# Appendix B
# Descriptions of the four Research Themes (RTs)

## 1. RESEARCH THEME 1 (RT1) – THE PHYSICAL-CHEMICAL CLIMATE SYSTEM

Climate change is recognized as the defining issue of our time. Still, fundamental questions on the physics and chemistry of the climate system remain. This knowledge gap hampers our ability to make well-informed policy decisions, e.g. with regard to mitigation and adaptation strategies, and capacity to estimate how much of our carbon budget is left to limit the global temperature increase to well below 2˚C. For example, we need quantitative information on regional and global future climate change, including the ability to anticipate possible climate catastrophes. To enable this, we need to understand and quantify Earth's transient climate response (TCR) and equilibrium climate sensitivity (ECS), which requires in particular better constraints on cloud feedbacks and cloud-aerosol interactions as well as a better understanding of the role of the oceans in modulating climate response. To translate this information to regional impacts and predict possible tipping points, we also need a solid physical understanding of the general circulation of ocean and atmosphere.

### 1.1 State-of-the-art and key knowledge gaps relevant for RT1

The recent progress in constraining climate sensitivity has been made without relying exclusively on models, and instead using other lines of evidence, such as process understanding, observational records, proxy data, and emergent constraints (IPCC AR6, Sherwood et al. 2020). Climate models however remain essential for attributing observed climate change to anthropogenic forcing, enhancing process understanding and predicting and projecting regional climate change, as well as interpreting paleo records and historical data. Hence, it is essential to continue developing Earth System Models (ESMs) to better represent reality and produce the right results for the right reasons. The spread between model estimates of climate feedback processes and sensitivity can primarily be ascribed to clouds and their response to warming (IPCC-AR6). The greatest uncertainties in forcing on the other hand are related to aerosols. Although significant progress has been made in the quantification of aerosol forcing, there remain several areas where we lack understanding as well as observational constraints, e.g. in cloud adjustments to climate change, aerosol-cloud interactions, including in particular the ice phase, and in determining the preindustrial background aerosol state (Bellouin et al. 2020, Bender 2020). Further, there is a need to translate the global climate change, which is mainly determined by large-scale forcing and feedbacks, to regional effects and weather patterns, and for this, the development of global models at horizontal scales that can resolve storms, convection and ocean eddies, will be central.

The two recent IPCC Special Reports (IPCC SR1.5, IPCC-SROCC), indicate that a number of Earth system components are at risk of rapid or irreversible change, even at lower warming levels (McKay et al. 2022). An example of such a tipping point is the melting of the Greenland ice sheet (Robinson et al. 2012). Furthermore, evidence exists that tipping points are interconnected across different biophysical systems and that there is a risk that exceeding a tipping point in one system might cause abrupt and large-scale changes in other systems. One such example that could have far reaching impacts is the proposed Greenland ice tipping-point that could cause a collapse of the Atlantic Meridional Overturning Circulation (AMOC), for which there is some evidence that it is already weakening (Worthington et al. 2021; Caesar et al. 2021). The finding is, however, contested and might be explained instead by an acceleration of the circulation in the sub-polar gyre that transports warm waters into the Arctic (Keil et al. 2020). CMIP6 projections generally show a reduction of the AMOC strength, but the estimates are highly model-dependent (Weijer et al. 2019). Even if unlikely, an abrupt future reduction of the AMOC could have dramatic effects on the climate in the North Atlantic sector (Jackson et al. 2015).

Polar areas are among the most vulnerable regions on Earth in terms of climate change impacts. The Arctic, for example, is warming at more than double the global mean rate (NOAA 2019). In response to this warming, the extent of Arctic sea-ice has decreased dramatically, particularly in summer (IPCC 2021). Future climate projections show a continuous decrease of Arctic sea ice under all future emission scenarios; however, the timing of a summer ice free Arctic is still uncertain (SIMIP 2020). Based on projections by a selection of CMIP6 models that best represent historical observations of Arctic sea ice and ocean heat flux into the Arctic, summer sea ice might disappear completely by as early as 2035 (Docquier and Koenigk 2021). Although debated, Arctic sea-ice reductions have also been linked to changes in weather and climate conditions at lower latitudes (Cohen et al. 2020).

Climate policy has evolved considerably over the last decades with countries agreeing to limit global warming to less than 2˚C compared to pre-industrial levels (the Paris Agreement). However, recent policies are not sufficient to reach the Paris Agreement and the world needs to prepare for global warming levels that temporarily or more permanently overshoot the Paris target. It is thus critical to assess how the risk of abrupt changes and their regional climate consequences vary as a function of the rate of global warming, the magnitude of temperature overshoot and the time spent above a target temperature. Understanding how the coupled Earth system will respond to different levels of warming stabilization is also urgently required (King et al. 2021). Drijfhout et al. (2015) assessed the occurrence of a range of different abrupt changes in CMIP5 models and found that the number of abrupt shifts increases with the radiative forcing. This suggests the potential for a gradual trend of destabilization of the climate with respect to such shifts, due to increasing global mean temperature change.

## 1.2 Key questions to be addressed within RT1

Research in RT1 will focus on improved understanding of the physics and chemistry of the climate system and its future change. This covers a wide range of processes in the ocean, atmosphere and other Earth system components. Particular focal topics of RT1 will include

**Climate sensitivity:** How much long term warming does a doubling of $CO_2$ cause? What can we learn from paleo proxies? How does ocean heat uptake affect global warming and climate feedbacks? How does the warming pattern affect feedback strength and time scale?

**Clouds, aerosols and precipitation:** How will different types of clouds change in response to warming, and what is the feedback on temperature? How will precipitation change? How much warming has been masked by aerosol forcing, including cloud-aerosol interactions? What can observed variability in clouds and aerosols teach us about cloud response to external forcing?

**Overshooting scenarios:** Are irreversible thresholds crossed in developments that involve a peak of warming followed by a long decline in global temperature towards the goals of the Paris Agreement? How does the risk for abrupt changes vary as a function of the magnitude of temperature overshoot and the time spent above a target temperature?

**Atlantic Meridional Overturning Circulation (AMOC):** How will the AMOC change in the future and how will these changes impact Arctic and European climate?

**Arctic climate and its impact on lower latitudes:** When will the Arctic Ocean be sea ice free in summer? How fast is winter sea ice declining and what does this mean for local and remote climate? How do the changes in ice extent and ocean temperature affect aerosol emissions in the Arctic? How do clouds and precipitation in the Arctic respond to the warming?

**Climate extremes:** What will the weather be like in a warmer climate? How will extreme weather events and climate hazards such as extreme precipitation events and floods, droughts, hot spells, and storms change in the future?

