LIQUIDICE

Milestone 6 Agreement on the scenarios used in LIQUIDICE, considering CMIP and ISMIP developments and needs of the downscaling task

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Contents

Introduction

Within the framework of LIQUIDICE, global simulations with Earth System Models (ESMs) will be performed, coupled to the vast ice sheets of the northern and southern hemispheres, namely the Greenland (Kalaallit Nunaat) and Antarctic ice sheets. Besides deciphering the impact of these interacting ice sheets on the global and regional climate state, these global simulations will be downscaled to LIQUIDICE's super-sites. At these super-sites, such as various glaciers in Svalbard and the Monte Rosa valley in the Italian European Alps, local-scale and specialized simulations will be performed to assess the vulnerability of the land cryosphere to climate change and project the cryosphere's future. Therefore, the global simulations fulfill three purposes.

First, LIQUIDICE will contribute substantially to the Ice Sheet Modeling Intercomparison Project (ISMIP) under the CMIP umbrella. An ISMIP branch is dedicated to systems comprised of ESMs and ice sheet models (ISMs). In these two-way coupled setups, ice sheets respond to the climate computed in the ESM, while the simulated evolution of an ice sheet influences the Earth System; e.g., shrinking ice sheets change the orography in the atmosphere and release meltwater as additional freshwater into the ambient ocean. Since all contributing groups will perform simulations following the same protocol, systematic analyses of all ISMIP simulations will reveal model spread, allowing quantification of uncertainties.

Second, we aim to understand better how the improved representation of large-scale interacting ice sheets affects climate warming trajectories with and without these dynamically evolving ice sheets. In addition, we aspire to identify the strength of feedback loops between ice sheets and the general climate system in our model systems.

Third, we strive to uncover how these interactions leave an imprint on regional to local cryospheric environments ranging from the high Arctic in Greenland and Svalbard, to the temperate European Alps, and beyond to the West Himalaya Asia region. Consequently, we shed light on how the commonly neglected cascading effects of neglecting interacting large-scale ice bodies in downscaled simulations determine the cryospheric future across different landscapes and communities.

This milestone describes the rationale for the selected global climate scenarios. Furthermore, this document lists fields from global simulations that LIQUIDICE partners will use to downscale climate states to regional and local scales, allowing specialized simulations to determine various impacts in collaboration with WP4 on hydrological conditions, tourism development (Italy), electrification and climate adaptation (e.g., Greenland). Finally, it summarizes the existing coupled climate-ice-sheet efforts.

CMIP and ISMIP scenarios under development

The ISMIP protocol describes the climate scenarios to be used in the framework of this international exercise to perform coupled Earth System Model-Ice Sheet Model (ESM-ISM) simulations. The related ISMIP working groups, under the lead of Robin Schmidt (UK), are currently drafting the protocol. Since it hasn't been finalized nor published, we discuss the drafted scenarios further below.

In general, past Climate Modeling Intercomparison Project (CMIP) climate scenarios have generally used the so-called "concentration-driven" mode, in which the atmospheric concentrations of greenhouse gases are predefined. Therefore, for each greenhouse gas, a time series of atmospheric concentrations has been constructed for each scenario. For CMIP6, the related approach is described by Eyring et al. (2016) and O'Neill et al. (2016). This approach has been used because previous Earth System Models have not been able to reasonably compute atmospheric carbon dioxide (CO2) from atmospheric emission rates. These emission rates include anthropogenic emissions from land-use changes and the burning of fossil fuels.

The carbon exchange between the atmosphere and land on one hand and between the atmosphere and the ocean on the other hand had been difficult to represent realistically because model deficits had hindered progress. In addition, the long intrinsic time required for the model to establish a quasi-equilibrium carbon dioxide distribution makes it computationally expensive to reach this state. In the ocean, establishing a quasi-equilibrium tracer distribution typically takes a millennium or more. Furthermore, compared to passive tracers, the ocean's carbon chemistry and its interactions with the aquatic biosphere and sediments increase the complexity. Unfortunately, this quasi-equilibrium is required to avoid unrealistic trends in carbon dioxide exchanges with the atmosphere that drive atmospheric concentration trends. Those trends would disturb or even suppress the interpretation of model simulations.

