modules: population, economy, education, water, food (including diet change), energy, carbon cycle, climate and biodiversity. The model is global (1 world region) and simulates from 1900 to 2200. Figure 33 shows the general structure of the model.

The carbon cycle module of FeliX calculates carbon emissions through a carbon production intensity multiplied by the production of energy, differentiating several energy sources (non-renewable and renewable ones). Forest and the agricultural land area also generate carbon emissions. The module is an eddy diffusion model with carbon stocks in the atmosphere, biosphere, mixed ocean layer and four deep ocean layers (Rydzak, Obersteiner, Kraxner, & Fritz, 2013).

The climate module of FeliX is based on the C-ROADS model. The endogenous CO2 emissions come from the carbon cycle module whereas the rest of the GHG emissions are exogenous. The global temperature change is driven by radiative forcing, feedback cooling due to outbound longwave radiation, and heat transfer from the atmosphere and Upper Ocean to the four deep ocean layers (Rydzak, Obersteiner, Kraxner, & Fritz, 2013).

The model includes different effects of climate change in other modules such as economy, biosphere, water supply, and land fertility. The current version of the FeliX model also includes a simple extreme weather events module based on (Beckage, et al., 2018), mainly including a stock of events used afterwards to calculate a risk perception index that drivers dietary behavioural change.

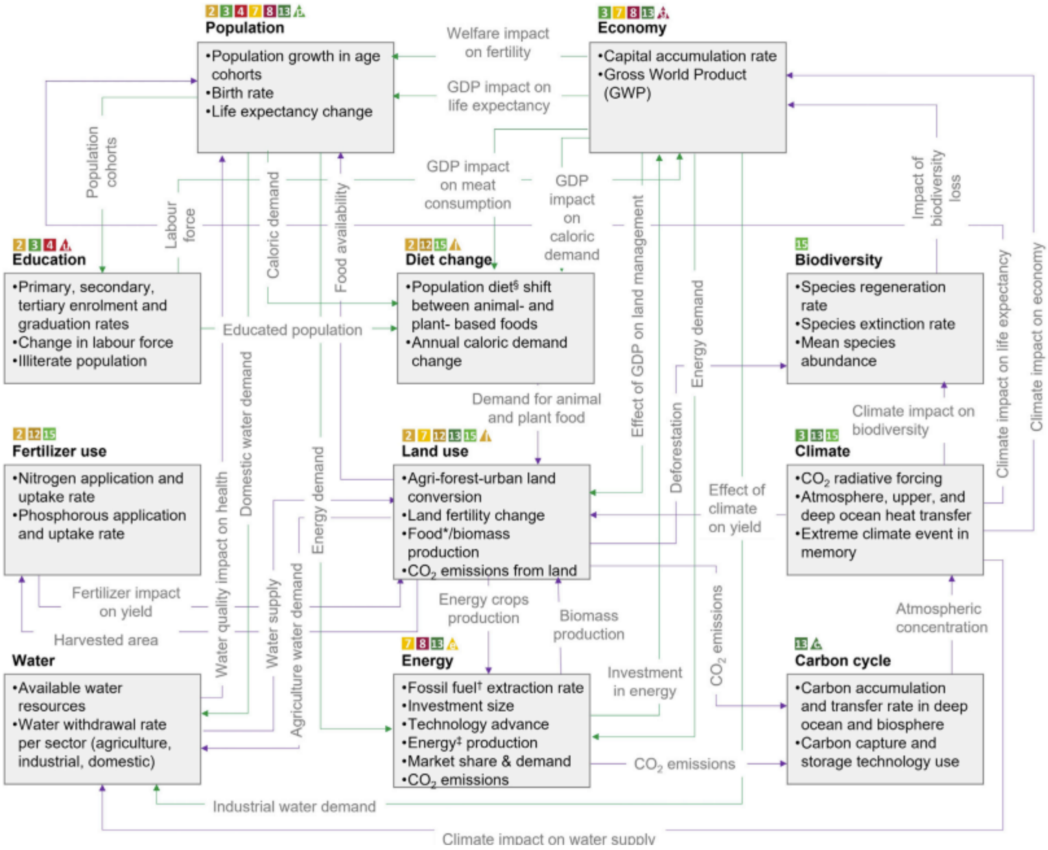

Figure 33. FeliX model structure. Source: (Moallemi, et al., 2022).

4.1.3 Resume

This section presents various tables (Table 2, Table 3 and Table 4) summarising the information gathered in the previous review. The main variables/features analysed are listed in this resume in order to facilitate a quick overview of the characteristics available in the RC Models. It is specified if the feature is calculated endogenously or exogenously ("Endo" or "Exo", respectively), if the model does not include it (-) or if it is just partly represented.

Table 2. Resume of the review of MAGICC, FaIR, ESCIMO and HECTOR. Source: Own elaboration.

Submodule	FEATURES	MAGICC	FaIR	ESCIMO	HECTOR
Emissions	Land use change CO_2 emissions	Exo	Exo	Endo	Exo
	Anthropogenic CO_2 emissions	Exo	Exo	Endo	Exo
	N_2O emissions	Exo	Exo	Exo	Exo
	Fossil fuel CH_4 emissions	Exo	Exo	Exo	Exo
	Natural CH_4 emissions	Endo	Exo	Exo	Exo
	Agriculture CH_4 emissions	Exo	Exo	Exo	Exo
	Tropospheric aerosols	Exo	Exo	Exo	Exo
	Ozone precursors	-	-	-	-
	Halogenated gases	Exo	Exo	Exo	Exo

Submodule	FEATURES			MAGICC	FaIR	ESCIMO	HECTOR
Main GHG cycles	Terrestrial carbon cycle			Endo with 3 boxes	Endo	Yes, several boxes	Endo with 3 boxes
	Ocean carbon cycle			Endo	-	Endo	Endo, 4 boxes
	CH_4 cycle			Endo	-	-	Endo, exponential decay from the atmosphere
	N_2O cycle			Endo	-	Partly	
	Other GHG's cycles			Endo (43 cycles)	-	Partly	
	Water vapour			-	Partly, exo	Partly	-
RF	Carbon dioxide			Endo	Endo	Endo	Endo
	Other well-mixed GHGs (long-live gases)	CH_4 RF		Endo	Endo	Endo	Endo
		CH_4 oxidation		Endo	Endo	Endo	Endo
		N_2O		Endo	Endo	Endo	Endo
		MP gases		Endo	Endo	Endo	Endo
		HFCs, PFCs & SF_6		Endo	Endo	Endo	Endo
	Stratospheric water vapour			-	-	Endo	-
	Ozone	O_3 strat.		Endo	Endo	Partly	-
		O_3 trop.		Endo	Endo	Partly	Endo
	Short-live gases	CO		-	-	-	Endo
		NMVOC				-	
		NOx				-	
	Aerosols (and precursors)	ERFari	BC	Endo	Endo	Partly	Endo
			Nitrate	Endo	Endo	Partly	Endo
			SO_2	Endo		Partly	Endo
			OC	Endo	Endo	Partly	Endo
			Dust	-	-	-	-
		Aerosol-Cloud		Endo	Endo	Endo	Endo
	Albedo	Surface Albedo RF		Endo	Endo	Endo	-
	Contrails & aviation-induced cirrus			-	Endo	-	-
	Volcanic eruptions			-	Exo	Exo	-
	Solar irradiance	Solar variability		-	Exo	Exo	Endo
Climate module	Heat exchange			Upwelling diffusion climate model	Top-of-atm. energy imbalance	Yes, light and heat, both in the atm. and ocean	Yes, ocean-atm. heat flux dynamics
	Climate sensitivity			Yes, time-variable	Yes	Yes	Yes

Submodule	FEATURES	MAGICC	FaIR	ESCIMO	HECTOR
		climate sensitivity			
	Oceanic heat uptake	Endo	Endo	Endo	Endo
Climatic Response	Mean Temperatures	Hemispheric & GMT	GMT, ocean	GMST	GMT & SOT
	Sea level variation	Endo	-	Endo	-
	Extreme wheatear events	-	-	-	-
	Ice cover	-	-	Endo	-
	Ocean acidification	-	-	Endo	Endo
Tipping points	Permafrost	Endo	Partly	Endo	Exo
	Coral reefs	-	-	-	-

Table 3. Resume of the review of ANEMI, BERNSCM, FUND and DICE. Source: Own elaboration.

Submodule	FEATURES		ANEMI	BernSCM	FUND	DICE
Emissions	Land use change CO_2 emissions		Endo	Exo	Exo	Exo
	Anthropogenic CO_2 emissions		Partly	Exo	Endo	Endo
	N_2O emissions		-	Exo	Exo	-
	Fossil fuel CH_4 emissions		-	Exo	Exo	-
	Natural CH_4 emissions		Endo	Exo	Exo	-
	Agriculture CH_4 emissions		-	Exo	Exo	-
	Tropospheric aerosols		-	Exo	-	-
	Ozone precursors		-	Exo	-	-
	Halogenated gases		-	Exo	-	-
Main GHG cycles	Terrestrial carbon cycle		Endo	Endo with 4 boxes	Endo with 5 boxes	Endo
	Ocean carbon cycle		Endo	Endo	-	-
	CH_4 cycle		Endo	-	Endo	-
	N_2O cycle		Endo	-	Endo	-
	Other GHG's cycles		Partly	-	Endo	-
	Water vapour		Endo, 5 boxes model	-	-	-
RF	Carbon dioxide		Endo	Endo	Endo	Endo
	Other well-mixed GHGs (long-live gases)	CH_4 RF	Exo	Endo	Exo	Exo
		CH_4 oxidation	-	-	-	Exo
		N_2O	Exo	Endo	Exo	Exo
		MP gases	Exo	-	Exo	Exo
		HFCs, PFCs & SF_6	Exo	Endo	Exo	Exo
	Stratospheric water vapour		-	-	-	-
	Ozone	O_3 strat.	Exo	-	-	-

Submodule	FEATURES			ANEMI	BernSCM	FUND	DICE
		O_3 trop.		Exo	-	Exo	-
	Short-live gases	CO		-	-	Exo	-
		NMVOC		-	-	Exo	-
		NOx		-	-	Exo	-
	Aerosols (and precursors)	ERFari	BC	-	-	-	-
			Nitr.	Exo	-	Exo	-
			SO_2	-	Exo	Exo	-
			OC	-	-	Exo	-
			Dust	-	-	-	-
		Aerosol-Cloud		-	-	-	-
	Albedo	Surface Albedo RF		-	-	-	Endo
	Contrails & aviation-induced cirrus			-	-	-	-
	Volcanic eruptions			Exo	-	-	-
	Solar irradiance	Solar variability		Exo	-	-	-
Climate module	Heat exchange			0-dimensional global model	Climate impact module	-	Heat dynamics ocean-atm.
	Climate sensitivity			Yes, exo	Yes, 3°C	Yes, 3°C	Yes, 1,8°C
	Oceanic heat uptake			Endo	-	-	Endo
Climatic Responses	Mean Temperatures			GMST & SAT	GMT & regional	-	Ocean, atmosphere & GST.
	Sea level variation			-	Endo	-	Endo
	Extreme wheatear events			-	-	-	-
	Ice cover			-	-	-	-
	Ocean acidification			-	-	-	-
Tipping points	Permafrost			-	-	Exo	Exo
	Coral reefs			-	-	-	-

Table 4. Resume of the review of GREB, CICERO-SCM, EMGC and OSCAR. Source: Own elaboration.

Submodule	FEATURES	GREB	CICERO-SCM	EMGC	OSCAR
Emissions	Land use change CO_2 emissions	-	Exo	Exo	Endo
	Anthropogenic CO_2 emissions	-	Exo	-	Exo
	N_2O emissions	-	Exo	-	Exo
	Fossil fuel CH_4 emissions	-	Exo	-	Exo
	Natural CH_4 emissions	-	Exo	-	Endo
	Agriculture CH_4 emissions	-	Exo	-	Exo

Submodule	FEATURES			GREB	CICERO-SCM	EMGC	OSCAR
	Tropospheric aerosols			-	Exo	-	Exo
	Ozone precursors			-	-	-	Exo
	Halogenated gases			-	Exo	-	Exo
Main GHG cycles	Terrestrial carbon cycle			-	Endo	Partly	Endo
	Ocean carbon cycle			-	Endo	-	Endo
	CH_4 cycle			-	Endo	-	Endo
	N_2O cycle			-	Endo	-	Endo
	Other GHG's cycles			-	Endo	-	Endo
	Water vapour			Yes, hydrological cycle	-	-	Partly
RF	Carbon dioxide			Endo	Endo	Exo	Endo
	Other well-mixed GHGs (long-live gases)	CH_4 RF		-	Endo	Exo	Endo
		CH_4 oxidation		-	Endo	Exo	Endo
		N_2O		-	Endo	Exo	Endo
		MP gases		-	Endo	Exo	Endo
		HFCs, PFCs & SF6		-	Endo	Exo	Endo
	Stratospheric water vapour			-	-	-	-
	Ozone	O_3 strat.		-	Endo	Exo	Endo
		O_3 trop.		-	Endo	Exo	Endo
	Short-live gases	CO		-	-	Exo	-
		NMVOC				Exo	
		NOx				Exo	
	Aerosols (and precursors)	ERFari	BC	-	Exo	Exo	Endo
			Nitrate		Exo	-	Yes, Endo
			SO_2		Exo	-	-
			OC		Exo	-	-
			Dust		-	-	-
		Aerosol-Cloud		Cloud albedo	Just indirect effect of sulphates	-	-
	Albedo	Surface Albedo RF		Endo	Exo	Exo	Endo
	Contrails & aviation-induced cirrus			-	Exo	-	Exo
	Volcanic eruptions			-	Exo	Exo	Exo
	Solar irradiance	Solar variability		-	Exo	Exo	Exo
Climate module	Heat exchange			Heat transport & atm. exchange	Upwelling-diffusion model	Exo	Yes, only at global scale

Submodule	FEATURES	GREB	CICERO-SCM	EMGC	OSCAR
	Climate sensitivity	Yes	Yes, 2-2,5°C	Yes	Yes
	Oceanic heat uptake	Endo	Endo	Endo	Endo
Climatic Responses	Mean Temperatures	GMST	GMST & NSHT	SST & GMST	GST & deep ocean
	Sea level variation	-	Endo	-	-
	Extreme wheatear events	-	Endo	-	-
	Ice cover	Endo	-	-	Endo
	Ocean acidification	-	-	-	-
Tipping points	Permafrost	-	-	-	-
	Coral reefs	-	-	-	-

* endo=endogenous; exo=exogenous; SST=Sea Surface Temperature; GST=Global Surface Temperature; SOT=Surface Ocean Temperature; SAT=Surface Air Temperature; NSHT=Near Surface Hemispheric Temperature