**Air quality and climate:** How will reductions in aerosol emissions for air quality improvement affect climate? What are the potential synergy effects, or risks related to air quality measures for climate?

### 1.3 Key methodologies in RT1

The research within RT1 will be based on numerical modelling as well as in-situ observations, remote sensing and laboratory experiments. A range of models from simple component models to fully coupled ESMs and convection-permitting (km-scale) climate models will be utilized. On a regional scale, large-eddy simulation will be used to understand the details of the time evolution of the atmospheric boundary layer, cloud and precipitation formation, and the interactions between atmospheric aerosols, clouds and the underlying surface. Large-scale climate models will be used to perform climate sensitivity experiments to understand the processes governing this sensitivity, storm-resolving simulations to investigate extremes and local changes, and long-term coupled simulations and future projections to better understand the long-term Earth system response to anthropogenic warming, and feedbacks between components. To further investigate processes or isolate the response of single Earth system components to a forcing, component models are useful tools. Since component models are computationally less demanding they allow for running long periods, performing large sets of experiments or increasing the spatial resolution within the single component. The research will also rely on both in-situ and remote sensing observational systems, such as e.g. data collection from polar expeditions of the icebreaker *Oden* (e.g. *Synoptic Arctic Survey 2020–2022* or the *ARTofMELT – Expedition* [Atmospheric rivers and the onset of sea-ice melt] in 2023, which will be supported by RT1), and measurement stations in the ACTRIS network, as well as laboratory experiments (utilizing various chamber experiments on e.g. sea spray emission, atmospheric chemistry, as well as aerosol and cloud microphysics, Lehtipalo et al. 2016), and use of long-term reanalysis data sets and satellite monitoring of the climate system.

The Bolin Centre with its expertise in both modelling and observation, and across scales from microphysical to global, provides unique opportunities to jointly tackle the key RT1 questions.

### 1.4 Expected outcomes from RT1 and interactions with other RTs

The collaboration between experimentalists and modellers on cloud processes and aerosol-cloud interaction is expected to lead to 1) better understanding of cloud changes in response to warming, and subsequent effect on climate; 2) identification of the most important processes and ultimately to more physically sound representation of these processes in climate models. The development of global storm-resolving models will contribute to more reliable, and more regionally and societally relevant projections of future climate change, in particular climate extremes. Improving the representation of Earth system processes in ESMs and new long-term future scenarios will provide new knowledge on the likelihood of reaching tipping points at various warming and overshooting levels, and will inform policy and mitigation actions.

RT1 will closely work together with the other RTs of the Bolin Centre. It will provide climate change information and data at different scales as input for analysis of hydrology and ecosystem (RT2 and RT4). RT1 will learn from the knowledge on past climates (RT3) for the future climate; e.g. on climate sensitivity, sea level rise, Arctic warming, Atlantic Meridional Overturning Circulation. RT1 will work together with the other RTs on model development and use and provide improved climate models and new future projections with those models.

RT1 will provide science-based understanding of the Earth system and provide advice on future changes of the Earth system at global and regional scale, so that policy makers, societies and individuals can make fact-based decisions. The dissemination and communication activities will happen mainly as part of the European and national projects and through centrally organized communication activities of Bolin Centre and the involved Bolin Centre partners. Parts of the results will contribute to the national Swedish climate services at SMHI.

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## 2. RESEARCH THEME 2 (RT2) – WATER, BIOGEOCHEMISTRY AND CLIMATE

### 2.1 State-of-the-art and key knowledge gaps relevant to RT2

The dynamics of the coupled water and biogeochemical cycles are central to understanding the Earth System's response to climate variation and human interference. The sixth assessment report of the IPCC highlights a limited capacity to quantify and project changes in temperature, the cycles of water, nutrients, and metals for carbon sequestration and ecosystem responses (Canadell et al., 2021). Important knowledge gaps exist regarding the climate change impact on ecosystems and the adaptive capacity to droughts, wildfires, ocean warming, ocean deoxygenation, and the warming cryosphere-driven carbon, nutrient and contaminant mobilization and their export to catchments and the ocean. Local, regional, and global climate variability and natural and human developments alter still water and groundwater resources (Messager et al., 2016), and hydrological changes in the ocean affect its heat uptake and circulation, and as a consequence, sea ice melting, calving rates, and ocean stratification and in the long-term sea-level rise (Ingvaldsen et al., 2021; Carmack et al., 2016). However, regional climate change impacts on water quantity and quality have been challenging to detect due to the spatial patchiness of the corresponding hydroclimatic changes, including patterns, magnitude and variability (Angel and Kunkel, 2010; Greve et al., 2014).

As a result, for terrestrial systems, knowledge gaps have emerged on how surface and groundwater resources are currently changing due to direct (e.g. human water withdrawal) and indirect (e.g. climate change) human activities, which are the specific drivers of change, and how these changes have a long term effect on terrestrial ecosystems providing essential biogeochemical functions. For the ocean, the human influences on ocean altering heat fluxes, increasing stratification, and changing ocean acidification levels are very certain, but critical knowledge gaps exist concerning regional differences, e.g., for the Arctic Ocean regarding Atlantification, the impact of Greenland ice sheet melting on marine productivity, making effects for marine ecosystems difficult to predict. Lastly, there is still major uncertainty on the future mobilization of methane from destabilizing gas hydrates on the Arctic marine shelf areas, as well as from thawing permafrost in Arctic land areas and their potential impact on the atmosphere and global climate warming. Natural and managed ecosystems with high carbon sequestration potential are promoted to support mitigation actions to climate change, but these systems also play a major role in maintaining biodiversity to provide critical ecosystem services that humanity depends on. This calls for improved knowledge of potential trade-offs and synergies when managing the climate adaptation and mitigation potential of ecosystems.

Examples of Bolin Centre research themes relevant to the knowledge gaps are studies on permafrost carbon and nitrogen mobilization (Hugelius et al., 2020), carbon sequestration and methane fluxes in the land-ocean transition zone (Roth et al., 2023), climate impacts on active layer and permafrost dynamics (Hamm and Frampton, 2021; Magnússon et al., 2022), wetlands (Thorslund et al., 2017; Åhlen, 2023), soil-vegetation interactions (Keuper, Wild et al., 2020; Manzoni et al., 2022), and regionalized assessment of terrestrial carbon export into the Arctic Ocean (Martens et al., 2020). Many of the principal mechanistic changes in hydrological and biogeochemical processes from climate and human pressures are well-studied; relevant examples include ocean acidification, eutrophication, land use change, intensification of the hydrological cycle, and microbial processes regulating climate-relevant trace gases. Nevertheless, the strong temporal and spatial variability of key parameters and processes, and their interdependencies, prevent reliable up-scaling or representation into mechanistic models capable of future projections. These shortcomings are reflected in an inability to avoid double-counting in broad-scale GHG budgets (Saunois et al., 2020), to quantify interventions to the water cycle and water resources (Destouni 2012, Jaramillo 2015, Gleason et al. 2020), or insufficient time resolution and general underrepresentation of, e.g., the coastal zone in Earth system models (Ward et al., 2020).