Recent progress in modeling the essential compartments of the carbon dioxide cycle has motivated the investigation of carbon-cycle feedback within the Earth system. Therefore, the newest generation of CMIP scenarios will also use "emission-driven" scenarios, in which the temporal and spatial emission of anthropogenic carbon dioxide are provided as boundary conditions to Earth System Models. The models internally establish atmospheric carbon dioxide concentration by accounting for carbon exchanges with the land biosphere, including the soil, and the ocean's biogeochemical carbon cycles. As described by Sanderson et al. (2024), the cycles of carbon dioxide and aerosols shall be explicitly resolved in ESM for the upcoming CMIP7 activities, whereas for the remaining greenhouse gases, e.g., nitrous oxide, CFCs, and HFCs, concentrations are prescribed as in the former "concentration-driven" approach. This hybrid approach for explicitly modeling the carbon cycle and describing other radiation-relevant chemicals is a pragmatic way to represent better carbon cycle feedback loops, which are of foremost importance for studying the impact of various Carbon Dioxide Removal (CDR) techniques. Since these CDR studies are beyond LIQUIDICE's objectives, we follow the ISMIP protocol and perform concentration-driven simulations.

The carbon dioxide is exchanged with the ocean is determined by the ocean's overturning time scale of about 1000 years. It is an expensive modeling effort to establish the required quasi-equilibrium, particularly given LIQUIDICE's ambitions to run global ESM simulations at high resolution. Besides the efforts to reach the quasi-equilibrium, the computational cost of the related processes is high, and, in particular, the requirements for storing additional variables related to biogeochemical cycles are nowadays a burden, as storage becomes a scarcer resource than computational time. In addition, emission-driven simulations may need to include aerosol calculations, which are known to be computationally intensive.

In terms of computational effort, we are keen on high resolution in the atmosphere and ocean because we expect better representation of atmospheric fields controlling the surface mass balance along the marginal ice sheets. These margins are characterized by its steep elevation gradient. Furthermore, this area is prone to topographically steered precipitation, and it is characterized by relatively narrow ablation zones. For instance, most of Greenland's overall mass balance losses occur in these ablation zones, where surface meltwater that is not refrozen runs off into the ambient ocean. The same applies to other mountain terrains, where other LIQUIDICE super-sites are located.

Also, adequate representation of the ocean circulation around Greenland and, in particular, Antarctica is necessary to obtain a consistent and, probably, more realistic climatic state. Consequently, we aim for higher spatial resolution to potentially better represent feedback loops of the interacting ice sheets, which impact the climate state itself.

LIQUIDICE addresses another central challenge: Closing the global water cycle by including the largest frozen water bodies on Earth in our Earth System Model simulations. It is an intermediate step toward eventually closing the whole water cycle by including regional glaciers as well in global simulations in upcoming projects. LIQUIDICE will lay some groundwork by including the debris cover effect in our Surface Mass Balance (SMB) model as part of Deliverable D3.3, "CISSEMBEL code: Debris cover, coupling to OpenIFS."

For all these reasons, in LIQUIDICE, global Earth System Models will apply the concentration-driven model configurations. This configuration choice is also consistent with the ISMIP protocol for coupled ESM-ice sheet model systems under construction. Furthermore, the obtained simulations will foster an inter-model comparison which is focused on the ice-sheet's interaction with its global environment, rather than on differences in the carbon cycle. In addition, this approach simplifies LIQUIDICE's downscaling activities because, for each scenario, the concentration time series are identical across all global ESMs, which will be downscaled; here, we follow established CORDEX procedures.

Global climate scenarios

LIQUIDICE aims for global Earth System Model (ESM) simulations following the ISMIP protocol for coupled ESM-ISM system in the task T3.1 "Land ice in Climate and Earth System Models (ESM): From global to regional scales" as part of the working package WP3 "Modelling and future projections: Global to Local and Integrated to Process-based." Therefore, LIQUIDICE will make a substantial contribution to this international effort. In addition, the global warming simulations will be downscaled by task T3.2, "Downscaling Climate Scenarios to the Local Scale of Glacier Basins," to provide spatially enhanced climate states. Ultimately, those downscaled climate scenarios will drive regional and local simulations of land ice in tasks T3.3, "Glacier-Hydrological modelling using Downscaled Data," and T3.4, "Dynamic-thermodynamic glacier and ice sheet modelling."