4.2 Analysis of GCMs

4.2.1 Analysis of the application of information from GCMs in RC Models

GCMs, as explain before, are usually used as standard references for climate modelling so they can be leveraged to calibrate and validate the outputs of SCMs. Additionally, some SCMs take the outputs of GCMs as own exogenous variables (instead of taking them from databases). However, the larger drawback of global models is that they are very complex and difficult to run, contrary to the speed of simple models (Knutti & Sedlácek, 2016). Thus, some of the uses of GCMs in the SCMs reviewed are shown below:

4.2.1.1 As exogenous inputs

SCMs can use outputs from GCMs as exogenous variables that act as inputs to equations and other features. The information provided by GCMs is assumed to be very accurate, so some of their outputs, such as GHG emissions or volcanic eruptions, are utilised by SCMs to calculate temperatures, precipitation, etc. Some examples of SCMs applying data from GCMs are listed below and shown in the Table 5.

a) BernSCM: it uses output data from the CMIP3 and CMIP5, in particular CESM, HadGEM and MIROC. The variables where this data is applied are: emissions (anthropogenic CO_2 emissions), radiative forcing (CH_4, N_2O, HFCs, PFCs, SF_6, stratospheric and tropospheric O_3 and some aerosols such as nitrates and organic carbon), volcanic activity and solar radiation (Strassmann & Joos, 2018).

b) CICERO-SCM: it takes input data from NorESM-GCM. The data is relative to: sea surface temperature and sea ice extent.

c) ESCIMO: it uses data from EC-Earth GCM (surface temperature and sea ice extent). (Skeie, Berntsen, Aldrin, & Holden, 2018).

d) OSCAR: the emissions from several gases such as CH_4, NOx, CO, VOCs, SO_2 and NH_3 are based on a GCM intercomparison project called ACCMIP (Atmospheric Chemistry and Climate Model Intercomparison Project) (Gasser, Ciais, Boucher, Quilacaille, & Tortora, 2017).

e) ANEMI: this model does not take outputs of GCMs to use them as exogenous variables, but for a temporal and spatial disaggregation. ANEMI offers the possibility to disaggregate climate variables such as temperature and rainfalls from yearly global values to monthly regional/local data. This process is carried out through a linear regression which needs parameters of data matrixes and these are taken from GCMs. This spatial disaggregation can serve as an example for the development of the second activity of *Task 3.2 (geographical distribution of global variables values in the IAM)* (Breach & Simonovic, 2021), (Akhtar, Simonovic, & Wibe, 2011).

f) EM-GC: the model takes TSI (total solar irradiance) time series from the CMIP6 for the range of 1850-2014. Moreover, the time series for SAOD (Stratospheric aerosol optical depth) is a mix of values computed from extinction coefficients for the CMIP6 GMCs and the GloSSAC (McBride, Hope, & Canty, 2021).

Table 5. Exogenous variables taken from GCMs. Source: Own elaboration.

Models	Features	List of variables
Bern-SCM // Oscar	Emissions	CH_4, NOx, CO, VOCs, NH_3, CO_2, N_2O, KT, MT
CICERO-SCM	Planetary Boundary (Ice melting)	Sea ice extent
BERN-SCM // EM-GC	Radiative Forcing	GHGs, Total Solar Irradiance, Aerosols (SAOD), Volcanic activity
CICERO-SCM	Climatic response: Mean temperatures	Surface temperature
ANEMI	Spatial and temporal disaggregation	Surface temperature and Precipitations

4.2.1.2 For calibration

In order to validate their own parameters and results, SCMs can calibrate their outputs and coefficients with their GCM equivalents so as to verify potential deviations and uncertainties, as GCMs are much more precise thanks to their complexity. In the following paragraphs, several examples of SCMs calibrated with GCMs are described and gathered in the Table 6.

a) C-ROADS (Fiddaman, Siegel, Sawin, Jones, & Sterman, 2017): this is the SCM included in WILIAM (adapted and improved as explained before). In particular, as explained in the Section 3.2 it includes the effect of temperature that leads to a decrease of the flux of C from the atmosphere to biomass due to rising temperature, and also the impact of temperature in carbon equilibrium between atmosphere and ocean (solubility). In particular, it assumes a “linear relationship”, which is driven by a sensitivity parameter, which can be modified by the user. The default value of this parameter that indicates the effect of temperature on flux of carbon to land is calibrated with the results found in (Friedlingstein, et al., 2006). In this article, 11 coupled climate-carbon cycle model are used and compared based on same historical and projected emissions from old IPCC scenarios. These 11 models showed (all) that climate change will increase the fraction of anthropogenic CO_2 emissions that remain airborne, being able to estimate the “additional warming” of this positive feedback. However, it is necessary to remark that there is still large uncertainty in this aspect.

The whole equation that includes the effect of the temperature is the following:

$$\mathrm{NPP} = \mathrm{NPP}_0\left(1+\beta_b \ln\frac{C_a}{C_{a,0}}\right) * \text{Effect of Warming on } C_{\text{flux to biomass}} =$$
$$= \mathrm{NPP}_0\left(1+\beta_b \ln\frac{C_a}{C_{a,0}}\right) * \left(1 + \text{Strength of T effect on C flux to land } * \ \Delta T_{\text{preindustrial}}\right)$$

Equation 5

where:

- NPP_0 is the reference Net Primary Production.
- β_b is the biostimulation coefficient.
- $C_{a,0}$ is the reference Carbon concentration in atmosphere (preindustrial).

The effect of warming on the flux of carbon from atmosphere to biomass is reflected as a fractional reduction. In particular, the effect is a reduction of the flux of C with rising temperatures. As can be seen in the equation, C-ROADS assumes a linear relationship (based on the range for warming by 2100). This relation is influenced by the “Strength of temperature effect” , in $\left(\frac{1}{^{\circ}\mathrm{C}}\right)$ on this carbon flux.

The whole effect of warming is described by the following equation:

$$\text{Effect of Warming on } C_{\text{flux to biomass}} =$$
$$= \left(1 + [\text{Sensitivity of } C_{\text{Uptake}} \text{to T} * \text{Strength of T effect on land } C_{\text{flux mean}}] * \ \Delta T_{\text{preindustrial}}\right)$$

Equation 6

where:

- Sensitivity of C_{Uptake} to T (temperature) is the coefficient that allows to control the strength of the feedback effect of temperature on the carbon uptake by land and oceans. This means that a coefficient of 0 means that there is not temperature-carbon uptake feedback, while a default of 1 yield to the average value found in (Friedlingstein, et al., 2006). By default, in WILIAM the value is therefore 1.
- And the Strength of T effect on $\text{land}_{\text{flux mean}}$ is the average effect of temperature on flux of carbon to land. This is precisely the parameter that is calibrated based on the average value found in (Friedlingstein, et al., 2006). In particular, the “default Sensitivity of C Uptake to Temperature” of 1 corresponds to the mean value from the 11 models tested.

On the other hand, the equation which represents the impact of temperature in carbon equilibrium between atmosphere and ocean (solubility) is the following:

$$\text{Equil}_{C_{\text{MixLayer}}} = C_{\text{pre-MixLayer}}\left(\frac{C_a}{C_{a,0}}\right) * \text{Effect of Warming on DIC pCO}_2 =$$
$$= \left(1 - \text{ Sensitivity of pCO}_2 \text{ DIC to Temperature} * \ \Delta T_{\text{preindustrial}}\right)$$

Equation 7

where:

- $\text{Equil\_C}_{\text{MixLayer}}$ is the equilibrium carbon content of mixed layer.
- $C_{\text{pre-MixLayer}}$ is the preindustrial carbon content in mixed layer.
- $Ca_{,0}$ is the reference C in atmosphere (preindustrial).

As can be seen in this equation, the model also assumes a linear relationship to reflect the reduction of solubility of CO_2 in the ocean with rising temperatures (based on the range for warming by 2100). This relation is influenced by the "Sensitivity of $\mathrm{pCO_2}$ (partial pressure of carbon dioxide) of dissolved inorganic carbon in ocean" to temperature, in $\left(\frac{1}{℃}\right)$.

The whole effect of warming is described by the following equation:

$$\begin{aligned}&\text{Effect of Warming on DIC pCO}_2 = \\ &= \left(1 - (\text{Sensitivity of C}_{\text{Uptake}} \text{ to T} * \text{Sensitivity of } \text{pCO}_2 \text{ DIC to T}_{\text{mean}}\,\right) \\ &* \Delta\text{T}_{\text{preindustrial}}\end{aligned}$$

Equation 8

where:

- Sensitivity of C_{Uptake} to T is the same coefficient as before, in particular here allows to control the strength of the feedback effect of temperature on the carbon uptake by oceans. C coefficient of 0 means that there is not feedback, while a default of 1 yield to the average value found in (Friedlingstein, et al., 2006). By default, in WILIAM the value is 1.
- And the Sensitivity of pCO_2 DIC to T_{mean} is the sensitivity of equilibrium concentration of dissolved inorganic carbon to temperature. This is precisely the parameter that is calibrated based on the average value found in (Friedlingstein, et al., 2006). In particular, the "default Sensitivity of C Uptake to Temperature" of 1 corresponds to the mean value from the 11 models tested.

b) BernSCM: the simulations of this SCM are compared to CMIP4 & CMIP5, among other intercomparison projects, i.e. the response to a CO_2 emission pulse to the atmosphere (Strassmann & Joos, 2018).

c) HECTOR: various calibration experiments are carried out in this model for a total of seven Hector parameters, mainly emissions-driven factors: four climate and three carbon-cycle parameters. The four climate parameters are the climatic sensitivity (S), ocean heat diffusivity (κ), the aerosol forcing scaling factor (α_a), and the volcanic forcing scaling factor (α_v). The three carbon-cycle parameters are preindustrial CO_2 concentration (ppm_v), the CO_2 fertilization factor (β, unitless), and the heterotrophic respiration temperature sensitivity factor (unitless). Through these parameters calibration, CO_2 concentration, ocean-heat flux and temperature are validated, using models like CCSM4, GFDL-CM3 or MRI-CGCM33 (from the CMIP5) (Dorheim, Link, Hartin, & Kravitz, 2020).

d) OSCAR: several parameters from different variables are calibrated in this model. This set of parameters is listed below (Gasser, Ciais, Boucher, Quilacaille, & Tortora, 2017):

  - Three CMIP5 models are used to calibrate two parameters (π_{mld} and γ_{mld}) related to the mixed-layer depth (h_{mld}) (Equation 9).

$$\boldsymbol{\Delta h_{mld} = h_{mld,0}\pi_{mld}(\exp\left[\gamma_{mld}\Delta T_s\right] - 1)}$$

Equation 9

where Δh_{mld} is the variation of the mixed-layer depth, π_{mld} represents the maximum relative intensity of the stratification and γ_{mld} represents the sensitivity to sea surface temperature change.

- The parameters for the transient response of npp ($\gamma_{npp,P}$ and $\gamma_{npp,T}$) can be calibrated on seven models of CMIP5 (Equation 10).

$$\Delta \mathrm{npp}^{i,b} = \eta^{i,b}(F^{i,b}_{fert}[\Delta CO_2](1 + \gamma^{i,b}_{npp,T}\Delta T^i_L + \gamma^{i,b}_{npp,P}\Delta P^i_L) - 1)$$

Equation 10

where the doublet $^{(i,b)}$ represents the "average" biome b of the i-th region, Δnpp represents the variation of the net primary productivity, η represents the preindustrial intensity, F_{fert} represents the CO2 fertilization function and ΔT_L, $\gamma_{npp,T}$, ΔP_L and $\gamma_{npp,P}$ are the changes in local surface temperature and local yearly precipitations and their linear sensitivities, respectively.

- Fire-related parameters (transient response of the wildfires: $\gamma_{igni,C}$, $\gamma_{igni,T}$ and $\gamma_{igni,P}$) are calibrated on four models of CMIP5.

- Global chemical sensitivities of tropospheric ozone drivers ($X^{O_{3t}}_{CH_4}$, $X^{O_{3t}}_{NOx}$, $X^{O_{3t}}_{CO}$, $X^{O_{3t}}_{VOC}$), CO, VOCs and NOx) and the sensitivity to global climate change (Γ_{O3t}) (Equation 11) are calibrated with several ACCMIP models, as well as methane-OH lifetime.

$$\Delta O_{3t} = X^{O_{3t}}_{CH_4} \ln\left[1 + \frac{\Delta CH_4}{CH_{4_0}}\right] + \Gamma_{O_{3t}}\Delta T_G + \sum_{x\epsilon(NOx,CO,VOC)} x^{O_{3t}}_x \sum_r \omega^r_x \sum_i \pi^{r,i}_{reg}(E^i_x + E^{x,i}_{bb})$$

Equation 11

- SO_4, SOA (Equation 12) and BC global lifetimes (τ_X) and climate sensitivities (Γ_x)

$$\Delta \mathrm{SOA} = \tau_{\mathrm{VOC}}(\mathrm{E}_{\mathrm{VOC}} + \sum_{\mathrm{i}} \Delta \mathrm{E}^{\mathrm{VOC,i}}_{\mathrm{bb}}) + \tau_{\mathrm{BVOC}}\Delta \mathrm{E}_{\mathrm{BVOC}} + \Gamma_{\mathrm{SOA}}\Delta \mathrm{T}_{\mathrm{G}}$$

Equation 12

- Global surface temperature is calibrated following a procedure of four steps based on changing the steady-state temperature at quadrupled CO_2 and fitting the parameters using a formula for a two-box model from GCMs (Gregory, Ingram, & Palmer, 2004).

e) MAGICC: in the preparation of the IPCC AR4, MAGICC was calibrated for 19 AOGCMs of the CMIP3. The calibrated parameters were: climate sensitivity; Land-Ocean warming ratio (RLO); vertical diffusivity in ocean (K_z); sensitivity of feedback factors to radiative forcing change (ξ); sensitivity of vertical diffusivity at mixed layer boundary to global-mean surface temperatures (dK_z/dT); land-Ocean heat exchange coefficient (k_{LO}); amplification factor for the ocean to land heat exchange (μ) (Meinshausen, Raper, & Wigley, 2011).

f) EM-GC: this model compares its outputs with corresponding GCMs ones (from CMIP6) through a metric called AAWR (attributable anthropogenic warming rate), the time rate of change in GMST due to humans from 1975-2014 (McBride, Hope, & Canty, 2021).

Table 6. Feature and Parameters from reviewed RC Models calibrated applying GCMs data.