## 2.2 Key questions to be addressed within RT2

Filling the knowledge gaps defined above requires multiple perspectives. The Bolin Centre research community hosts diverse research groups focusing on biogeochemical cycles and water-related research questions from atmospheric, hydrological, chemical, glaciological, physics-based, catchment-based, limnological, fluvial and oceanographic perspectives. Furthermore, the spatial coverage of research within the Bolin Centre, which includes studies on different continents, biomes, and various hydrological and biogeochemical systems, becomes an asset. Some of the key research themes and questions that could be of focus within the Bolin Centre in RT2 are suggested below:

**Climate change impacts on hydrology and their implications for water availability and quality:** Both drivers and effects need to be identified and quantified, with expertise in these tasks pertaining to the Bolin Centre. For instance, how do the combined increase in atmospheric carbon dioxide concentration and altered rainfall patterns affect the water use efficiency of vegetation (Wang et al., 2022)? From a system's perspective, the term "tipping point" has been defined as the value of the critical threshold at which the future state of a system is qualitatively altered, with important implications for humans, ecosystems and resources. However, the importance of "tipping points" are not yet well understood and studied in hydrological systems. For example, can non-linearities and tipping within hydroclimatic systems create persistent changes in water availability on land? There are also fundamental gaps in understanding potential non-linear components and multiple stable states in affecting bio-geochemistry systems enforcing tipping points that can lead to strong feedback effects on the global climate. To answer these questions, we need a better understanding of the hydrological processes occurring in the atmosphere, biosphere, surface-atmosphere interface, and belowground, and how these systems interact with other drivers of change. The drivers reflect the llinks between people and water, supply and provision of ecosystem services and conflicting values. An increased account of the mentioned subjects could also lead to knowledge of how effective different nature-based climate mitigation strategies are and if these strategies have adverse effects.

**Biological, geochemical, and hydrological changes related to the cryosphere:** How do carbon-sequestering biota respond in composition and activity to Arctic ocean warming and glacial or permafrost thawing-induced changes in nutrient inventories and -cycling? How does the melting of sea ice affect the exchange of the climate-active trace gases carbon dioxide, methane, and nitrous oxide into the atmosphere? How are ice sheet and glacier dynamics affected by climate variations, and what effect does that have on sea level rise for land systems? What are the processes and quantities of organic and inorganic material transferred between the Siberian permafrost region and the Arctic shelf and slope systems under current and upcoming climate change?

**Hydrological and biogeochemistry changes in wetlands:** The Bolin Centre has consistently researched the hydrology and biogeochemistry of wetlands–a key freshwater resource and GHG. Wetlands occur in Artic, boreal and tropical regions and may be inland or coastal, fully or partially saturated with water, such as peatlands, and are indispensable for sustainable development (Jaramillo et al., 2020). The breadth and heterogeneity of research focus within the Bolin cover all these types (e.g., the Global Wetland Hydrology Network-GWEN). Interestingly, wetlands are left out of common sustainability and hydrological frameworks. For instance, the 21 Unsolved Problems of Hydrology of the International Association of Hydrological Sciences (Blöschl et al., 2019) do not explicitly account for wetlands or any other inland surface water resource despite their importance for the Earth's system. This represents an opportunity for Bolin to showcase the importance of hydrological and biogeochemistry research on wetlands and inland waters. How is water availability changing in wetlands and water are the drivers of these changes?

**Land-ocean export and coastal transition zone:** Due to the combined strong marine and terrestrial expertise within this research theme, the Bolin Centre research community is well-positioned to address climate research questions, especially in fields where these two areas of expertise meet. One central research topic is how climate-related biogeochemical and hydrological changes impact land-ocean transport of carbon, metals and nutrients, coastal marine productivity, and carbon sequestration in marine sediment.

**Coupled cryotic, hydrological and transport processes:** In regions with permafrost, the active layer is a critical zone of exchange which connects the atmosphere and biosphere through the hydrosphere and strongly influences energy fluxes, hydrological flows, biogeochemical cycles, and solute and contaminant mass transport. A key topic to address is how solutes and contaminants are transported by surface and groundwater flow in the active layer of warming permafrost and to study how attenuation mechanisms specific to arctic environments influence residence times. Understanding links is difficult because of the inherent nonlinear coupling of processes leading to significant complexity between drivers and effects. The collective expertise within the Bolin Centre enables these challenges to be addressed through the combined model analysis and field investigation.

## 2.3 Key methodologies in RT2

The Bolin Centre has, by national and international standards, a strong capacity for field and laboratory-based measurements of water and biogeochemical cycles. Bolin Centre scientists conduct fieldwork in ecosystems across the globe and run long-term field experiments and monitoring stations. There are excellent facilities for analyses of the climate-active trace gases $CO_2$, $CH_4$, and $N_2O$, as well as organic biomarkers, particularly in stable isotope analysis. This analytical competence is further expanding, putting Stockholm University (SU), with its Bolin Centre scientists, in the top range of European climate and geoscience-oriented research institutions. We are also uniquely positioned in our capacity to conduct high-resolution data assessments using cutting-edge technology based on land or from research vessels. These include, among others, strong expertise in conducting continuous ship-based trace-gas exchange-rate measurements using, e.g., using eddy covariance that is extremely relevant for local climate-relevant estimates. The vicinity of the Baltic Sea next to making it an important study area, also enables us to classify this neglected, large brackish water body with its different and very distinct geochemical cycling processes into the climate context from a local and regional perspective.

The strong logistical infrastructure and expertise for marine- and land-based Arctic climate research, including the use of the icebreaker Oden and its synergies and collaborations with the Baltic Sea Centre through the Askö Laboratory and the CoastClim project, position the Bolin Centre at the international forefront for studies of the cryosphere and biogeochemical cycles in the Arctic.

The Bolin Centre hosts researchers working on using remote sensing and geodetic technologies to study water resources to track water availability in an emerging field called Hydrogeodesy. Some of these technologies can measure the changes in the Earth's solid and aquatic surfaces and can therefore be used to assess changes in water resources' distribution, movement, and properties. These technologies are already being used at the Bolin Centre, positioning it as a hydrogeodetic hub in Northern Europe. The attribution and causality of changes in freshwater resources require remote sensing, in-situ observations and datasets of hydroclimatic variables to quantify the hydrological changes.