The ISMIP coupled ESM-ISM exercise requires performing simulations following different climate scenarios. To be part of this ISMIP exercise, the core simulations of the Tier 1 group must be run. These Tier 1 simulations comprise four simulations (Table 1), in which ice sheets are either active or passive. In the first case of active ice sheets, the coupling between the ESM and ice sheet models is a two-way coupling. The ESM influences the ice sheet model (ISM), and the ISM changes are fed back to the ESM. In the latter case, ice sheets are passive in the sense that they do not change their shape in the ESM and ice sheet growth or decay does not influence the mass and energy fluxes seen by the ESM. This configuration could be achieved through a one-way coupling, in which information flows only from the ESM to the ISM.

In all cases, the ESM provides climate forcing that drives ice sheet model simulations. It is within the modeling groups' discretion to rectify biases in atmospheric and oceanographic forcing fields to address existing climatic biases in the ESM model before deriving the ice sheet model's climatic forcing. The applied climatic forcing excites changes in the ice sheet's geometry and extent. In an actively coupled configuration, changes in ice geometry and extent influence the glaciated ice sheets in the ESM, e.g., by adjusting the ice sheet's orography. In addition, the related modification of the freshwater fluxes between ice sheets and the ESM is accounted for by altering the freshwater amount that reaches the ocean. The coupling between the ESM and the ice sheet model shall be performed for each model year.

For both the active and passive configurations, a control simulation and an idealized climate warming scenario shall be performed. In general, the (coupled) simulations start in the year 1950 to avoid creating starting conditions for unknown ice sheet geometries in the pre-industrial era. This procedure contrasts with the otherwise common starting year of 1850, which represents the pre-industrial era. The simulations shall last at least 200 years (until model year 2150), but it is recommended that the simulations span 500 years (model year 2450).

The global warming simulations of these Tier 1 simulations are considered for downscaling. For good comparability, both active and passive configurations shall start from the same ice sheet configurations. Since ice sheet simulations shall also be performed for the passive case, groups may decide to run them as offline simulations after the corresponding ESM simulations.

Control climate

For both control climate scenarios named 1950ctrl-withism and 1950ctrl-withoutism, we assume unaltered conditions throughout the simulations starting in 1950. It means the atmospheric greenhouse gas concentrations and the Ozone distribution are kept constant. Also, the solar constant and the radiation influencing aerosol boundary conditions (e.g., mixing ratios or optical properties) are constant too. In case the ESM is subject to a seasonal cycle of the above-mentioned properties, this cycle shall be repeated throughout the simulations.

If the ESM includes a dynamical vegetation component, it is at the modeling group's discretion to freeze the vegetation.

Climate warming

In the climate-warming scenario, the ISMIP protocol calls for an idealized 1% scenario, in which the atmospheric carbon dioxide concentration increases by 1% per year until it reaches four times the starting concentration. Afterwards, the atmospheric carbon dioxide concentration stabilizes at four times its starting concentration. For other greenhouse gases, ozone concentration distributions, and aerosol-related properties, the simulations shall follow the CMIP standards. As for the control climate, simulations for active ice sheets (1pctCO2-withism) and passive ice sheets (1pctCO2-withoutism) are required.

In an early discussion of the ISMIP protocol, it was suggested that the 4xCO2 is relative to the year 1950, leading to a higher final atmospheric CO2 concentration than the "classical" 4xCO2 scenario relative to 1850. The relevant ISMIP working group has not yet finalized this point.

Table 1 Tier 1 climate scenarios under the ISMIP protocol to perform simulations of coupled ESM-ice sheet models. Only one ensemble member is required.