Models	Features	List of key variables	Explanation//Parameters
Oscar	Ocean carbon cycle	Mixed-layer depth	π_{mld} and γ_{mld},
Oscar & Hector	Terrestrial carbon cycle	NPP & Heterotrophic respiration	β_{npp}, $\beta_{e,npp}$, CO_{2cp},…
Oscar	Tropospheric ozone	Tropospheric O_3 global chemical sensitivity; Global CC sensitivity	Global chemical sensitivities: χ^{O3t}_{CH4},χ^{O3t}_{NOx} … The sensitivity to global CC: Γ_{O3t}
Oscar	Mean temp.	GMST	-
Oscar	Aerosols DRF	Aerosols global lifetimes	For SO_4, POA, and BC, the apparent global lifetimes: τ_X
Hector	Carbon cycle	CO_2 concentration	-
Hector	Terrestrial carbon cycle	CO_2 fertilization factor	-
Hector & Magicc	Heat exchange	Ocean heat diffusivity	κ
Hector	Heat exchange	Ocean heat flux	Incoming and upward short and longwave radiation: S_d, L_d, S_u and L_u & sensible and latent heat flux: F_s and F_l

4.2.2 Review of information available from GCM models

Global climate projections are simulations based on different concentration scenarios of greenhouse gases (GHG), aerosols, and other atmospheric particles. These simulations provide the Earth's climate projections for future decades, typically until 2100. They are obtained using numerical Global Climate Models (GCMs) with coarse spatial resolution. GCMs are recognized as the most appropriate tools to understand future climate changes at global and regional scales, arising from natural factors and human influences like GHG emissions. CMIP6 is a collection of climate projections from around 100 different climate models produced by 49 modelling groups (Eyring, et al., 2016). These models are part of the Coupled Model Intercomparison Projects (CMIPs). CMIP6 data underpin the Intergovernmental Panel on Climate Change 6th Assessment Report (IPCC, 2021).

Projections in CMIP6 are based on assumptions called Shared Socioeconomic Pathways (SSPs), which represent projected global socioeconomic changes up to 2100. SSPs combine new narratives about future societal development with previous Representative Concentration Pathways (RPCs), describing trajectories of atmospheric GHG and aerosol concentrations over time. The purpose of SSP-based scenarios is to provide a consistent logic of primary causal relationships, capturing trends traditionally difficult for models to predict. The SSP-based scenarios range from very ambitious mitigation to ongoing growth in emissions. The most ambitious scenario aligns with the low end of the Paris Agreement global temperature goal, aiming to limit the increase in global temperature to well below 2°C above pre-industrial levels and pursue efforts to limit it to 1.5°C.

Eight CMIP6 climate models will be taken into account to enable the calculation of model ensembles and the assessment of the inter-model variability for the *Task 3.2 "Downscaling of climate information"*, which also includes the spatial disaggregation of global climate variables of WILIAM, and, therefore, the analysis has been also focused on these eight models. The chosen models are the following:

a) ACCESS-CM2 (Australia): it refers to the Australian Community Climate and Earth System Simulator - Coupled Model version 2 and it is designed to simulate and predict climate variability and change on a global scale, combining components of the atmosphere, ocean, land surface, and sea ice to create a comprehensive Earth system model. The model is based on the coupled general circulation model (CGCM) framework, which means that it simulates the interactions and feedbacks between different components of the Earth system. It takes into account factors such as solar radiation, atmospheric composition, greenhouse gases, ocean currents, sea ice dynamics, and land surface processes (Bi, et al., 2020).

b) CNRM-ESM2-1 (France): it is a climate model developed by the Centre National de Recherches Météorologiques (CNRM) in France. CNRM-ESM2-1 is a coupled climate model that simulates the interactions between the atmosphere, oceans, land surface, and sea ice. The model is used to study temperature, precipitation, wind patterns, ocean circulation, and the carbon cycle. It can be used to simulate historical climate conditions and project future climate scenarios under different greenhouse gas emission scenarios. CNRM-ESM2-1 contributes to international climate assessments, such as those conducted by the IPCC (Séférian, et al., 2019), (Voldoire, Saint-Martin, & Sénési, 2019).

c) IPSL-CM6A-LR (France): it is a climate model developed by the Institut Pierre-Simon Laplace in France. IPSL-CM6A-LR is a coupled Earth System Model that simulates the interactions among the atmosphere, oceans, land surface, and sea ice. The model is used to study various aspects of the Earth's climate, including temperature, precipitation, atmospheric circulation, ocean flows, and the carbon cycle. It is employed for simulating historical climate conditions and projecting future climate scenarios under different greenhouse gas emission scenarios. IPSL-CM6A-LR contributes to international climate assessments, such as those conducted by the IPCC, and helps in understanding the impacts of climate change on regional and global scales (Eyring, et al., 2016).

d) MIROC6 (Japan): MIROC6 (Model for Interdisciplinary Research On Climate) is a climate model developed by a consortium of research institutions in Japan. It is a coupled Earth System Model that simulates the interactions between the same components as the previous models. The atmospheric component is based on the MIROC, the oceanic component is based on the Model for the Oceanic General Circulation (MIROC-O), and the land surface component is based on the Community Land Model. The sea ice component is represented using the Los Alamos Sea Ice Model. It can be used for simulating historical climate conditions, projecting future climate scenarios under different emission scenarios, and assessing the impacts of climate change on regional and global scales. It undergoes continuous refinement and updates as new scientific understanding and observational data become available (Tatebe, Ogura, & Nitta, 2019).

e) NorESM2-MM (Norway): it is a climate model developed by the Norwegian Earth System Model (NorESM) community that focuses specifically on representing the marine biogeochemical processes in the Earth's climate system. It combines various modules such as an atmospheric and an oceanic component. The marine biogeochemical processes, including the carbon cycle and ocean ecosystem dynamics, are incorporated into NorESM2-MM using the Norwegian Marine Ecosystem Model. The model is used to study various aspects of the Earth's climate system, including temperature, precipitation, atmospheric circulation, ocean currents and marine biogeochemistry. It enables simulations of historical climate conditions, projections of future climate scenarios under different greenhouse gas emission scenarios, and assessments of the impacts of climate change on regional and global scales, with a particular focus on the marine environment. It undergoes ongoing development and improvement as new scientific understanding and observational data become available (Seland, Bentsen, & Seland Graff, 2020).

f) CESM2 (USA): CESM2 (Community Earth System Model version 2) is a state-of-the-art Earth system model developed by the National Center for Atmospheric Research and its collaborators. It is an advanced tool used for studying and simulating the interactions between the atmosphere, oceans, land surface, and sea ice in the Earth's climate system. The atmospheric component is based on the Community Atmosphere Model, which simulates atmospheric processes such as radiation, clouds, and precipitation. The oceanic component is based on the Parallel Ocean Program, which represents ocean dynamics and thermodynamics. The land component is based on the Community Land Model, and the sea ice component is represented using the Community Ice CodE. CESM2 also includes components for representing biogeochemical cycles, including carbon and nitrogen cycles. The model is used to study a wide range of climate phenomena and processes, including temperature changes, precipitation patterns, atmospheric circulation, ocean currents, sea ice extent, and carbon cycle dynamics. It undergoes continuous development and refinement as new scientific understanding and observational data become available (Danabasoglu, Lamarque, & Bacmeister, 2020).

g) EC-Earth3-Veg-LR (Europe): EC-Earth3-Veg-LR is a climate model developed by the EC-Earth consortium. It is an advanced Earth system model that incorporates vegetation dynamics and land surface processes to provide a more comprehensive representation of the interactions between the atmosphere, oceans, land surface, and vegetation. EC-Earth3-Veg-LR allows for the simulation of climate conditions, including temperature, precipitation, atmospheric circulation patterns, ocean currents, sea ice extent, and vegetation distribution. By including vegetation dynamics, it can capture feedbacks between the land surface and the atmosphere, such as the influence of vegetation on surface energy and water fluxes. This enables a more comprehensive understanding of the Earth's climate system and its response to external forcing. The model is used for a range of applications, including studying the impacts of climate change on ecosystems and the environment (Wyser, Lorenz, & Craig, 2020).

h) HadGEM3-GC31-LL (UK): HadGEM3-GC31-LL is a climate model developed by the Met Office Hadley Centre in the United Kingdom. It is an advanced Earth system model designed to simulate and study the interactions between the atmosphere, oceans, land surface, and cryosphere in the Earth's climate system. HadGEM3-GC31-LL enables simulations of historical climate conditions, future climate projections, and investigations of climate variability and change. It can be used to study various climate phenomena, including temperature patterns, precipitation, atmospheric circulation, ocean currents, sea ice extent, and interactions between different components of the Earth system (Williams, Copsey, & Blockley, 2020).

The Equilibrium Climate Sensitivity (ECS) of these models is shown in Table 7. The ECS indicates the long-term temperature rise (equilibrium global mean near-surface air temperature) that is expected to result from a doubling of the atmospheric CO_2 concentration.

Table 7. List of CMIP6 models. The table reports the Equilibrium Climate Sensitivity (ECS) in order to assess the GCMs climate sensitivity to CO_2. Source: Own elaboration.

GCMs	ECS (°C)
ACCESS-CM2	4,7
CESM2	5,2
CNRM-ESM2-1	4,8
EC-Earth3-Veg-LR	4,3
HadGEM3-GC31-LL	5,6
IPSL-CM6A-LR	4,6
MIROC6	2,6
NorESM2-MM	2,5

This review shows results aligned with the WILIAM climate sensitivity, which has a value of 3.0 °C. As previously explained, this WILIAM parameter was determined according to the evidence shown in the 2021 IPCC AR6 report for which the ECS is in a likely range between 2.5°C to 4°C, with the best estimate being 3°C.

In coordination with the objectives and the activities to deploy in other WPs and Task 3.2, it has been analysed the CMIP6 Essential Climate Variables (ECVs) projections for SSP2-4.5, and SSP5-8.5 pathways. These include the near surface air temperature: mean (tas), minimum (tsamin), and maximum (tasmax); the precipitation (pr) and the near surface wind speed (sfcwind). They cover 150 years (1950-2100) and are available at daily frequency. These variables could be used for WILIAM improvements during the development of Task 3.2 to spatially distribute the global temperature and rainfalls. It is important to mention that not all CMIP6 variables are available for all models and SSPs. Table 8 shows the different ECVs and their data availability.

Table 8. Variable availability for the daily CMIP6 GCMs. Source: Own elaboration.

CMIP6 GCMs	EXPERIMENT	tasmax (K) [daily]	tsamin (K) [daily]	tas (K) [daily]	pr (kg/m2·s) [daily]	sfcWind (m/s) [daily]
ACCESS-CM2	Historical	✓	✓	✓	✓	✓
	SSP245	✓	✓	✓	✓	✓
	SSP585	✓	✓	✓	✓	✓
CESM2	Historical	x	x	✓	✓	✓
	SSP245	✓	✓	✓	✓	✓
	SSP585	✓	✓	✓	✓	✓
CNRM-ESM2-1	Historical	✓	✓	✓	✓	✓
	SSP245	✓	✓	✓	✓	x
	SSP585	✓	✓	✓	✓	x
IPSL-CM6A-LR	Historical	✓	✓	✓	✓	✓
	SSP245	✓	✓	✓	✓	✓
	SSP585	✓	✓	✓	✓	✓
MIROC6	Historical	✓	✓	✓	✓	✓
	SSP245	✓	✓	✓	✓	✓
	SSP585	✓	✓	✓	✓	✓
NorESM2-MM	Historical	✓	✓	✓	✓	✓
	SSP245	✓	✓	✓	✓	✓
	SSP585	✓	✓	✓	✓	✓
EC-Earth3-Veg-LR	Historical	✓	✓	✓	✓	✓
	SSP245	✓	✓	✓	✓	x
	SSP585	✓	✓	✓	✓	x
HadGEM_GC3_LL	Historical	✓	✓	✓	✓	✓
	SSP245	✓	✓	✓	✓	✓
	SSP585	✓	✓	✓	✓	✓

As it is mentioned in the previous section, GCMs can be used to calibrate some coefficients of SCMs. The GCMs can provide information from regional climate patterns, biophysical impacts, extreme events etc. Table 9 presents some sub-modules where GCMs could be applied for calibrating other IAMs:

Table 9. Climate sub-modules that can be used by GCMs to calibrate IAMs

Model	Climate Project.	Regional Climate Patterns	Biophysical Impacts	Biogeochemical Flows	Extreme Events	Feedbacks
ACCESS-CM2	X	X	Sea level, Ocean circulation & Ecosystem dynamics			
CESM2	X	X		Carbon, nitrogen & phosphorus		
CNRM-ESM2-1	X	X			X	
IPSL-CM6A-LR	X	X	Sea level, Ocean circulation & Ecosystem dynamics			Atmosphere, ocean, and land surface
MIROC6	X					
NorESM2-MM	X	X				
EC-Earth3-Veg-LR	X	X	Sea level, Ocean circulation & Ecosystem dynamics			
HadGEM_GC3_LL	X	X	Sea level, Ocean circulation & Ecosystem dynamics	Carbon, nitrogen & phosphorus	X	

From this table, it is possible to detect some features that could be interesting to analyse comprehensively as GCMs information could be applied for improving WILIAM climate module. These are listed below:

1. On the one hand, both climate projections and **regional climate patterns** (which appear in almost all of the GCMs) will be utilised in order to correlate WILIAM climate inputs with necessary to carry out the downscaling of global climate variables that will be carried out in Task 3.2.
2. As in (1) the GCMs climate variables will be used to define **extreme events** and correlate their probability of occurrence with WILIAM climate inputs. As such, it could be useful for calibrating this type of phenomena in WILIAM. Furthermore, the calibration on extreme events will permit the analysis of extreme scenarios with extreme values of CO2 levels deriving from natural sources (e.g. volcanoes, wildfires etc.), thus, indirectly assessing the impact on climate of such events. This will be further explored in Task 3.3
3. Finally, **sea level rise** is a feature already included in WILIAM that could be **calibrated** as well as spatially distributed in order to also, in posterior steps (Work Package 4: climate change impacts in WILIAM), determine the related climate change impacts on land. This is something already started in LOCOMOTION project. Moreover, some feedback mechanisms related to temperature in the atmosphere-ocean-land loops could add accuracy to the IAM if contrasted with GCM information.

5 STEP 2 – Selection and Prioritisation

5.1 Selection and prioritization criteria

In order to select and then prioritize the potential improvements or new features to be included in WILIAM, it has been established a set of criteria based on: (i) **the necessity of implementing** the feature because of its importance for the rest of activities in NEVERMORE (e.g. calculation of climate change impacts or the inclusion of planetary boundaries); and (ii) **the feasibility of implementing/integrating** it in WILIAM either directly or through a proxy. Both conditions are rated with values which range from 1 (least feasible or needed) to 3 (realizable, possible implementation and essential) and these ratings depend on several factors:

- Necessity: After reviewing the current features of the WILIAM model as well as those mostly included in other SCMs, some functionalities were detected as potential improvements (see Table 10). Thus, the new features were grouped in four broad categories: 1) planetary boundaries (related to Task 3.3), 2) geographical distribution of climate variables (related to Task 3.2), 3) tipping points and 4) additional variables of interest included in other SCMs that could be useful also for delivering climate change impacts in WILIAM (WP4 related Tasks).