Furthermore, scientists linked to the Bolin Centre also conduct extensive work on hydrological, biogeochemical, and water quality modelling across scales ranging from soil pores to catchments and regional representations. We integrate modelling at smaller scales to support Earth system modelling initiatives, which, combined with extended hydrological observations worldwide and in Sweden, can allow for validation, calibration and predictive simulation. A key objective of our future over the next five years will be to establish ESM expertise in the Bolin Centre that explicitly allows the RT2 community to address coastal zone hydrological and biogeochemical processes. This expertise is currently not well developed but bears great potential.

### 2.4 Expected outcomes from RT2 and interactions with other RTs

Our key working goal will be to deepen our understanding of hydroclimatic and biogeochemical changes and their interactions worldwide. Hydroclimatic research will particularly emphasise the physical processes driving water and energy availability. This will include a novel assessment of high-resolution wetland water availability changes worldwide and knowledge on how water resources and fluxes are changing across different spatial and temporal scales, especially the least studied ones such as wetlands and small lakes – having implications for and connecting to all the other RTs. We further expect to deliver significantly improved assessments for bottom-up quantification of $CH_4$ and $CO_2$ exchange in the land-ocean transition zone, including northern temperate coastal wetlands and improve current knowledge of projected carbon mobility and transformation in thawing Arctic environments. With further regard to ongoing cryospheric changes, RT2 work will deliver new data and a better understanding of the effects of changing ice cover in Greenland fjord systems and the marginal ice zone in the Arctic Ocean for productivity, nutrient availability, ocean acidification, and trace gas cycling – which has direct implications for the work within RTs 1 and 4, for instance, by exploring biodiversity-ecosystems-water-society connections. These studies should be evaluated and tested mechanistically using regional and global Earth system models, for which we strive to obtain expertise, in particular about implementing hydrological and biogeochemical processes in the coastal zone and coastal wetlands.

Around 60% of the world's population lives within 100 km of the coast. Assessing the drivers and climate impact of hydrological and biogeochemical changes in this zone is paramount. The portfolio of planned research activity bridges the complete range of climate-related research from their physical basis to impact assessment and assessment of potential mitigation scenarios using nature-based solutions for carbon uptake. Our hydrological research is critical concerning the reduced water availability projected by Earth system models, especially for central and southern Europe, Asia, and northern South America. These densely populated regions face significant agricultural and drinking water supply challenges that need urgent attention. The ongoing climate changes in high latitudes also change available natural resources to indigenous communities. They are an integral part of the incipient and planned use of the Arctic for land and sea transport, natural resource exploitation, and strategic military planning. Understanding the sensitivity of this environment remains a fundamental research and societal objective for the coming years.

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# 3. RESEARCH THEME 3 (RT3) – PAST CLIMATES

## 3.1 State-of-the-art and key knowledge gaps relevant for RT3

The unabated rapid rise of greenhouse gas concentrations and corresponding global warming leads to fundamental changes in Earth's climate, with no recent historical precedents. Our inability to limit $CO_2$ to below 550 ppm is steering us towards 800 ppm $CO_2$, a concentration not seen in over 35 million years (Zhang et al. 2013). To comprehend Earth's climate under such high $CO_2$ levels requires us to look back to the geological past into the Pliocene ~3 Ma (Million years ago) or even the early Eocene (~49–56 Ma) (Fig. 3.1). This highlights the geological dimension of the climate crisis.

To contextualise present climate impacts, we must integrate longer-term global change with climate modelling and geological records of the past. Proxy estimates or high $CO_2$ world simulations from past greenhouse intervals suggest that many Earth system models may underestimate climate sensitivity (Royer, 2016; Foster et al., 2017; Tierney et al., 2020). In contrast, some recent CMIP6 models seem to overestimate ECS, resulting in unrealistic paleoclimates (e.g. Zhu et al. 2020; 2022). Resolving this discrepancy in new model versions is crucial. One challenge lies in obtaining more accurate spatial estimates of past climate change (see e.g. Mauritsen 2016; Zhou et al. 2021). The state-dependency of ECS and its potential increase (e.g. Caballero and Huber 2013) or decrease (e.g. Pfister and Stocker 2017) with rising $CO_2$ concentrations continues to be a debate subject in climate studies.

While the Earth has experienced extended warm greenhouse climate states before, the pace of current warming is likely much faster than historical events (Zeebe et al., 2016). Foster et al. (2017) even argue that business-as-usual could push the climate system into a state not seen in at least the last 420 Ma. Geological archives of the deep past have recorded periods of high $pCO_2$ comparable to present and near-future levels (Steinthorsdottir et al., 2021), as well as periods of rapid $pCO_2$ change (Westerhold et al., 2020). On the other hand, studying climate variability at millennial time scales throughout the Quaternary period (Mottl et al., 2021) is vital for enhancing proxy records interpretation obtained from the higher precision in this period. Insights from centennial to millennial time scales help quantify insights into transient climate response to specific forcing (such as orbital and greenhouse gases) and identify the processes and feedbacks that drive climate instability and abrupt shifts.