Name	Start year	Required length	Preferred length	GIS	AIS
1950ctrl-withism	1950	200	500	On	On
1950ctrl-withoutism	1950	200	500	Off	Off
1pctCO2-withism	1950	200	500	On	On
1pctCO2-withoutism	1950	200	500	Off	Off

Teleconnections among the ice sheets interacting in the ESMs

Since we aim to have both the Greenland and Antarctic ice sheets as actively coupled components in our ESMs, we should consider performing Tier 3 simulations in which one sheet is active, and the other is passive (Table 2). These simulations shall help to determine whether teleconnections between the active ice sheets occur and whether the sum of only one active ice sheet equals both active ice sheets. We may restrict these simulations, in addition to Tier 1, to a lower-resolution version of our models.

Table 2 Subsection of Tier 3 climate scenarios under the ISMIP protocol to perform simulations of coupled ESM-ice sheet models. Only one ensemble member is required.

Name	Start year	Required length	Preferred length	GIS	AIS
1950ctrl-withismonlyGrIS	1950	200	500	On	Off
1950ctrl-withismonlyAIS	1950	200	500	Off	On
1pctCO2-withismonlyAIS	1950	200	500	On	Off
1pctCO2-withismonlyGrIS	1950	200	500	Off	On

Implications of the not-yet-finalized ISMIP protocol

Since the related ISMIP protocol has not yet been finalized, this Milestone report is based on our involvement in drafting the protocol and on close communication with the authors. The existing uncertainty is related to scenarios not used in the LIQUIDICE framework. Those uncertainties are summarized.

Triggered by discussion in the ScenarioMIP working group, the ISMIP definitions of the current Tier 2 high scenarios (highscenario-withism and highscenario-withoutism), Tier 3 low scenarios (lowscenario-withism and lowscenario-withoutism), and Tier 3 mid scenarios (midscenario-withism and midscenario-withoutism) are still under discussion because ISMIP scenarios shall be aligned with other CMIP activities. ScenarioMIP seems to favor six scenarios, which might be labeled very-low (VL), low (L), medium-low (ML), medium (M), high (H), and high-low (HL). The latter is related to ISMIP's Tier 3 overshoot scenarios (overshootscenario-withism and overshootscenario-withoutism), which might involve a 3-degree overshoot before 2100 and rapid recovery afterward.

Since the ISMIP community has been clear about the currently Tier 1 scenarios (Table 1), our use of those scenarios both leads to a significant ISMIP contribution of LIQUIDICE and reduces the risk compared to scenarios under discussion. If the ISMIP protocol changes, we may adjust our work plan after reevaluation accordingly. Also, the recently questioned target carbon dioxide concentration of four times the starting atmospheric concentration should be easily adjustable in our ESM frameworks.

List of global fields for downscaling activities.

Downscaling will be performed by two different means. Statistical downscaling will use various procedures. Further details on statistical downscaling approaches and the use of downscaled fields are available in LIQUIDICE's Milestone 4 (MS4), "Survey of climate data needs from local-scale modellers." Performing climate simulations with a regional climate model is known as dynamical downscaling, which is also exercised by CORDEX (see https://cordex.org).

Statistical downscaling

For statistical downscaling, the following fields shall be written out and preserved by global models (Table 3). The required output can be written out more frequently than listed in Table 3. This frequency is determined by the requests listed in Table 1 of the Milestone 4 and, in particular, by the needs for the domain "Fuglebekken and Ariebekken."

Table 3 Statistical downscaling requirements: Atmospheric fields from global ESMs for statistical downscaling to various sites; see also Table 1 of the MS4-report: "Survey of climate data needs from local-scale modellers."

Fieldname	Frequency (hours)	Comment
Temperature, surface	6	e.g., 2m-air temperature
Precipitation, surface	6	total precipitation
Humidity, surface	6	e.g., at a height of 2 m
Wind velocity u-component, surface	6	e.g., 10m-wind
Wind velocity v-component, surface	6	e.g., 10m-wind
Solar radiation downward, surface	6	
Thermal radiation downward, surface	6	
Topography	(static)	or surface geopotential height

Dynamical downscaling

For dynamical downscaling, boundary conditions from the global ESM are required at a sufficient temporal resolution to drive the regional climate models. In the LIQUIDICE framework, we will run two regional climate models: RegCM for the European Alps domain and REMOglacier for the West Himalaya domain. Table 4 lists the requirements for different models. In addition to the listed atmospheric fields, time series of atmospheric greenhouse gas concentrations are also required. Specifically, we need concentrations of carbon dioxide, nitrogen dioxide, methane, CFC-11, and CFC-12.