  All planetary boundaries were considered very important as their inclusion brings a very high value to the model (in fact T3.3 is very focused on this) and so these features were rated as necessary (i.e. with a value of 3) while the remaining functionalities depended on a somewhat more subjective criterion determined mainly by CARTIF, in consultation with the other partners involved in this task.

  In addition, it was also taken into account whether the drivers of these features can be endogenously calculated in WILIAM, i.e., whether the impacts of these features can be modelled in it, in order to have really endogenous this potential new feature and fully integrated into WILIAM IAM and its emissions scenarios. These two considerations serve to determine whether the feature fits the capabilities of the studied model. After all, following these three parameters (drivers, impacts and feature type), each was scored from 1 to 3.

- Feasibility: The potential inclusion of new features mainly depends on the process to link them to specific variables in the model avoiding potential double accounting, respecting the same approach, assuring alignment, etc. For this it is important to analyse if there are variables similar to the one to be included, if there is open or accessible information on databases, etc. Thus, the first condition taken into consideration was if the feature is included in other SCMs or GCMs, giving greater importance to those models that, like WILIAM, are modelled also with the system dynamics technique (e.g. ANEMI, ESCIMO and FELIX), which would facilitate the integration in WILIAM.

  Next, the method for coupling that feature to WILIAM or including it through variables that make the link to this new feature, were analysed, as well as the data sources necessary in each case. Finally, before implementing a new characteristic in WILIAM that is based on a different model, it is necessary to respect the copyright requirements of the original modellers, either by citing them and by consulting them if they agree with this application of their model.

  In the best case, a feature could be rated with a value of 3 (very feasible implementation) if it is endogenously calculated in a system dynamics model, whose information is easily accessible and does not present copyright problems.

According to both necessity and feasibility, each feature received a final valuation (see

Table 11) that has been used to decide which one is prioritized over other to explore in more detailed the method for their implementation in WILIAM.

A final rating above 2 leads to the implementation of that functionality or at least to a thorough exploration of it. If the score ranges between 1-2, the feature is not expected to be included in this project but is not ruled out for implementation in future ones. Finally, a value below 1 means that the functionality is too difficult to implement or not interesting enough to make an effort.

Table 10. List and description of potential new features and improvements analysed. Source: Own elaboration.

Features analysed	Description	Task related	Indicators (Planetary boundary)	Drivers included endogen. in WILIAM?	Is it a PB?	Related to impacts to be modelled by WILIAM?
Planetary boundaries						
Stratospheric ozone depletion	Gradual thinning of the ozone layer caused by ODSs	3.3. Planetary boundaries	-EESC concentration -O3 concentration	No	Yes	No
Regional freshwater withdrawal proportion available freshwater resources	Regional freshwater withdrawal exceeds the available resources	3.3. Planetary boundaries	-Maximum amount of blue water use; -Water stress resources	-	Yes	No
Ocean acidification	Reduction in the pH of the ocean over an extended period of time, caused primarily by uptake of carbon dioxide	3.3. Planetary boundaries	-pH of ocean; -Aragonite saturation state	Yes	Yes	Yes
Biogeochemical Flows: Phosphorous	Movement of P between various boxes (rocks, sediments, water, soil and plants)	3.3. Planetary boundaries	-Systems in the ocean; -Erodible soils	No	Yes	No
Biogeochemical Flows: Nitrogen	Conversion of atmospheric N into a useful form for living organisms, primarily through nitrogen fixation.	3.3. Planetary boundaries	-Industrial and Intentional biological fixation of N	No	Yes	No
Climate change	Long-term shifts in global weather patterns and temperatures, caused by increased GHG levels	3.3. Planetary boundaries	-CO2 atmospheric concentration; -Energy imbalance at top-of-atm.	Yes	Yes	Yes
Atmospheric aerosol loading	Amount of small particles in the air, which can affect climate, human health, and ecosystem functioning.	3.3. Planetary boundaries	-Aerosol Optical Depth (AOD) -% of Anthr. AOD of total	No	Yes	No
Biosphere integrity	Extinction of species and loss of ecosystem services due to irreversible damage to ecosystems	3.3. Planetary boundaries	-Extinction rate; -Primary Forest Surface;	No	Yes	No

Features analysed	Description	Task related	Indicators (Planetary boundary)	Drivers included endogen. in WILIAM?	Is it a PB?	Related to impacts to be modelled by WILIAM?
Land system change	Human-induced changes to natural ecosystems, transforming natural soils into agricultural, urban or other soils.	3.3. Planetary boundaries	-Annual forest stock change; -% Biome; -Area off forested land as % of original forest cover	Yes	Yes	Yes
Additional features (common in other SCMs)						
Other albedos (clouds & aerosol scattering)	These three features are all related to the solar wave reflection, better known as albedo. Solar waves can be reflected / scattered by land or by clouds and this phenomena varies depending on the type of cloud, aerosol or land implicated	3.1. Improvement of the climate module	-Low cloud albedo; -High cloud albedo; -Aerosol scattering	No	No	Yes
Earth's surface albedo		3.1. Improvement of the climate module	-Albedo from land biomes; -Albedo from ocean and ice	Yes	No	Yes
Black carbon on snow		3.1. Improvement of the climate module	Black carbon on snow radiative forcing	No	No	Yes
Tipping Points						
Permafrost collapse: Carbon release	Perennial ice layer on the ground that locks up large amounts of carbon in form of dead plants and biomass whose melting release CO2 and CH4	3.4. Uncertainty-Tipping Points	CH4 release//capture from permafrost	Yes	No	Yes
Coral Reefs Die-off	Temperature rise and ocean acidification lead to the bleaching and disappearance of coral reefs	3.4. Uncertainty-Tipping Points	pH threshold	Yes	No	Yes
Variables from GCMs						

Features analysed	Description	Task related	Indicators (Planetary boundary)	Drivers included endogen. in WILIAM?	Is it a PB?	Related to impacts to be modelled by WILIAM?
Regional Sea Level Rise	Both calibration and geographical distribution of sea level rise	3.2. Downscaling of climate information // 4.2. Impacts and risks	Global sea level rise	Yes	No	Yes
Extreme Weather Events (EWEs)	Use of proxy variables such as evaporation, wind strength, rainfall, etc. to calculate indicators of EWEs, e.g. fires (burnt area) or floods (flooded area and flood height)	3.2. Downscaling of climate information // 4.2. Impacts and risks	Climate variables from GCMs	No	No	No
Regional climate variables	Regionalisation of climate variables derived from GCM information such as: Regional Mean Surface Temperature, Annual precipitations, Maximum and Minimum Annual Temperatures, etc.	3.2. Downscaling of climate information	-GMST change; -Variables from GCMs	Some of them	No	Yes

Table 11. Prioritization/rating of the analysed features. Source: Own elaboration.

Features analysed	Necessity rating (1 to 3) *	Explanation of the necessity rating	From what RC Models or GCMs can this information obtained?	Comments	Feasibility rating (1 to 3) **	Final valuation (1 to 3)***
Planetary boundaries						
Stratospheric ozone depletion	2	It is a PB but drivers and impacts are not endogenous	**RC Models**: MAGICC, FaIR, CICERO, OSCAR	Quite developed in several models	3	2,5

Features analysed	Necessity rating (1 to 3) *	Explanation of the necessity rating	From what RC Models or GCMs can this information obtained?	Comments	Feasibility rating (1 to 3) **	Final valuation (1 to 3)***
Regional freshwater withdrawal proportion available freshwater resources	-	Partially implemented. Not part of WILIAM's climate module (see T3.3)	**GCMs**: HadGEM2-ES, IPSL-CM5A-LR	Need improvements that have to addressed in a future work	-	-
Ocean acidification	3	It is a PB and both drivers and impacts are endogenous	**RC Models:** OSCAR, BERN, ANEMI, ESCIMO **GCMs**: IPSL-CM5A-LR, HadGEM2-ES, CESME1	Easy to implement based on literature	3	3
Biogeochemical Flows: Phosphorous	2	It is a PB but drivers and impacts are not endogenous	**RC Models**: ANEMI, BERN **GCMs**: HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM	ANEMI as a System Dynamics model could be the basis	2	2
Biogeochemical Flows: Nitrogen	2	It is a PB but drivers and impacts are not endogenous	**RC Models**: ANEMI, BERN, CICERO, Hector, Oscar **GCMs**: HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM	Included in several models; ANEMI as main reference	2	2
Climate change	-	Already implemented	**RC Models**: All **GCMs**: HadGEM GC3 LL, IPSL-CM6A-LR, MIROC6	-	-	-
Atmospheric aerosol loading	2	It is a PB but drivers and impacts are not endogenous	**RC Models**: MAGICC, FaIR, HECTOR, OSCAR and ESCIMO **GCMs**: GISS ModelE, ECHAM5/MPI-OM, CESM1-CAM5	Aerosol DRF is easy to calculate, It is not very direct the PB indicator	2	2
Biosphere integrity	-	Not related to WILIAM's climate module (see T3.3)	**RC Models**: FeLiX **GCMs**: MIROC-ESM, HadGEM2-ES, PSL-CM5A-LR	Not very developed feature that is been addressed in other projects	-	-

Features analysed	Necessity rating (1 to 3) *	Explanation of the necessity rating	From what RC Models or GCMs can this information obtained?	Comments	Feasibility rating (1 to 3) **	Final valuation (1 to 3)***
Land system change	-	Partially implemented. Not part of WILIAM's climate module (see T3.3)	**GCMs**: MIROC-ESM, HadGEM2-ES, PSL-CM5A-LR	-	-	-
Additional features (common in other SCMs)						
Other albedos (clouds & aerosol scattering)	1	Although it is relevant for temperature change, it is hard to be related with other modules	**RC Models:** MAGICC, FaIR, ESCIMO & OSCAR **GCMs**: CESM, MIROC-ESM, HadGEM2-ES	Some of them only include the cloud albedo, while others combine both. ESCIMO could be a good source of information.	2	1,5
Earth's surface albedo	2	It can be related to land use changes	**RC Models**.: ESCIMO, MAGICC, FaIR, ANEMI	ESCIMO (SD) could be guideline, but some variables could be difficult to implement	1,5	1,75
Black carbon on snow	1	Its effect on albedo is not entirely clear and its contribution may not be very important	**RC Models**: OSCAR, FaIR **GCMs**: CESM, MIROC-ESM, HadGEM2-ES"	The models in which it is included are not SD so their implementation might be difficult	1	1
Tipping Points						
Permafrost collapse: Carbon release	2,5	Its contribution to the RF can be quite important	**RC Models**: MAGICC and ESCIMO,	There is a lot of literature uncertainty and the modules are often quite complex.	1	1,75

Features analysed	Necessity rating (1 to 3) *	Explanation of the necessity rating	From what RC Models or GCMs can this information obtained?	Comments	Feasibility rating (1 to 3) **	Final valuation (1 to 3)***
Coral Reefs Die-off	2	Important for T4.2	None	Easy to implement based on literature	3	2,5
Variables from GCMs						
Regional Sea Level Rise	1,5	Validation and regionalisation of WILIAM's impact	**GCMs**: ACCESS-CM2, IPSL-CM6A-LR, Earth3-Veg-LR & HadGEM_GC3_LL	Data can be extracted and aggregate to match WILIAM	1	1,25
Extreme Weather Events (EWEs)	2	Important for T3.3	**GCMs**: CNRM-ESM2-1 & HadGEM_GC3_LL	Data can be created by post processing GCMs data and aggregate to match WILIAM	3	2,5
Regional climate variables	2	Important for T3.2	**GCMs:** ACCESS-CM2, CESM2, CNRM-ESM2-1, IPSL-CM6A-LR, NorESM2-MM, EC-Earth3-Veg-LR & HadGEM_GC3_LL	Data can be created by post processing GCMs data and aggregate to match WILIAM	2	2

*Necessity rating → 1= not very necessary, 2 =necessary, 3 = high priority/limiting;

**Feasibility rating → 1: challenging, 2: moderate difficulty, 3: easy to implement

**Final rating →Final feature rating: <1: it will not be performed, between 1-2: it could be explored in future projects, >2: it will be performed or comprehensively explored

5.2 Preliminary improvements and new functionalities selected

After analysing the WILIAM model to detect possible shortcomings in terms of functionalities and carrying out a review of literature and other SCMs, a set of features that would provide great added value to the model has been rated and, based on that feasibility + necessity rating (previous section), prioritized.

Those features with a rating below 1 have not been considered as a functionality to be implemented, while those with a rating between 1 and 2 will be initially explored for potential future implementation, but the actual feasibility still needs to be determined. Those with a rating above 2 will be deeply explored as they will be implemented during this project. The preliminary selected features or improvements are listed below:

Table 12. Preliminary selected features.

Feature group	Feature selected	Final rating	Selected?	Detailed analysis (section)
Planetary boundaries	Stratospheric ozone depletion	2.5	To be implemented	5.2.4
	Regional freshwater withdrawal proportion freshwater resources	-	Discharged	-
	Ocean acidification	3	To be implemented	5.2.5
	Biogeochemical Flows: Phosphorous	2	To be implemented	5.2.2
	Biogeochemical Flows: Nitrogen	2	To be implemented	5.2.2
	Climate change	-	Discharged	-
	Atmospheric aerosol loading	2	To be implemented	5.2.6
	Biosphere integrity	-	Discharged	-
	Land system change	-	Discharged	-
Additional features (common in other SCMs)	Other albedos (clouds & aerosol scattering)	1.5	Initial exploration	-
	Earth's surface albedo	1,75	Initial exploration	5.2.1
	Black carbon on snow	1	Discharged	-
Tipping Points	Permafrost collapse: Carbon release	1.75	Initial exploration	5.2.3
	Coral Reefs Die-off	2.5	To be implemented	-
Variables from GCMs	Regional Sea Level Rise	1,25	Initial exploration	5.3
	Extreme Weather Events (EWEs)	2,5	To be implemented	5.3
	Regional climate variables	2	To be implemented	5.3

After the selection of these features, a deeper analysis with respect is conducted in order to analyse with detail the structure of the feature that will serve as a basis to define the method that will be used for their integration in WILIAM (STEP 3- Implementation).

The following sections establishes a theoretical framework and contextualisation of the feature and/or improvement selected, as well as (in cases where the feature is based on another model) an explanation of the structure of the feature and main variables involved

5.2.1 Albedo

This part is not modelled in WILIAM as all the radiative forcing due to this effect is included exogenously in WILIAM. For this objective the most feasible option is to rely on another SCM such as ESCIMO to create this new submodule. The reference SCM considers several types of albedo to calculate a variable called "Reflected Solar Short Wave". Therefore, the albedo value is the result of adding the "Albedo of Land Biomes", the "Albedo of Ocean with Artic Ice Changes", the "Cloud Albedo" and the "Atmospheric Scattering".