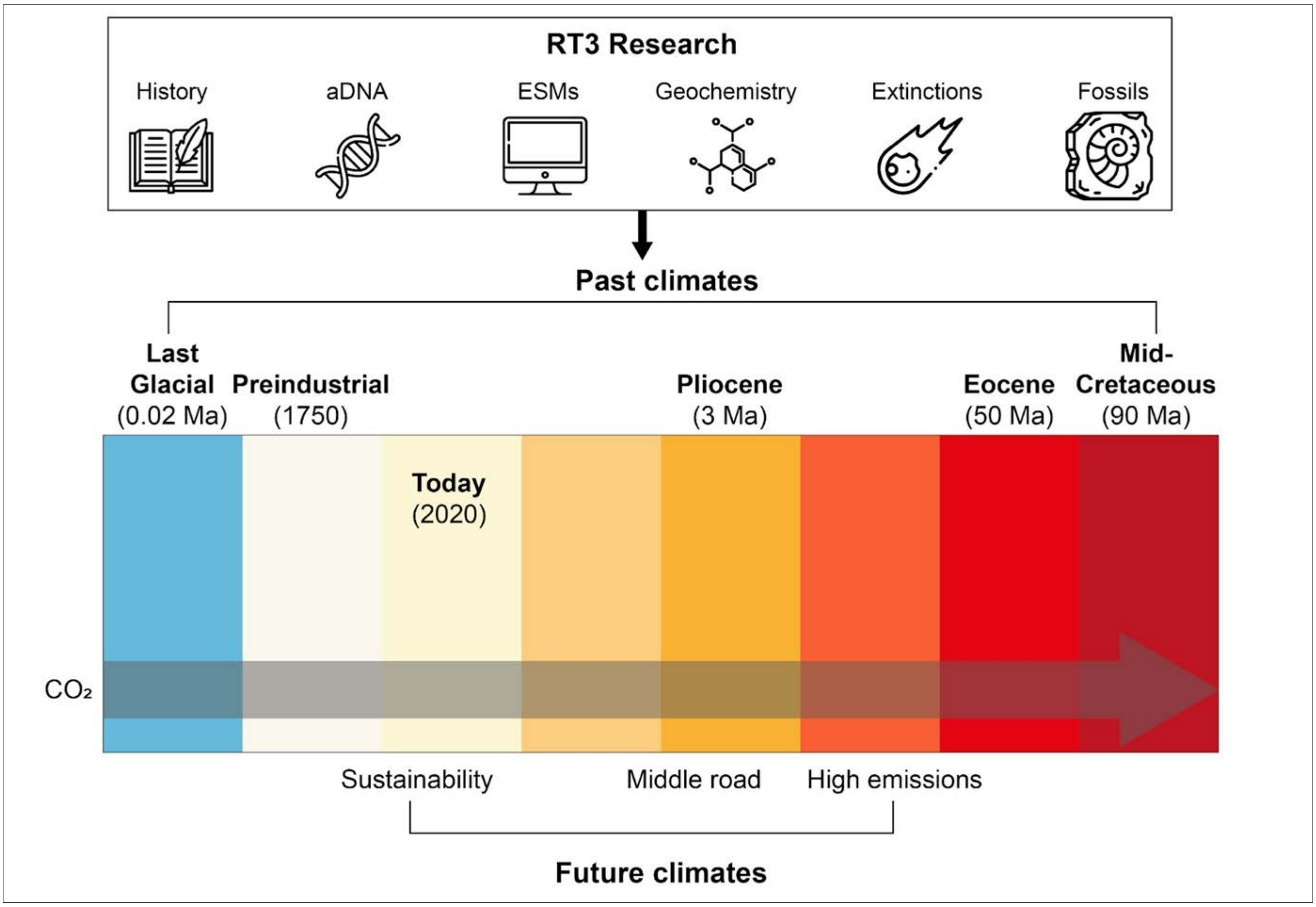


*Figure 3.1. Past climates provide context for Earth's future (modified after Tierney et al., 2020). The broad research in RT3 focuses on reconstructing past climates through a variety of proxies and methodologies, which provides necessary context for understanding climate change and climate variability in the present and near-future. Blue (colder) to red (warmer) climates are coloured by their estimated change in global mean temperature relative to preindustrial conditions. Future climates are represented by estimated global temperature anomalies at year 2300 from the Shared Socioeconomic Pathways (SSPs): "Sustainability" (SSP1-2.6), "Middle road" (SSP2-4.5), and "High emissions" (SSP5-8.5). Now, as in the past, increases in CO2 are linked with global warming. Ma, millions of years ago.*

Palaeoclimate research demonstrates that Earth's climate has always fluctuated, often resulting in significant impacts on biodiversity and society (e.g., Kirchner and Weil, 2000; Ljungqvist et al. 2020). In response to rapid climate changes, biota have exhibited range shifts, phenotypic plasticity, evolutionary adaptation, and extinctions, including mass extinctions (Davis and Shaw, 2001; Dalén et al., 2007; Bolinder et al., 2016; Bond & Grasby, 2017; Benton, 2018; McElwain, 2018; Lord et al., 2020; Vajda et al., 2020; van der Valk et al., 2021). A remaining knowledge gap is understanding how these processes influence survival (Nogués-Bravo et al., 2018). However, it is clear that intervals of rapid warming (hyperthermals with warming of >1°C) have frequently triggered global biodiversity crisis in the past (Bond and Grasby, 2017; Benton, 2018; Foster et al., 2018; Vajda et al., 2020), which were linked to disturbances in carbon and water cycles, as well as reduced oxygen and pH levels in the marine realm (Foster et al., 2018; Clapham and Renne, 2019). Investigating the dynamics of these previous extinctions is critical for appraising the current accelerating biodiversity crisis. Termed by some as the sixth mass extinction, there is a high degree of certainty that it poses a global threat to ecosystems and the continuation of human civilization (e.g., Barnosky et al., 2011; IPBES, 2019; Ceballos et al., 2020).

Gaining a comprehensive understanding of Earth's past climates and addressing these key knowledge gaps will be essential to inform and guide our response to the ongoing climate crisis, helping us better prepare for and potentially mitigate the severe impacts of climate change on biodiversity and society.

### 3.2 Key questions to be addressed within RT3

Research at the Bolin Centre on past climates spans a wide range of time scales, from tectonic and orbital to millennial and historical periods. Our research explores critical topics, such as extreme events like pan-glaciations and hyperthermals (Steinthorsdottir et al., 2021), recurring greenhouse and icehouse climate modes (Barbolini et al., 2020), climate feedbacks and mechanisms related to ice sheets (Schenk and Vinuesa 2019), and ocean temperatures during abrupt climate shifts (Schenk et al. 2018). We also investigate Earth system feedbacks (vegetation, ice sheets, etc.) at global (Feng et al. 2022) and continental scales, including the "Green Sahara" (Pausata et al. 2017; Berntell et al. 2021).

Using the ESM EC-Earth, the Bolin Centre contributes to the study of key paleoclimate periods defined by the Paleoclimate Model Intercomparison Project (PMIP4). We perform paleoclimate simulations for various warm states, such as the mid-Pliocene, Last Interglacial and mid-Holocene (Zhang et al. 2021). We also examine climate sensitivities and oceanic overturning circulation in the late Eocene (Hutchinson et al. 2018). On historical and millennial time scale, we use reconstructions and multi-model simulations to investigate the influence of external forcing (including volcanic eruptions and solar activity) versus internal climate variability (Moberg et al. 2005; Ljungqvist et al. 2016), as well as their impacts on societies and land use change (Ljungqvist et al. 2020).

In geosciences, considerable efforts have been made to reconstruct rapid termination of continental ice sheets during the Lateglacial period (~(~15–11 ka) in Scandinavia (e.g. Larsson and Wastegård, 2021; Larsson et al., 2022) and the marine components of the Greenland Ice Sheet (e.g. Jakobsson et al. 2018; O'Regan et al., 2021). Other focus areas are Lateglacial paleoenvironmental changes in Africa (Kylander et al., 2021), abrupt shifts in the southeast Asian monsoon region (Hallberg et al. 2022; Smittenberg et al. 2022), Holocene reconstructions of peatland formation and paleo-storminess over the Euro-Atlantic region (Kylander et al., 2019) and Holocene permafrost dynamics in subarctic peatlands (e.g. Sannel & Kuhry 2008; Sannel et al. 2018).