Table 4 Dynamical downscaling requirements. These atmospheric fields coming from the global ESMs are needed to drive regional climate models. Although the topography/orography of the ice sheet changes in the global ESMs, the topography across dynamical downscaled regions is unchanged. Therefore, the global modelers shall provide the first time-step of the required static fields.

Fieldname	Frequency (hours)	3D vs 2D	Comment
Temperature	6	3D	
Wind (horizontal)	6	3D	Alt.: vorticity and divergence
Humidity	6	3D	Mixing ratio or specific humidity
SST	daily	2D	From the ocean model
Surface pressure	(static)	2D	If on sigma pressure levels
Topography or surface geopotential heights	(static)	2D	If on sigma height levels

Radiation boundary conditions

The computation of radiation in regional climate models driven by climatic conditions from global models requires knowledge of the solar constant as a pure time-dependent irradiance function. Also, as described above, a time series of greenhouse gas concentrations is needed. Depending on the greenhouse gas specifics, these time series are either annual time series representative of the entire regional domain (1dim, time-only), may be subject to a latitudinal dependence (2dim, time and latitude), or be fully horizontally dependent (3dim, time, latitude, and longitude). Similarly, the atmospheric Ozone concentrations require including the vertical dependence, so that this is a 4-dimensional time series (time, longitude, latitude, height).

Surface boundary conditions

As lower boundary conditions, Sea Surface Temperature (SST; Table 4) is required for ocean-covered regions. For land points, the land and vegetation characteristics are needed. It includes the static and variable classifications (CLN PFT based on vegetation fields (LUCAS). The following fields are considered to be static: Urban, Lake, Wetland, and glaciers. Glacier points are an exception because REMOglacier treats glaciers as dynamic features, and the CISM ice model's representation of glaciers in RegCM is part of the LIQUIDICE development tasks.

Former coupled Earth System Model-Ice Sheet Model (ESM-ISM) systems

Commonly, the large ice sheets in Greenland and Antarctica are still considered passive components of the Earth system in climate models. Therefore, only a few systems have been developed so far. To cover long time periods, such as glacial-interglacial cycles, the Earth System is represented by Earth System Models of Intermediate Complexity (EMICs), such as LOVELCLIM (Driesschaert et al., 2007; Golledge et al., 2019) and CLIMBER (Calov et al., 2005, 2005a). Furthermore, some regional and global systems exist in which ocean models and ice sheets, including ice shelves, are coupled so that evolving ice shelves drive grounding line migration in the ocean model (Timmermann et al., 2012; Comeau et al., 2022; Yung et al., 2025). Also, some groups coupled ISMs to regional climate models, e.g., Le Clec'h et al. (2019), Pelletier et al. (2022), and Paice et al. (2025).

In the following, the description is restricted to more sophisticated global models. To our knowledge, the coupling of an ice sheet model with a state-of-the-art climate model has been pioneered by Fichefet at al. (2003), who coupled the Greenland Ice Sheet Model (GISM) with the LMD-CLIO climate model, and by Ridley et al. (2005), who coupled HadCM3 to GISM. Early attempts also included coupling MPI-ESM with SICOPOLIS (Mikolajewicz et al., 2007; Vizcaino et al., 2008, 2010). Later, the group replaced SICOPOLIS with PISM (Ziemen et al., 2014; Kapsch et al., 2021). Since then, CESM has initially been coupled to Glimmer (Lipscomb et al., 2013) and later to CISM (Muntjewerf et al., 2021). The Parallel Ice Sheet Model (PISM), which LIQUIDICE groups will also use, has been coupled to EC-Earth (Madsen et al., 2022) and AWI-ESM (Gierz et al., 2015; Ackermann et al., 2020). In most cases, the coupling is restricted to the Greenland ice sheet (GIS), while coupling to the Antarctic ice sheet (AIS) has been performed by Mikolajewicz et al. (2007), Vizcaino et al. (2008), and Smith et al. (2021).

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