The "Albedo of Land Biomes" includes the albedo caused by various biomes such: desert, urban areas, barren land, northern forests, tundra, grasslands, tropical forests, and ice on land. In turn, barren land takes into consideration both white and normal land, whereas deforested and burnt tundra, grasslands and tropical and northern forests are also covered by their corresponding variables. Finally, the "Ice on Land Albedo" includes the albedo of Greenland, Antarctica and glaciers other than those of the Arctic.

The "Albedo of Ocean with Artic Ice Changes" combines the albedo of both Artic Ice on Sea and Open Ocean. This variable is as well a key part of the Ice Melting feature which could be a potential new feature of WILIAM in the future. The "Cloud Albedo" calculates the effect of both low- and high-density clouds on how they reflect the incoming solar radiation.

The "Atmospheric Scattering" refers to the reflection of solar radiation under clear sky conditions. It depends on the incoming solar radiation and the net radiative forcing of aerosols as these compounds can absorb or scatter the radiation.

Three diagrams representing the different types of albedo are shown in Figure 34 and Figure 35.

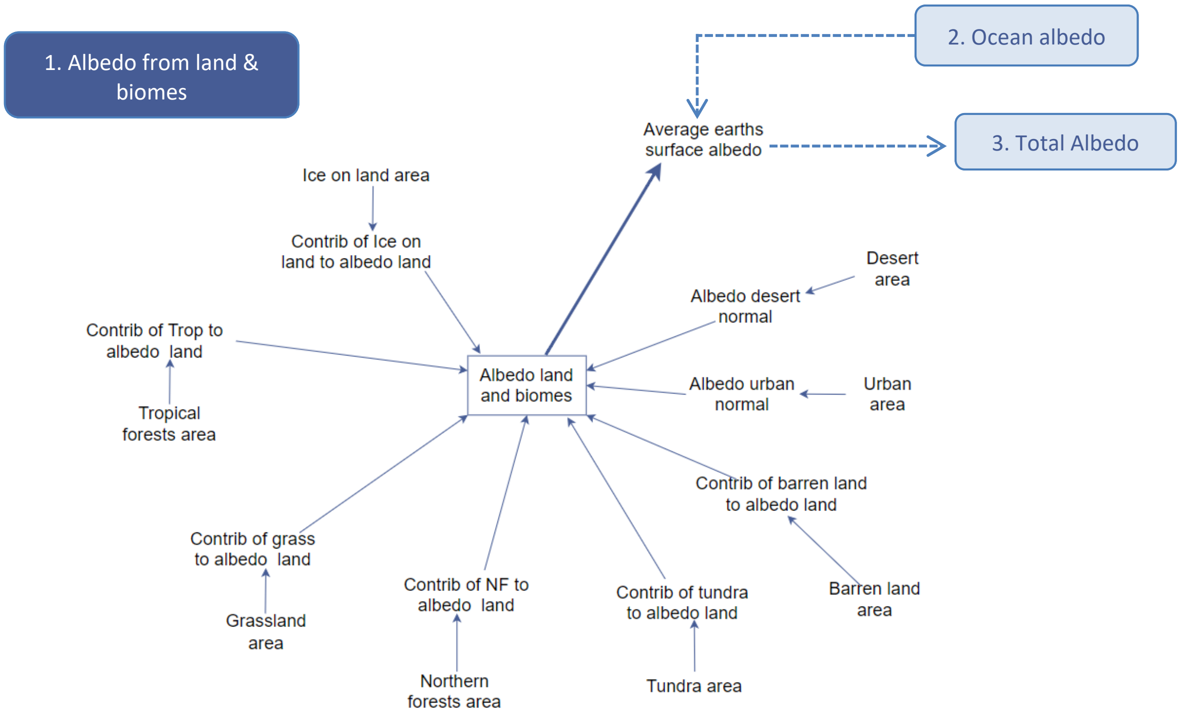

Figure 34. Land and biomes albedo representation view including the links with the other views. Source: Simplified scheme based on ESCIMO model (Randers, Golüke, & Wenstop, 2016).

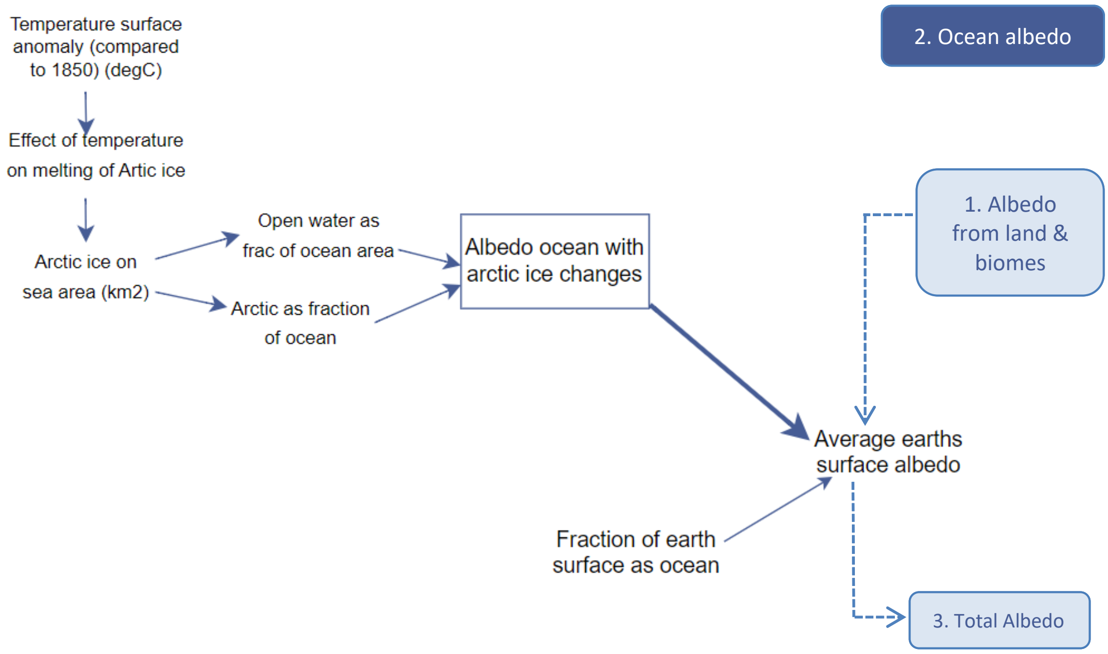

Figure 35. Albedo ocean representation. Source: Simplified scheme based on ESCIMO model (Randers, Golüke, & Wenstop, 2016).

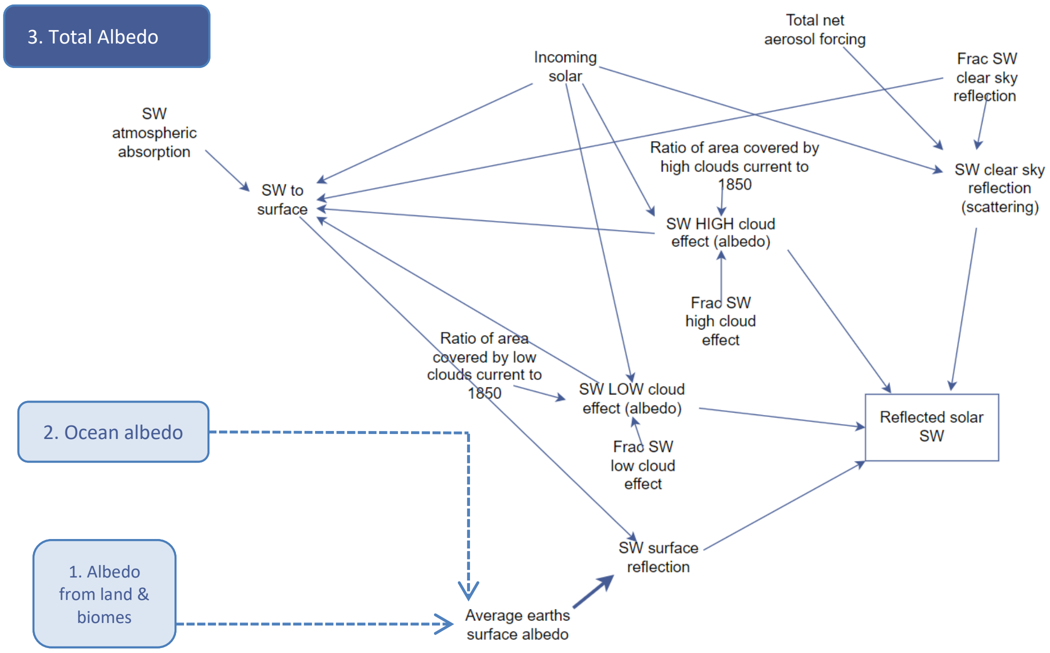

Figure 36. Other types of albedo & total albedo representation. Source: Simplified scheme based on ESCIMO model (Randers, Golüke, & Wenstop, 2016).

5.2.2 Biogeochemical cycles

The concentration of nutrients in surface waters can be used as an indicator to measure the water quality globally. These nutrients get into the water cycle as wastewater and agricultural inputs, being the main contributors to water quality degradation.

As in the case of the albedo, nutrient cycles are not incorporated in WILIAM, so a predefined framework is needed, this being the ANEMI model. This SCM introduces a "nutrient cycles" submodule to calculate the amount of total nitrogen and phosphorus-based nutrients in surface water in order to determine the water degradation. These compounds are not fixed, but move from several reservoirs, such as vegetation, soils, rivers, coastal waters and oceans (as well as the atmosphere in the nitrogen cycle) (Breach & Simonovic, 2021).
The cycles of nutrients can be represented with a quasi-steady-state model composed of sinks and sources. The transport processes follow a first-order decay relationship, assuming an initial steady-state condition from which the model is perturbed to account for human influence, mainly on the surface water element (domestic and industrial wastewater and agricultural runoff) (Breach & Simonovic, 2018).

5.2.2.1 Phosphorous cycle

P is a vital nutrient for vegetation development, and, as it occurs with the nitrogen cycle, its sources and transport processes are comparable to those of carbon cycle. The key difference is that phosphorous compounds are transported as runoff or as aerosols during the attachment of sediments. As the deposition of the P aerosols is relatively quick, this cycle does not usually include an atmospheric component (den Elzen, Beusen, & Rotmans, 1997).

Within this biogeochemical sub-module, four main boxes can de distinguished: land, river, coastal and ocean phosphorous. Each of these boxes apart from rivers is, in turn, composed by several sub boxes: land biota, humus and inorganic soil (land); coastal waters, biota and sediments; and surface, biota and deep ocean.

The main anthropogenic input of phosphorous takes place in the rivers box due to the wastewater discharge. These water streams contain this chemical compound as a result of industrial, domestic and agricultural activities. Industrial and domestic wastewaters are a mix of untreated, treated and reused water, while the agricultural phosphorous comes from leaching on arable land. In addition, phosphorous also gets into the cycle naturally, via the inorganic soil uplift. In contrast, it leaves the cycle through the burial of coastal and deep ocean sediments and through the fraction of water from rivers that is used for human supply.

Regarding Task 3.3, the global indicator for the planetary boundary is the phosphorous flow that goes from freshwater systems (lakes and rivers) into the oceans (Carpenter & Bennett, 2011), (Steffen, et al., 2015). Thus, in ANEMI, there is a variable called "Coastal-Open P", which would be the most appropriate proxy to represent this indicator. As the model calculates it as a molar flow (nP/year), Equation 13 is used to express the result in the proper units (TgP/year):

$$\text{Phosphorous flux (Tg P/year)} = \text{Mm (gP/nP)} * \text{ANEMI's P flux (nP/year)} * \frac{1\ \text{TgP}}{1 \cdot 10^{12}\text{gP}}$$

Equation 13

where Mm is the phosphorous molar mass and ANEMI's P flux is the calculated variable for each year by the model. A diagram representing the biogeochemical cycle of phosphorus is shown in Figure 37. The variable that would act as indicator is circled in green.

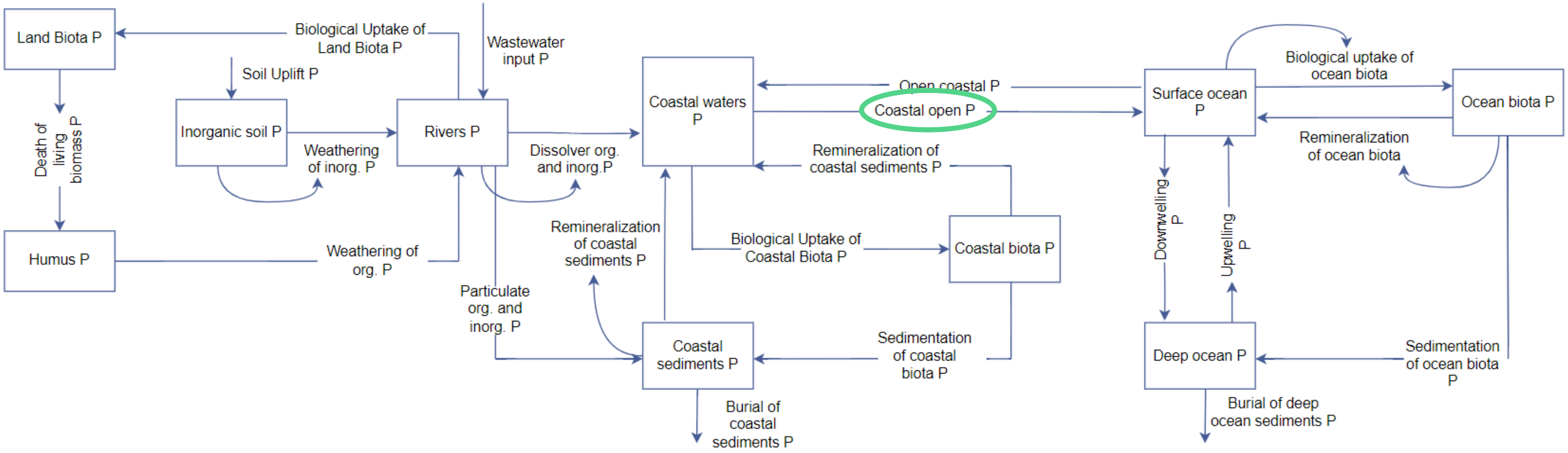

Figure 37. Phosphorous cycle representation. Source: Own elaboration, simplified diagram based on ANEMI model ((Breach & Simonovic, ANEMI3: A updated tool for global change analysis, 2021).