It is crucial to recognize that human achievements since the advent of agriculture have taken place within the relatively stable Holocene climatic. Today, we face the risk of departing from this familiar envelope. The Earth is now committed to climate states different from any experienced during the existence of the species Homo sapiens (Burke et al., 2018). Some of these changes and losses will be irreversible (IPCC, 2022). Current atmospheric CO2 levels (421 ppm) have already exceeded Quaternary levels, and a Representative Concentration Pathway (RCP) of 4.5 could lead to a Pliocene-like climate state by 2030 (Burke et al., 2018). However, the mid-Pliocene was characterised by near-modern $pCO_2$ levels of ~400 ppm, emphasizing the need to investigate deeper in time for appropriate future climate analogues (Steinthorsdottir et al., 2021).

**Key questions in deep-time paleoclimate research include:**

1. Reconstructing and modelling radiative forcing and temperature responses for high $CO_2$-worlds on tectonic time scales (e.g. Eocene-Oligocene Transition, Hothouse climates).

2. Quantifying past climate thresholds: Identifying and quantifying past climate tipping points can provide valuable insights into the risks and consequences associated with crossing such thresholds in the future. Research on past climate transitions can inform climate change mitigation and adaptation strategies.

3. Bridging the “language barrier” between climate model and deep-time proxy data, which sees paleoclimate information increasingly being directly incorporated to constrain model performance (Tierney et al., 2020).
4. Enhancing the accuracy and reliability of proxy data used to reconstruct past climates (i) providing a real past “observation” by reducing uncertainties, and (ii) improving the capability of ESMs to simulate past warm climates through model-data comparison.
5. Addressing the lack of connectivity between marine and terrestrial responses to past environmental change; many past biotic crises are either better characterised by one realm (Page et al., 2019) or marked by disagreement on whether terrestrial and marine extinctions occurred simultaneously (Rubidge et al., 2013). Atmospheric processes are key in understanding ocean-land dynamics during these crises (Bond and Grasby, 2017).
6. Linking the fossil record with findings and predictions of modern biodiversity and ecological responses to climate change (Bolinder et al., 2016; Barbolini et al., 2020; Mottl et al., 2021). The current rate of anthropogenic climate change is much faster than well-studied past intervals of rapid warming linked with biodiversity crises (Diffenbaugh and Field, 2013), making it difficult to directly compare palaeo-analogues with the future.

**Key questions in Quaternary climate research** focus on reconstructing and modelling transient climate variability, abrupt climate shifts, climate instabilities and Earth’s sensitivity to various combinations of external forcings, such as orbital configurations, greenhouse gas levels, and volcanic eruptions. These external forcings result in different global and regional climate changes involving numerous physical and dynamical feedbacks. There are currently five key time periods that are central to RT3 in recent and upcoming years:

1. Orbital time scales: Identifying past warm periods (interglacials and interstadials) in the Quaternary that were as warm or warmer than current climate. The question of a seasonally ice-free Arctic and sea-level changes at specific warming level in the past is a key aspect, with proxy-reconstructions and modelling, such as the Last Interglacial (LIG) simulation contribution to PMIP4.
2. Abrupt climate shifts and rapid termination of the last glaciation (Last Termination): Understanding the causes and impacts of abrupt cooling and warming periods on climate, ecosystems and biodiversity during the rapid warming at the end of the last glaciation are still poorly understood. This period is crucial for understanding feedback processes behind ice sheet collapse and interactions with ocean overturning circulation that cause hemispheric temperature changes greater than 10 degrees in years to decades.
3. Transient changes and trends in the Holocene: The “Holocene Temperature Conundrum” – a fundamental disagreement in the timing and even sign of multi-millennial long-term trends (~11.000 years) between climate model simulations and proxy reconstructions, is still unresolved. Key questions involve potential seasonal biases in proxy records and missing feedback processes in climate models. These aspects are essential for understanding future climate change.
4. Centennial to millennial climate variability: Recent studies question whether multi-decadal oscillations are truly internal variability of the climate system. As most control simulations do not show significant low-frequent variability, it is hypothesized that low-frequent variations are artefacts of forced variability (i.e. volcanic, solar). Resolving these questions is crucial for estimating the importance of low-frequent

variability in recent, present and future warming, as well as potential impacts on decadal climate predictions and future projections. Distinguishing between external and internal variability is vital for detection and attribution studies to quantify ongoing global warming's role in recent trends and extremes.

5. Historical climate variability: Classical climate proxies all rely on transfer functions that require constant revision. Independent assessment of these proxy-reconstructions can be made using historical measurements and documents that provide direct inference of ancient weather and climate extremes. There is an urgent need to digitise, homogenise and use more historical data dating back to the early 20th century or earlier, such as sub-daily data, which offers crucial information on long-term statistics of extreme events and potential changes due to global warming. For example, SMHI has recently started to digitise Swedish station data using machine learning methods in collaboration with KTH. Such historical data is vital for research with societal relevance but typically does not receive external research funding.

### 3.3 Key methodologies in RT3

Understanding the full range of Earth's climate variability requires us to look beyond the present-day climate and delve into the geological and historical past. By examining data beyond the range of instrumental records and linking observations from the natural archives with ESM simulations across multiple timescales, we can gain insights. Simulating past climate extremes allows us to test model capabilities in capturing mechanisms and feedbacks within the climate system, ultimately improving our confidence in predicting future climate change.

A wide range of proxies found in nature archives such as rocks, fossils, oceans and lake cores, terrestrial sediments, landforms, peatlands, ice sheets, cave deposits, tree-rings, and historical documents provide information about past temperature, atmospheric $CO_2$ levels, hydrology, and biogeochemical cycling. This information forms a basis for quantitative climate reconstructions at various points in time and for different climate modes. Combining proxies from the more recent past with historical documents allows us to explore how humans have adapted to climate change and variability over hundreds to thousands of years. Historical and archeological sciences offer valuable insights into land use changes during the Holocene and early impacts on the regional to global climate, that need to be accounted for in climate model simulations of the Common Era back to the mid-Holocene.