5.2.2.2 Nitrogen cycle

Through the "fertilisation effect," N is a key rate-limiting nutrient for the biological uptake of CO_2 by land and ocean vegetation (den Elzen, Beusen, & Rotmans, 1997). Most of the processes included in the nitrogen cycle can be compared to those of the carbon cycle, with the following exceptions: the land and ocean plants and organisms also fixate nitrogen from the air in addition to biological uptake; and rain and lightning are essential mechanisms for delivering nitrogen from the atmosphere to the Earth's surface and oceans. In contrast to carbon, which is primarily stored in the ocean, nitrogen is stored in the air and the atmosphere (Breach & Simonovic, 2021).

As well as with the previous cycle, ANEMI could be a solid basis to implement this feature in WILIAM. The representation of the cycle is very similar to the phosphorous one, but adding an atmospheric component which interacts with almost all the other boxes. The anthropogenic nitrogen input is again due to the wastewater discharges into rivers. The responsible activities of the releases also match with the phosphorous ones as well as the exits of the cycle. However, there are more natural inputs for nitrogen such as the humus uplift.

According to the planetary boundaries literature, a global indicator for the nitrogen flows is the "Industrial and Intentional-Biological fixation of N". It is related to the loss and intended biological and chemical fixation, especially in agricultural terms, avoiding the emissions of NOx from industry. This indicator shows the sum of NH_3 and N_2O emissions to air, and NO_3-N leaching/runoff from human activities to ground and surface waters (NOx emissions from agriculture are not meaningful) (de Vries, Kros, Kroeze, & Seitzinger, 2013). However, it is also valid a simplification of the indicator, considering only the NO_3 and inorganic N that goes to water, as can be seen in (Stockholm Resilience Centre, 2017).

The N fixation consists of converting the atmospheric nitrogen into forms that can be absorbed by plants through their roots. There are three processes for the N fixation: atmospheric, industrial and biological (Stockholm Resilience Centre, 2017), (Steffen, et al., 2015).

Atmospheric fixation takes place when the nitrogen reacts with solar radiation, oxygen and moisture to form nitrates which fall with the precipitations. Industrial fixation (Haber Process) is a human-made method which uses the hydrogen from natural gas and nitrogen to produce ammonia (frequently used in industrial agriculture as fertilizers) at high temperature and pressure conditions. Biological fixation occurs due to some bacteria that associate with plant to fix nitrogen in order to get sugars from the vegetation. Although this last one is a natural process, it can also be a human-induced activity, especially in legumes, called Intentional-Biological fixation (Jones & Toensmeier, 2023).

It is possible to extrapolate a proxy for the simplified indicator from ANEMI's cycle with a variable called "Wastewater Input N", but as with nitrogen units have to be converted. Therefore, total nitrogen flux is calculated according to the Equation 14:

$$\text{Nitrogen flux}\left(\frac{\text{Tg N}}{\text{year}}\right) = \text{Mm}\left(\frac{\text{gN}}{\text{nN}}\right) * \text{ANEMI's N flux}\left(\frac{\text{nN}}{\text{year}}\right) * \frac{1\ \text{Tg N}}{1 \cdot 10^{12}\text{gN}} =$$

Equation 14

where *Mm* is the nitrogen molar mass, $Nitrogen\ flux$ are the emissions for each year and ANEMI's N flux is the nitrogen wastewater input for each year.

A diagram representing the biogeochemical cycle of nitrogen is shown in Figure 38. The variable that would act as indicator is circled in green.

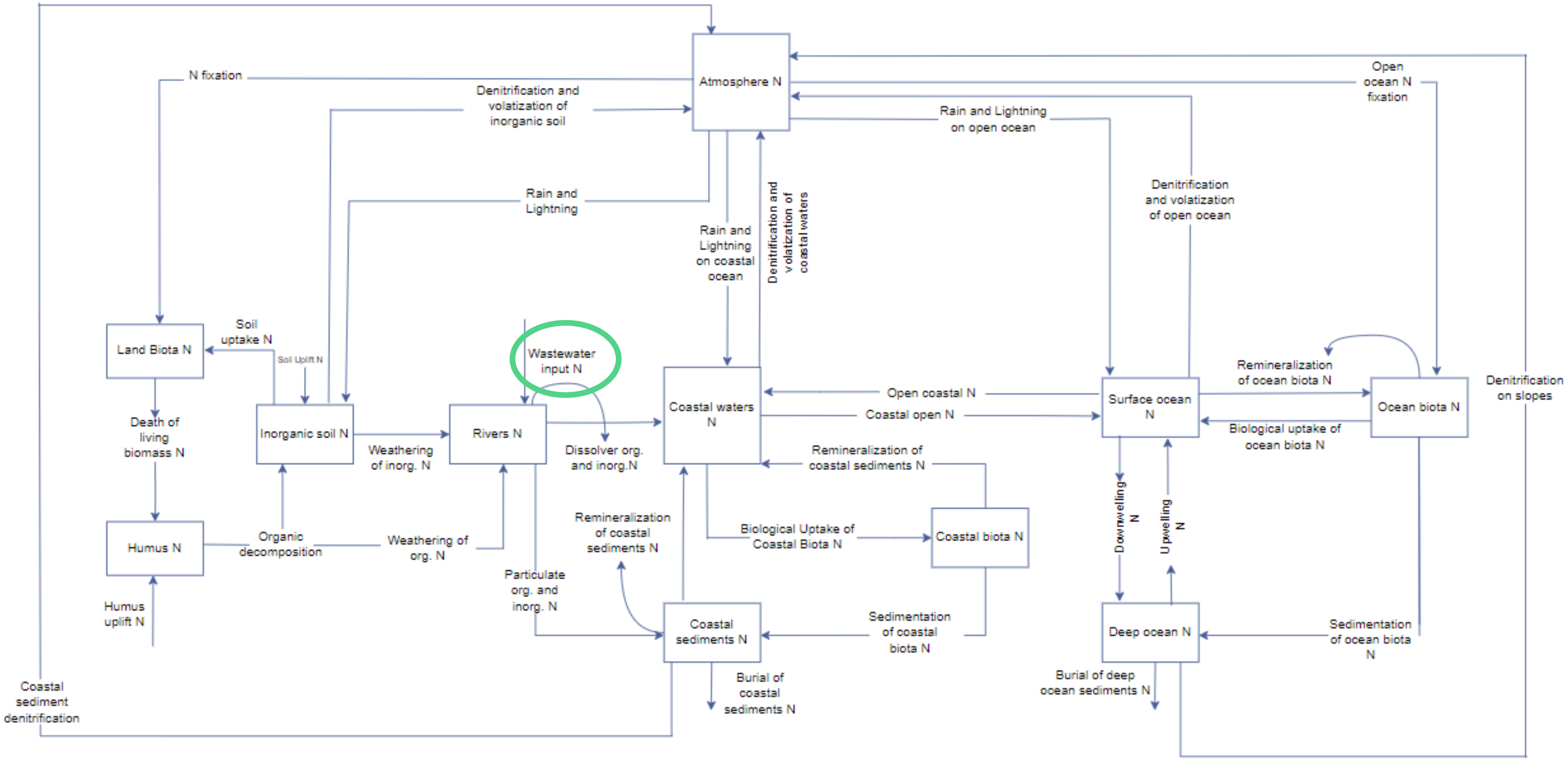

Figure 38. Nitrogen cycle representation. Source: Own elaboration, based on ANEMI model ((Breach & Simonovic, ANEMI3: A updated tool for global change analysis, 2021).

5.2.3 Carbon release from permafrost

Permafrost is a perennial ice layer on the ground, which can be covered by ice or snow. It is located in very cold regions such as tundra, mainly in the northern hemisphere (Alaska, Greenland, Siberia…). This ice sheet locks up large amounts of carbon in form of dead plants and biomass under its most superficial and active layer (mollisol) that thaws and refreezes periodically (Netting & Phillips, 2013). The increase in global temperature results in a faster melting of the ice, releasing CO_2 and CH_4 as well as bacteria, viruses and hazardous chemicals (Reuters, 2019).

As commented in the key terms, the melting of permafrost represents a tipping point due to the release of methane, which has a high contribution to climate change and, in turn, accelerates the thawing of permafrost (Reuters, 2019).

In the analysis conducted of RC Model, ESCIMO is the model of reference that could support the analysis of this feature and how it can be modelled in system dynamics. As commented before, in WILIAM this feature is included but deactivated due to its uncertainty. In ESCIMO, it is modelled the feedback of temperature to the permafrost system (increase of temperature melting permafrost), and its direct consequences that are the additional emissions of CH_4 and CO_2 to the atmosphere proportional to the rate of melting, and the feedback generated that makes increase quicker the temperature increase (self-reinforcing feedback). In particular, for the permafrost, ESCIMO assumes that the melting occurs from the outer radius linearly inwards, like a ring around the arctic ocean.

In particular a deeper analysis of literature for this feature will be conducted in Task 3.4 which is focused on tipping points, where “key variables (including interconnections) leading to Earth tipping points and their probability of occurrence, will be identified”

5.2.4 Stratospheric Ozone Depletion

It consists of the gradual thinning of the ozone layer in the Earth's stratosphere, which is caused by the release of ozone-depleting substances (ODSs) such as chlorofluorocarbons (CFCs) and halons (Steffen & Rockström, 2018).

To calculate the ozone depletion rate, it is necessary to determine the ODS concentration in the atmosphere which results pretty complicate in WILIAM since ODS cycles are not included within the model (exogenous emissions are converted into radiative forcing, being this radiative forcing directly included in WILIAM as exogenous inputs). The inclusion of this cycle would require a comprehensive analysis of each ODS and how they interact with the O_3 individually. The most common solution for this problem in other RC Models is the introduction of a new variable (a proxy) called the Equivalent Effective Stratospheric Chlorine (EESC).

The EESC is a measure used to assess the potential impact of several substances on stratospheric O_3 depletion. It relies on a substance's ability to destroy ozone, compared to the depletion potential of a given substance, normally the methyl chloride (CH_3Cl) or the CFC11. In this case, EESC would be expressed in terms of CH_3Cl/CFC11 equivalent mass, which allows for a direct comparison of the impact of different chemical substances on ozone depletion (World Meteorological Organization (WMO), 2022).

Although it is difficult to explicitly model a quantitative relationship between EESC and O_3 concentration due to the variety of influential factors (pollution, meteorological variables, solar radiation…), it is possible to establish a qualitative link since an increase in EESC concentration causes a higher O_3 atmospheric concentration and, thus, a thinner ozone layer (World Meteorological Organization (WMO), 2022).

This proxy is used in several RC Models to obtain the stratospheric ozone radiative forcing. Some examples are: MAGICC, FaIR, CICERO-SCM, OSCAR or EM-GC. The most widespread equations to calculate the EESC and, consequently, the stratospheric ozone forcing are described below (Newman, Daniel, Waugh, & Nash, 2007):

$$C_{EESC}\,(ppb) = r_{CFC11} \cdot \sum_{i \in ODS} \left(n_{Cl}(i) C_i \frac{r_i}{r_{CFC11}} + 45 n_{Br}(i) C_i \frac{r_i}{r_{CFC11}} \right)$$

Equation 15

where r_i refers to the fractional release for each ODS, n_{Cl} and n_{Br} represent the number of bromine and chlorine atoms in a given compound (with the factor of 45 because Br is 45 times more effective than Cl at ozone depletion) and C_i is the atmospheric concentration of each ODS in ppb.

$$RF_{O_3} = \mu_1 (\mu_2 \cdot C_{EESC})^{\mu_3}$$

Equation 16

where μ_1 is a sensitivity scaling factor ($\approx$-4,49·10^{-4} W/m^{-2}), μ_2 value is 1/100 ppb^{-1} and μ_3 is the sensitivity exponent ($\approx$1,7) (Meinshausen, Raper, & Wigley, 2011).

Besides estimating the O_3 concentration and radiative forcing, the EESC can be used as an indicator for the Planetary Boundary related to the ozone depletion, as the reference indicator from literature (% O_3 concentration reduction in Dobson Units) could be too complicated to be introduced in WILIAM. This topic will be further developed in Task 3.3 (method for including planetary boundaries).

5.2.5 Ocean acidification

Within WILIAM, a simple ocean pH module already exists, but with some small additions it could be greatly improved as it can be related to both a Planetary Boundary and a tipping point. The positive aspect of these improvements is that there is no need for an overly complex process or to look for alternatives in other models (actually, it is not explicitly modelled in any reviewed SCM), as with the information found in the literature it can be implemented in the model.

5.2.5.1 Planetary Boundary: Aragonite Saturation

The planetary threshold mainly depends on CO_2 levels in the atmosphere. The increase in carbon dioxide concentration leads to higher amounts of free H^+ ions in the ocean, as well as lower saturation state of aragonite (Steffen, et al., 2015).

Aragonite is a calcium carbonate compound that is part of many marine organisms and whose saturation state is often used as an indicator of the state of the planetary boundary (as a percentage change from the pre-industrial value). If the aragonite saturation is less than 1, the aragonite dissolves. With CO_2 values below 350, this boundary should not be exceeded (Steffen, et al., 2015).

5.2.5.2 Tipping point: Coral Reefs Die-Off

Regarding the tipping points, the one dependent on acidification is the coral reefs die-off. This phenomenon is caused by two main factors: the acidification of the oceans (in turn caused by rising atmospheric CO_2 concentration) and global warming. Thus, if this point is crossed (over 500 ppm of atmospheric CO_2), coral presence in reefs will be less frequent, reefs communities will be less diverse and many people will lose their jobs. In pH terms, the stipulated threshold in the literature is between

7,5 and 8, depending on the location of the reefs (i.e. 7,7 for Papua New Guinea corals and 8 for Galapagos corals) (Manzello, Enochs, Bruckner, Renaud, & Kolodziej, 2023).

5.2.6 Tropospheric aerosol direct radiative forcing

As previously explained in the key concepts section, aerosols have a major influence on climate evolution due to their radiative effects: direct, indirect and semi-direct. They also affect to air quality and their atmospheric loading is considered a planetary boundary. Aerosols therefore have key role in climate, however their effect on the climate is currently included as an exogenous variable in WILIAM.

Semi-direct and indirect effects of aerosols are quite complicated to implement in the model since there is a large uncertainty about both the data and the physicochemical process taking place. Few models include these effects and those that do, do so in shallow depth. Additionally, the influence of aerosols on air quality is more related to the socio-economic and health modules than to the climate module (influence on temperature change), so the inclusion of these socio-economic effects is not considered for this task.

Thus, the selected variable to model the environmental influence of aerosols is the DRF (Direct Radiative Forcing), which can have a positive or negative contribution to the total Radiative Forcing depending on whether they absorb or scatter radiation.

In this document the method for the integration in WILIAM is explored and preliminary defined in the next section, but the integration in WILIAM will be further explored in Task 3.3 (based on this deep analysis) in order to check real feasibility and the level of difficulty regarding the necessity of this feature to be implemented in NEVERMORE with respect the others.

5.3 Selection of information from GCMs to be used in WILIAM

As explained in section 4.2 and shown in Table 13, a set of variables can be calibrated or obtained from the GCMs for different purposes. Each of these variables has an application that affects a different task in this project.

It is necessary to mention previously that initially, a calibration of the temperature feedback on the NPP (carbon cycle) was proposed in order to update this relationship with data updated from CMIP6, but due to problems in aligning approaches and variables and models concept, and considering the deep work already pursued for CMIP4 in the article (Friedlingstein, et al., 2006), being this already used in WILIAM, the task was catalogued as too ambitious and we prioritize others.

Therefore, it was decided that the information from GCMs could be applied for 1) calibration of the sea level rise feature (including spatial disaggregation) based on WILIAM regions, which in turn is a climate impact that could be useful for WP4 (indirectly affects land use sector) and whose regionalisation could be carried out in T3.2. In addition, because some GCMs model Extreme Weather Events, it would be possible to extract information from them for T3.3, in particular, for exploring how to include extreme events in WILIAM. Finally, for T3.2 it has been decided to select a set of regional climate variables (explained in the following table) that are necessary to carry out the climate downscaling, regionalising as for example global temperature and precipitation.

Table 13. Features/variables extracted from GCMs. Source: Own elaboration.

Feature/Variable	Description	Units	GCM
Regional Sea Level Rise	Increase in the level of the world's oceans due to the effects of global warming	mm	ACCESS-CM2 CNRM-ESM2-1 EC-Earth3-Veg-LR HadGEM_GC3_LL

Feature/Variable	Description	Units	GCM
Extreme Weather Events (EWEs)	Weather conditions that deviate significantly from the expected and could cause significant impacts	-	CESM2 CNRM-ESM2-1
Regional Mean Surface Temperature	GMST regionalised	ºC	ACCESS-CM2 CESM2 CNRM-ESM2-1
HDD (Heating Degree Days)	Number of days in which temperature is above mean outdoor temperature recorded for a location during a period	d/yr	CNRM-ESM2-1 IPSL-CM6A-LR MIROC6
CDD (Cooling Degree Days)	Number of days in which temperature is below mean outdoor temperature recorded for a location during a period	d/yr	CNRM-ESM2-1 IPSL-CM6A-LR MIROC6
Maximum Annual Temperature	Average of the annual maximum temperature for each region	ºC	NorESM2-MM EC-Earth3-Veg-LR
Minimum Annual Temperature	Average of the annual minimum temperature for each region	ºC	NorESM2-MM EC-Earth3-Veg-LR
Annual precipitations	Average of the annual precipitation for each region	mm/yr	NorESM2-MM HadGEM_GC3_LL
Regional radiation forcing levels	Average of the RF levels for each region	W/m^2	NorESM2-MM EC-Earth3-Veg-LR HadGEM_GC3_LL

6 STEP 3- Implementation

6.1 Methodology for the implementation of the improvements in WILIAM

This section focuses on the selected improvements and new features listed in the previous section, but putting the attention in exploring the feasibility to be integrated in WILIAM, and the definition of preliminary methods necessary for the adaptation and integration in WILIAM. It also includes potential links and necessary alignments as the time of the simulation, and modifications or intermediate variables needed for the coupling/adding of new features from other RC Models.

6.1.1 Features to be implemented (Rating >2)

6.1.1.1 Biogeochemical cycles

Regarding current status of these features in WILIAM, phosphorous is not implemented in any of its forms, neither atmospheric emissions nor as a nutrient, so there will be no overlaps. Regarding nitrogen, N_2O emissions are included, as well as its atmospheric cycle. However, nitrogen as a nutrient is not modelled so there will be no problems between the two cycles.

Both nitrogen and phosphorous cycles have the same main input: wastewater discharges from human activities to rivers. These activities can be divided into agricultural, domestic and industrial activities and it is necessary to model their nutrient contributions to the cycles in WILIAM:

- Agricultural contribution: According to ANEMI, it is calculated as the leaching of N or P in croplands multiplied by the net arable land. Although net arable land is not a direct variable in WILIAM, there is another one equivalent called *Cropland_total_area* from we can make the link, as it is the effective area where the agricultural activity is taken place, and therefore its related emissions. Agricultural contribution is then calculated following this equation:

$$\mathrm{Emissions}_{\mathrm{agric}}\ (\mathrm{nN/year\ or\ nP/year}) = \mathrm{f}_{\mathrm{leaching}} \cdot \mathrm{Area}_{\mathrm{cropl}}$$

Equation 17

where $f_{leaching}$ is a factor which indicates the amount of leaching nutrient (mole/ha·year), and $Area_{cropl}$ refers to the global area dedicated to cropland (ha), which is directly related to the sum of two variables of WILIAM called "*land use area*" of rainfed and of irrigated cropland.

- Domestic and Industrial contribution: Both domestic and industrial emissions of nutrients come from treated, untreated and reused wastewaters. The pollution generated depends on a removal efficiency factor and the initial concentration of the wastewaters as indicated in the following equation:

$$\mathrm{Emissions}_{\mathrm{Dom//IndWW}}\left(\frac{\mathrm{nN}}{\mathrm{year}}\mathrm{or}\frac{\mathrm{nP}}{\mathrm{year}}\right) = [\mathrm{WW_U} - \mathrm{WW_R} + \mathrm{WW_T} \cdot (1 - \mathrm{RE})] \cdot \mathrm{C_{WW}}$$

Equation 18

where $WW_{\_U}$ is the untreated wastewater (km^3/year), $WW_{\_R}$ is the reused wastewater (km^3/year), $WW_{\_T}$ is the treated wastewater (km^3/year), RE is the removal efficiency for N or P and $C_{\_WW}$ is the concentration of N or P in wastewaters (4,28·10^9 and 1,071·10^9 moles/km^3, respectively, (Henze & Gujer, 2008)).

Reused wastewater from industrial and domestic activities depends on a variable called *Normal Water Production* which in turn depends on the *Available Surface Water*, among others. This latter variable can be directly linked with *water_available* of WILIAM.

On the other side, the treated and untreated wastewater from both households and industry are function of two ANEMI variables called *Desired Industrial Water Consumption* and *Desired Domestic Water Consumption*, respectively, which can be related to WILIAM variables *blue_water_demand_by_industries* and *blue_water_demand_by_households*.

Thus, the emissions from wastewater inputs can be calculated as the sum of those three contributions, as shown in Equation 19.

$$\mathrm{Wastewater\ Input} = \mathrm{Emissions}_{\mathrm{DomWW}} + \mathrm{Emissions}_{\mathrm{IndWW}} + \mathrm{Emissions}_{\mathrm{agric}}$$

Equation 19

A simplified scheme of the key variables for these two features implementation (N and P) is shown in Figure 39 with the "link variables" with WILIAM shaded in green.

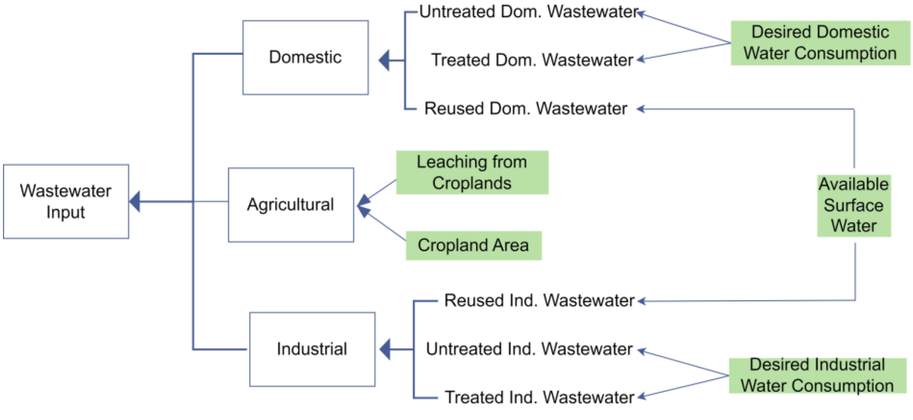

Figure 39. Simplified representation of wastewater input (N and P) based on Anemi model. Source: Own elaboration.

These calculated emissions are the input for the biogeochemical cycles and the rest of the interrelationships between the different boxes (soil, rivers, atmosphere...) are based on the model provided by ANEMI (see **Errore. L'origine riferimento non è stata trovata.** and Figure 38).

Table 14. Key variables of ANEMI to implement N and P biogeochemical flows in WILIAM.

ANEMI variable	Definition	Units	Variable to link with WILIAM	Type of linkage
Net Arable Land	It considers all arable land (whether cultivated or not) minus erodible land (which is land that is highly erodible and not cultivated) resulting in net cultivated land.	ha	CROPLAND_land_area	Direct
N//P Leaching Cropland	Amount of nitrogen or phosphorus leaching from croplands.	mole/ha·yr	CROPLAND_land_area	Exogenous the factor of emissions
Available Surface Water	Freshwater resources that are present on the Earth's surface and can utilized for various human purposes.	km^3/yr	Water_available_by_region	Direct
Desired Industrial Water Consumption	Optimal amount of water that industries aim to use in their production processes efficiently.	km^3/yr	blue_water_demand_by_industries	Direct
Desired Domestic Water Consumption	Ideal amount of water that households aim to use for their daily activities and needs.	km^3/yr	blue_water_demand_by_households	Indirect

6.1.1.2 Stratospheric Ozone Depletion

WILIAM takes this topic into account by including MP gases radiative forcing from an external source, in particular from the Table 8-5 of (Daniel & Velders, 2006). Values range from 0,326 to 0,222 W/m^2 between 2005 and 2050. Therefore, WILIAM does not currently considers the direct radiative forcing caused by stratospheric depleted ozone (according to IPCC, approximately -0,05 W/m^2). In order to avoid overlaps, this exogenous calculation will be removed to implement the updated feature which includes both radiative forcing.

The key input for this module is ODS emissions (16 gases defined by the Montreal Protocol and shown in Table 15), which are taken from RCPs, both historical data and future projection. The first step is the calculation of the atmospheric concentration of each ODS for the beginning of each year *t,* according to the two following equations:

$$\delta C_{t,i} = \frac{E_{t,i} \cdot \omega_a}{M_{atm} \cdot \mu_i} \delta_t \cdot 10^{12}$$

Equation 20

where $\delta C_{t,i}$ is the equivalent increase in the molar mixing ratio of the specie *i* in year *t*, $E_{t,i}$ is the average emissions of gas *i* through year *t* (kg/year), ω_a is the molecular weight of dry air (28,97 kg/kmole), M_{atm} is the atmosphere mass ($5{,}13 \cdot 10^{18}$ kg), μ_i is the molecular weight of gas *i* (kg/kmole) and δ_t is the temporal interval (1 year for annual emissions databases). (Smith, Forster, Allen, & Nicholas, 2018)

$$C_{t,i} = C_{t-1,i} + \frac{1}{2}\cdot\left(\delta C_{t-1,i} + \delta C_{t,i}\right) - C_{t-1,i}\cdot\left(1 - e^{\frac{-1}{\tau_i}}\right)$$

Equation 21

where $C_{t,i}$ the atmospheric concentration of gas *i* in year *t* (ppt), τ_i the net atmospheric lifetime of gas *i* (Meinshausen, Raper, & Wigley, 2011). Both the atmospheric lifetimes and the molecular weights, as well as the rest of the factors for the Equation 20 and Equation 21, are addressed in Table 15 from (Daniel J. V., 2011):

Table 15. Parameters for EESC and ERF calculations. Source: (Daniel J. V., 2011)

Gas	μ_i (kg/kmol)	τ_i (yr)	r_i	n_{Cl}	n_{Br}	RE (W/m2·ppb)	PI Concent. (ppt)
CFC11	137,37	45	0,47	3	0	0,26	0
CFC12	120,91	100	0,23	2	0	0,32	0
CFC113	187,38	85	0,29	3	0	0,3	0
CFC114	170,92	190	0,12	2	0	0,31	0
CFC115	154,47	1020	0,04	1	0	0,25	0
CCl_4	153,81	26	0,56	4	0	0,17	0
CH_3CCl_3	133,40	5	0,67	3	0	0,07	0
HCFC22	86,47	11,9	0,13	1	0	0,21	0
HCFC141b	116,94	9,2	0,34	2	0	0,16	0
HCFC142b	100,49	17,2	0,17	1	0	0,19	0
Halon 1211	165,36	16,0	0,62	1	1	0,3	0
Halon 1202	209,82	2,9	0,62	0	2	0,27	0
Halon 1301	148,91	65	0,28	0	1	0,3	0
Halon 2402	259,82	20	0,65	0	2	0,31	0
CH_3Br	94,94	0,8	0,60	0	1	0,005	5,8
CH_3Cl	50,49	1	0,44	1	0	0,08	504

The initial concentration of each ODS refers to 2005 values (first year of WILIAM simulation) and can be obtained from the RCPs. The simulation time goes from 2005 to 2050 (aligned with the rest of radiative forcing).

The concentration of each gas is then utilised to calculate the EESC concentration (also necessary for the Planetary Boundary threshold) and the radiative forcing due to the ozone depletion following the Equation 15 and Equation 16. In this way, WILIAM would be able to improve the calculation of the the radiative forcing from both the Montreal Protocol gases (positive contribution, already included in the model exogenously, Equation 22) and the depleted ozone (negative contribution).

$$ERF_{ODS} = \sum_{i\in ODS} RE_i \cdot \left(C_{t,i} - C_{PI,i}\right)$$

Equation 22

where RE_i is the radiative efficiency of the specie *i* ($W/m^2 \cdot ppb$), and $C_{PI,i}$ is the pre-industrial atmospheric concentration of the specie *i* (ppb).

6.1.1.3 Ocean acidification

Currently, WILIAM has an individual view for ocean acidification, in particular for the calculation of ocean pH. This climate impact is an endogenous feature and is function of CO_2 atmospheric concentration and several constants. The equation (Equation 3) is taken from (Bernie D. , Lowe, Tyrrell, & Legge, 2010). This feature will be improved adding a new variable for the planetary boundary and a threshold for the tipping point of coral reefs.

On the one hand, the reference indicator for the Planetary Boundary, besides the oceanic pH, is the aragonite saturation state of the ocean. This variable depends on the pH and some constants as shown in the following equation:

$$\text{Aragonite Saturation} = \alpha \cdot \mathrm{pH}^2 - \beta \cdot \mathrm{pH} + 213{,}544$$

Equation 23

where pH is the ocean pH, α is the first constant with a value of 3,873 and β is the second constant with a value of 57,371. All the parameters of this equation are dimensionless.