The Bolin Centre has facilitated collaboration between modellers and the proxy community within RT3, and further strengthening this connection is essential. Over the years, RT3 scientists have produced numerous climate model simulations covering deep-time hothouse and icehouse periods, Quaternary cold/warm periods, abrupt climate shifts, and historical to millennial variability simulations. These simulations have not been extensively incorporated into corresponding proxy studies within RT3. Therefore, we aim to prioritize future research projects that concentrate on common time periods and utilize both model and proxy data for a comprehensive understanding of system change. Upcoming collaborations can emphasize refining and validating models using paleoclimate data, or even tuning the models for significantly different climate conditions, given that current model physics are parameterized and tuned based on present-day climate conditions.

There is enormous potential in employing novel statistical methods, including machine learning, to link the growing coverage of proxy records with multivariate full-field information from completed model simulations. A crucial next step in proxy studies is upscaling local information to derive large-scale, spatially consistent patterns, enabling hemispheric to global estimates of radiative forcing and temperature changes with the help of model simulated fields. Currently, there is a need to develop capabilities regarding isotope-enabled climate modelling and establish a systematic approach to ice sheet modelling that can benefit from the robust geoscientific fieldwork at SU and existing paleoclimate model output that can be used as forcing.

### 3.3 Expected outcomes from RT3, interactions with other RTs and key stakeholders

Evidence from palaeoclimates and past biotic responses indicates that substantial ecological, evolutionary, and socio-economic impacts have already been caused by climate changes over the last centuries (IPCC, 2022). A major outcome of RT3 is to better understand the causes of these impacts and apply this knowledge to develop mitigation and adaptation strategies for present and future climate change.

Research on past climates involves a diverse range of field-, laboratory- and computer-based disciplines, including physical geographers, geologists, geophysicists, palaeoceanographers, palaeontologists, palaeogeneticists, climate modellers, statisticians, archaeologists, and historians. We will prompt interdisciplinary collaboration to address knowledge gaps and stimulate innovative research ideas. By bridging these disciplines, researchers can investigate effects of climate change on food production and availability, land and sea transport, fuel consumption, and human health. Additionally, we can identify measures taken by humans in the past to reduce vulnerability to climate change impacts.

It is crucial to invest in communication and outreach efforts to make paleoclimate research more accessible and understandable for policymakers, funding agencies, stakeholders, and the general public. By doing so, we can help raise awareness about the importance of past climates in shaping our understanding of future climate change.

RT3 encompasses research covered by all other Bolin Centre RTs, but applied to the past. The physical-chemical climate system (RT1), water and biogeochemical cycles (RT2), and ecosystems and biodiversity relationships with climate (RT4) are all investigated across various timescales. It is thus particularly important for RT3 to foster existing collaborations and forge new synergies with researchers from the other RT's.

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## 4. RESEARCH THEME 4 (RT4) – CLIMATE, ECOSYSTEMS AND BIODIVERSITY

Climate is the fundamental factor controlling ecological processes at individual organismal to ecosystem levels. Biophysical processes mediate climatic effects on organisms. These processes affect community composition and genetic variation within populations across terrestrial and aquatic ecosystems. Along with species interactions, climate also drives the distribution of species and biomes, steering where, from local to global scale, species can establish and survive. Variation in climate, across both space and time, is one of the main determinants of natural selection that lead to the evolution of adaptations within species. Throughout the history of life on Earth it is clear that major changes in populations, species, and ecological communities, along with the associated changes in biodiversity, have been driven by long-term changes in climate.

### 4.1 State-of-the-art and key knowledge gaps relevant for RT4

The relatively rapid ongoing change in climate negatively impacts many ecosystems and is one of the main drivers for biodiversity loss (IPBES 2018, Román-Palacios & Wiens 2020). Climate change has already led to major alterations in seasonal timing and the geographic distribution of many species. In temperate areas, spring events are occurring earlier (i.e. change in phenology, Parmesan 2006, Thackeray et al. 2016, Kharouba et al. 2018), and the ranges of many species have shifted poleward (Chen et al. 2011, Macgregor et al. 2019). In response to these recent variations in environmental and ecological conditions, evolutionary changes in natural populations are also under way (Bradshaw & Holzapfel 2001, Parmesan 2006, Helm et al. 2019, Merckx et al. 2021).

Another major driver of biodiversity decline is land use change (IPBES 2018). The combined effect of land use and climate change is one of the key questions in future projections of changes in biodiversity and ecosystem health. The combined effect of land use and climate change can either be additive, synergistic or antagonistic and hence the nature of these interactions will affect biodiversity and ecosystems differently (Oliver & Morecroft, 2014). The local climate can also deviate substantially from average conditions in a region. For example, Christiansen et al. (2022) and Greiser et al. (2020) show that both forest management and microclimate impact plant communities at local scales, which may counterbalance the climate effect on larger scales. Many species also react slowly to land use change, causing an extinction debt (Kuusaari et al. 2009), which is crucial for understanding the effects of climate.

## 4.2 Key questions to be addressed within RT4

Research on climate, ecosystems and biodiversity at the Bolin Centre aims to understand how climate affects ecological and evolutionary processes (Fig. 4.1). As ecosystems are a combination of biotic and abiotic interactions, we investigate these interactions in relation to climate. Although our research focus is on the effects of climate on ecosystems and biodiversity, it is important to realize that there are also feedbacks from ecosystems and biodiversity back on climate systems (Zhang et al. 2017). The specific research questions RT4 will focus on are elaborated in more detail below, divided into three complementary themes:

**Ecological and evolutionary consequences of climate variation:** How does spatial and temporal variation in climate affect the demography of populations, seasonal phenology and migration, species interactions and community structure of plants, animals, fungi and bacteria? What are the evolutionary consequences of climate variability and climate change? What is the potential of eco-evolutionary dynamics to mitigate effects of climate change on present ecosystems? How have genetic variation, population structure and population size of animal species (both extant and extinct) changed over time, especially in the context of changes in climate during the Late Pleistocene (i.e. the last ice age)?