On the other hand, the acidification of oceans is one of the main drivers of coral reefs die-off, currently considered as a tipping point. According to (Hoegh-Guldberg, Mumby, & Hooten, 2007) the threshold for this tipping point takes place at an atmospheric CO_2 concentration (CO_{2Th}) of 480 ppm and it is calculated according to the following equation:

$$\text{pH threshold} = k_1 - k_2 \cdot CO_{2_{Th}} + k_3 \cdot \left(CO_{2_{Th}}\right)^2 - k_4 \cdot \left(CO_{2_{Th}}\right)^3$$

Equation 24

where k_1, k_2, k_3 and k_4 are pH constants with values of 8,554, 0,0017 ppm^{-1}, $1{,}326 \cdot 10^{-6}$ ppm^{-2} and $4{,}494 \cdot 10^{-10}$ ppm^{-3}, respectively (Bernie D. , Lowe, Tyrrell, & Legge, 2010).

6.1.1.4 Tropospheric aerosol direct radiative forcing

The latest version of WILIAM only includes an exogenous input related to aerosol radiative forcing named *other_forcing*. However, this variable does not only cover aerosols, but also other gases such as tropospheric ozone precursors (CO, NMVOCs…). Thus, it is necessary to differ which contribution has the aerosols of the total value of that variable, as well as to define the particular aerosols modelled.

To model this feature, the first step is to determine which compounds are to be included, as not all RC Models consider the entire aerosol spectrum and a distinction has to be made between primary aerosols and secondary aerosol precursors. In the case of WILIAM, the list could include black carbon and organic carbon as primary aerosols and SO_2 and NH_3 & NOx as sulphate and nitrate precursors, respectively.

As discussed in section 4, this method is a preliminary and exploratory process, as the ultimate goal is to link aerosol emissions with the different production sectors of WILIAM (transport, agriculture, industry...) in order to endogenize the process as much as possible and align the pathways of aerosol emissions with the scenarios of WILIAM to evaluate their influence in the climate. In case it is needed a simple method for estimating the aerosols emissions projections, it could be linked the aerosols emissions to some simple activity factors of WILIAM sectors (e.g. energy consumed, CO_2 emitted, etc.), and calibrate it based on historical data of emissions of these aerosols, as for example the data of EDGAR database[5].

Due to their short lifetime, the atmospheric concentrations of these aerosols are approximated by their emissions. The calculation of the DRF for each is carried out with their corresponding Radiative Efficiency (RE) which have been calculated empirically according to (Henze, Shindell, Farhan, Spurr, & Pinder, 2012). With past RF patterns and emission projections the DRF is calculated following the next equation:

$$\mathrm{DRF_i} = \mathrm{E_{atm,i}} \cdot \mathrm{RF_i}$$

Equation 25

Each aerosol makes a different contribution to the total RF, which can be positive or negative, so it is necessary to add them all together to obtain the net DRF derived from tropospheric aerosols.

Other improvements could be related to endogenize other RFs such as volcanic eruptions (stratospheric aerosols), mineral dust or the indirect RF of these same tropospheric aerosols, but these improvements should be previously evaluated in terms of efforts and also if they are a priority over others listed in this section.

6.1.2 Features to be initially explored (Rating between 1-2)

6.1.2.1 Albedo

The representation of albedo effect in WILIAM just consists of an exogenous radiative forcing variable called *Mineral_Aerosols_and_Land_RF* (constant value of -0,3 W/m^2) derived from the IPCC and which is part of the *other forcing* variable which include several GHGs of different types.

The total radiative forcing due to albedo, according to the literature, can be separated into three different contributions which depend on their origin: Surface albedo from biomes and ocean, scattering due to aerosols and cloud albedo.

- Cloud albedo can be taken exogenously from ESCIMO since there are not adequate WILIAM variables to link with. Cloud albedo varies with the type of cloud: high or low density.
- Aerosol scattering: As with the previous one, at this point there is no direct link with a WILIAM variable since the aerosol RF is exogenous. It would be possible to use in an exogenous way what ESCIMO calculates, however future projections should be adapted to the “shape” of scenarios from WILIAM. As the implementation of an aerosol feature is also considered in this task, a link between the two could be established when it is implemented. It will also be necessary to consider radiative forcing from volcanic eruptions and solar radiation incoming, which can be taken also exogenously from ESCIMO.
- Surface albedo: This variable is in turn composed of the albedo from the ocean plus arctic ice and the albedo from land biomes:
    - Ocean and arctic ice: The main variable that can establish a link with WILIAM is the change in temperature since preindustrial times, since it is the one that affects and determines the melting or freezing of the ice in the glacier-ocean transformation.
    - Land biomes: This variable is highly influenced by land use change, as each biome provides a different albedo contribution, so it is essential to correctly link it to the “Land

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[5] EDGAR - Emissions Database for Global Atmospheric Research. Global Air Pollutant Emissions https://edgar.jrc.ec.europa.eu/dataset_ap61

use" module of WILIAM. For this like, previously is needed to align concepts and naming, being necessary to adapt the areas of grassland, tropical forests, desert, northern forests, tundra (exogenous from ESCIMO as it is not in WILIAM), barren land and urban land. All the links with WILIAM are shown in the **Errore. L'origine riferimento non è stata trovata.**.

A simplified scheme of the key variables for this feature implementation is shown in Figure 40 with the link variables shaded in green and the exogenous variables in blue.

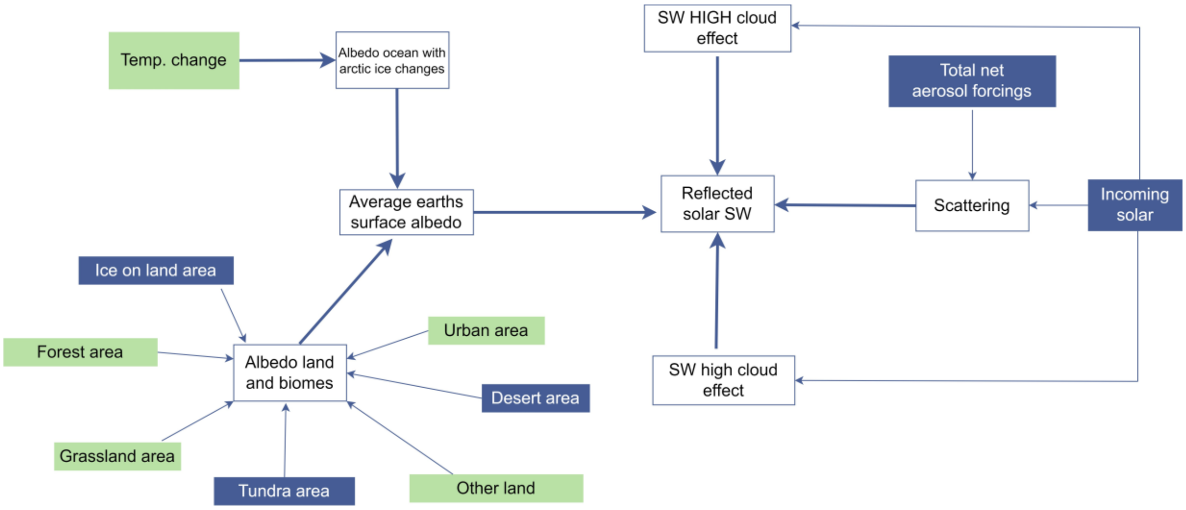

Figure 40. Simplified representation of albedo module based on ESCIMO model adapted to WILIAM. Source: Own elaboration.

Table 16. Key variables of ESCIMO to implement albedo in WILIAM. Source: Own elaboration

ANEMI variable	Description	Units	Variable to link with WILIAM	Type of linkage
Incoming Solar	Solar radiation reaching the earth. Module not included in WILIAM.	W/m2	-	Exogenous
Total net aerosol forcing	DRF generated by aerosols (tropospheric and stratospheric). Not yet included in WILIAM.	W/m2	-	Exogenous
T surface current/1850 value	Ratio between current T and its value in 1850	K	Temperature_change	Direct
Grass area	Area of grasslands. To be adapted with grassland land use type	Mkm^2	Grassland_area	Direct
Desert area	Desert is not separated in WILIAM	Mkm^2	-	Exogenous
Tropical forest area	Forests located between the tropics and in boreal areas, respectively. Necessary to align with Forest land (plantations, primary and managed) of WILIIAM considering their evolution (e.g. deforestation…)	Mkm^2	Forest_area	Indirect
Northern Forest area				
Tundra area	Flat, treeless regions with frozen subsoil. It is not included in WILIAM	Mkm^2	-	Exogenous
Barren land	Dry and bare land with very few plants and no trees. It can be	Mkm^2	Other_land	Indirect

	derived from WILIAM variable “Other_land”.			
Urban area	Locations with a high population-density and an infrastructure of built environment. It can be linked with a WILIAM variable	Mkm^2	Urban_area	Direct
Glaciers area, Greenland, Antarctic, ice on water	These extreme biomes are not considered dynamic in WILIAM, but should be aligned with the “snow_ice_waterbodies” land use type	Mkm^2	-	Indirect/need adaptation

6.1.2.2 Carbon release from permafrost

As commented in Section 3.2, the feedback of the carbon release from permafrost due to temperature increase it is included already in WILIAM based on RC model C-ROADS. However, by default is deactivated due to high uncertainties (no feedback). It is necessary to note that permafrost is in a continuous process of warming and melting, but the uncertainty relates to the magnitude and timing of these changes.

In particular, WILIAM model includes the release of CH_4 from permafrost and clathrate stores. The value of reference of emissions of CH4 from permafrost and clathrates per °C of global temperature change used is 50 Mt/year·°C.

As explained before in Section 5.2.3, ESCIMO could be a reference for improving the permafrost part, along with the last updated literature review that could help in estimating key values as the “reference” of emissions released by temperature increase, Mt/year·°C, or for estimating the threshold or limit of temperature change when permafrost starts melting more quickly.

Further analysis about this tipping point will be carried out in Task 3.4 where more key variables leading to this tipping point and their probability of occurrence, will be better analysed.

6.2 Implementation plan

Once the methodology for the implementation of improvements and new features is preliminary defined (design phase), the technical implementation in WILIAM needs to be carried out. This second step will be addressed in future Task activities and deliverables:

- Tasks 3.3, regarding planetary boundaries and exploration of climate impacts and extreme events data for M18.
- Geographical distribution of global variables and (Task 3.2 for M24).
- Tipping points, such as the permafrost feature (Task 3.4 for M24).

For this second step, the initial method described for integrating the features which has been listed in this document will be reviewed and deeper analysed, and, in case of unfeasibility, prioritizing and/or discarding some of the features that were explored in this Deliverable. In addition, they could be also prioritised regarding the requirements of WP4 for modelling climate impacts in WILIAM.

In particular the improved IAM climate module (first release) is due to M24 as part of the milestone number 5 (MS5) and dependent of Deliverable 3.4.

Figure 41 shows a Gantt diagram with the expected schedule for the modelling of improvement in the WILIAM climate module in the frame of WP3 of the NEVERMORE project. Thus, feedback from Task 3.2 (lead by NCSRD) related to downscaling of climate data is expected by M20 and several meetings between tasks and partners involved are foreseen to follow up on the improvements of the module.

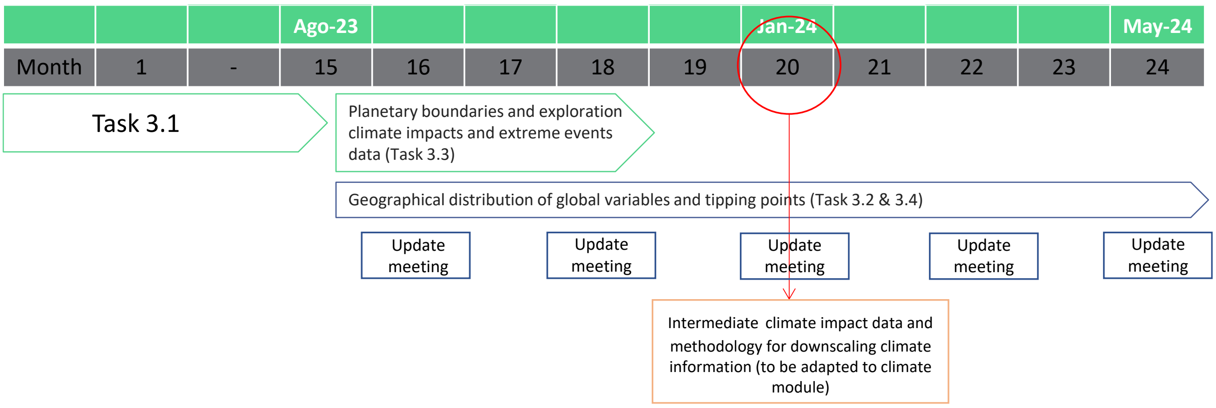

Figure 41. Expected schedule for the development of the WILIAM climate module (first release) framed into the WP3 of the NEVERMORE project.

7 Conclusions

In this document the different activities conducted within Task 3.1 have been described. Considering the basic climate part of the WILIAM IAM, other climate models and climate data have been reviewed and analysed to improve and update the climate submodule.

In addition, among the list of potential applications of the RC models and data analysed, there have been chosen, based on prioritisation, 4 different improvements/new features which has been analysed in detailed in the literature and proposed a preliminary method for its technical integration in WILIAM. Moreover, other 2 functionalities have been explored for a potential implementation in a future work, but deeper analysis is still needed. In addition, GCM data has been considered interesting for future calibration purposes, as the spatial disaggregation of sea level rise and other climate variables in Task 3.2, as well as data about extreme events which are going to be explored in Task 3.3.

Throughout this document, the features chosen as priorities for improving WILIAM have been theoretically described and, additionally, it has been proposed an initial method on how they could be implemented within the model, highlighting the necessary inputs, the equations used and the links with other variables previously included to facilitate their integration. However, the new features detailed in section 5, have still to be further evaluated in other to check their feasibility in terms of technical and temporal efforts before really implementing them in WILIAM.

As a conclusion of the initial exploration, in the case of improving the ocean acidification feature of WILIAM for obtaining indicators to calculate the planetary boundary and the tipping point of “coral reefs die-off”, the methodology seems quite feasible to implement. The same happens with the “stratospheric ozone depletion” for delivering also the planetary boundary (for Task 3.3). In addition, the nitrogen and phosphorus cycles (nutrient) could be feasible to be integrated in WILIAM according to specific variables to be linked to and the methodology proposed. “Tropospheric aerosol effect” is the feature to be implemented with the greatest uncertainty because it is still necessary to link emissions to the WILIAM productive sectors, but it is assumed to be achievable. However, in the case of Albedo and specially permafrost, the integration could be more challenging, so it needs to be revaluated during their implementation, discarding some of them in case the integration is not feasible.

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