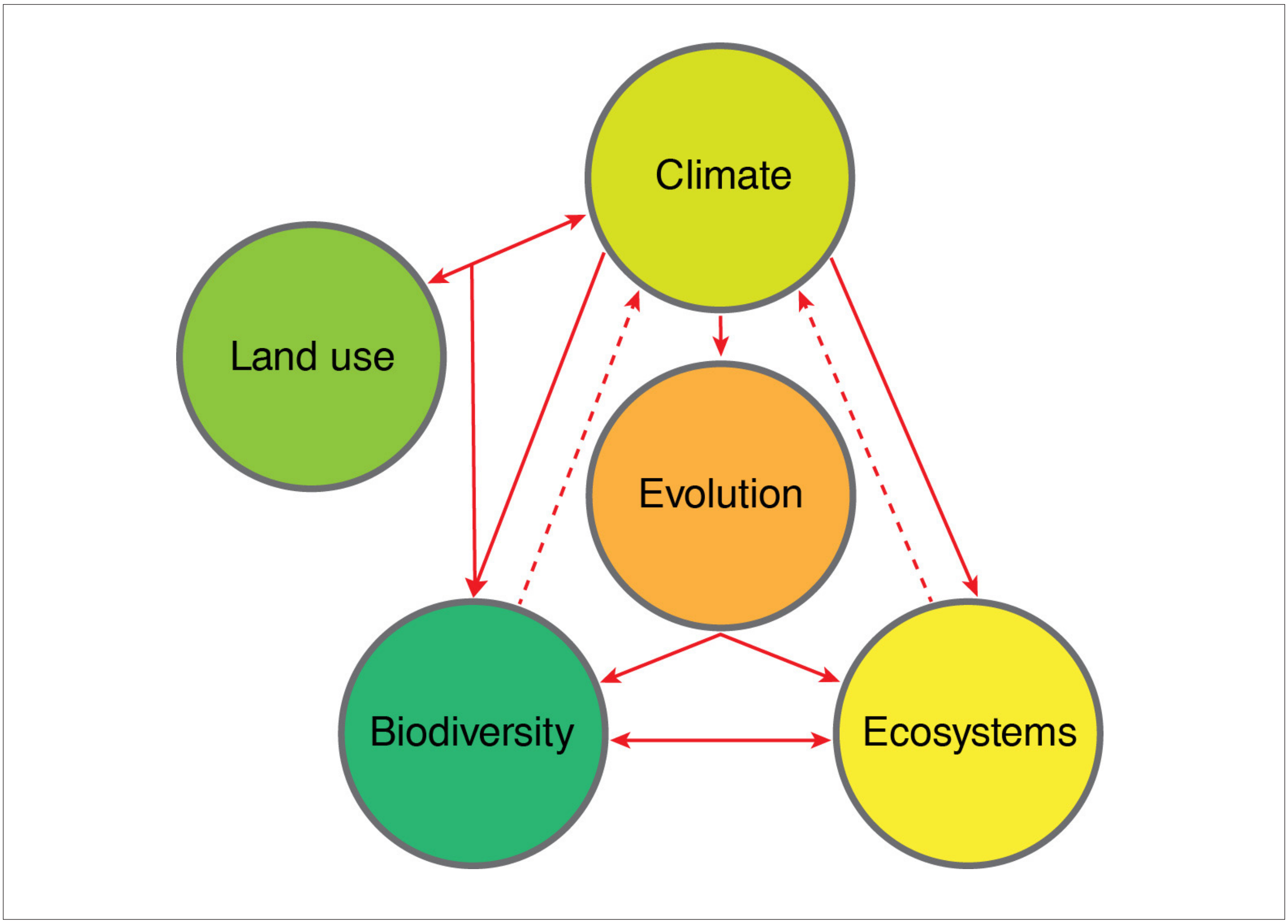


*Figure 4.1. The research within RT4 focuses on how climatic variation effects biodiversity and ecosystems as well as the combined effect of land use and climate on biodiversity (solid lines). How changes in biodiversity and ecosystems feedback on climate is important but less studied within the RT (dashed lines).*

**Climate and land-use interactions:** How do land-use and climate change interact? How do these in turn affect vegetation, ecosystems and biodiversity? How do land-use and climate change affect soil micro-organisms and their functions (e.g. greenhouse gas emissions and carbon storage in soil)? How do land use and climate change affect local microclimates that are relevant for vegetation and species distribution at the landscape scale?

**Wetland hydrology and biodiversity:** How does the changing climate influence the hydrological characteristics and nutrient cycling in wetlands and consequently their biodiversity, ecological functions, and provision of ecosystem services (water flow regulation, climate mitigation, nutrient retention)?

## 4.3 Key methodologies in RT4

Due to the complex interaction between biotic and abiotic factors affecting evolutionary and ecological processes, researchers in RT4 work at spatial scales ranging from millimeters to landscapes to the globe, as well as studying both past and current conditions in order to predict future changes. We use a broad variety of methodologies and tools including field observations (e.g., Greiser et al. 2020), citizen science data and laboratory experiments (Merckx et al. 2021), assays of genetic variation (Rodrigues et al. 2022), modelling (e.g., Manzoni et al. 2022), phylogenetic reconstruction (Braga et al. 2021), and paleogenetics (van der Walk et al. 2021) to explore ecological, evolutionary and biophysical responses to climate variation over space and time. Empirical investigations support and are inspired by theoretical advances using dynamical models. We also use GIS and remote sensing to collect data on large spatial scales as well as big data, including citizen science data, for modelling consequences of climate change on biodiversity.

## 4.4 Expected outcomes from RT4 and interactions with other RTs and key stakeholders

Based on the fundamental understanding of how climate affects ecosystems and species, we can provide answers to overarching questions such as: How does climate change affect the abundance and distribution of species, composition of ecological communities, and evolutionary responses of populations in natural and managed ecosystems? How do these biotic factors interact with abiotic components of ecosystems, such as atmospheric conditions, water availability, and soil properties? How do changes in the interactions of climate, ecosystems and biodiversity influence human societies and ecosystem services? Specifically, the research within RT4 will contribute to: 1) studying the potential of eco-evolutionary dynamics to mitigate the effects of climate change on present ecosystems; 2) assessing the importance of climate change for population processes that may lead to species extinctions; 3) improving predictions of water quality and quantity, ecosystem processes involved in climate change mitigation, and greenhouse gas emission changes across the globe.

We will further develop methods for adapting to and mitigating negative effects of climate change on biodiversity and ecosystems and their services, especially in environments exposed to agriculture, forestry and urbanization. Through our research we are also able to better understand and mitigate conflicts between Sustainable Development Goals (SDGs) such as conflicts between clean water (SDG 6), climate action (SDG 13), life below water (SDG 14) and life on land (SDG 15).

RT4 interacts with all the other RTs. It can receive data related to climate from e.g. RT1, as well as contribute to the development of global-scale modeling tools together with the other RTs. RT4 will collaborate with RT2 on the interactions between climate and biosphere, hydrologic cycle, and biogeochemical cycles, especially related to land use and wetland dynamics. RT3 researchers are natural collaborators in RT4 activities focusing on paleoecology and paleogenetics. RT4 will provide input to RT1 e.g. about the potential climate feedback mechanisms associated with the biosphere (e.g. via responses in emissions of greenhouse gases, water vapor and other relevant chemical species such as volatile organic compounds). Similarly, RT4 will provide input to RT2 about the changing role of the biosphere in hydrologic and biogeochemical cycles under changing environmental conditions, and to RT3 about the role of the biosphere in the past climate evolution and events.

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