1 Introduction

The Antarctic Ice Sheet (AIS) is an integral part of Earth's climate system that interacts in multiple and complex ways with other components, affecting regional and global sea level, climate, oceanic and atmospheric circulations, and biogeochemical cycles [3, 4]. Interactions with the surrounding Southern Ocean can influence ice-sheet stability [6-8], ocean heat and carbon uptake [10], and amplify or drive global climate variability through oceanic and atmospheric teleconnections [12-14].

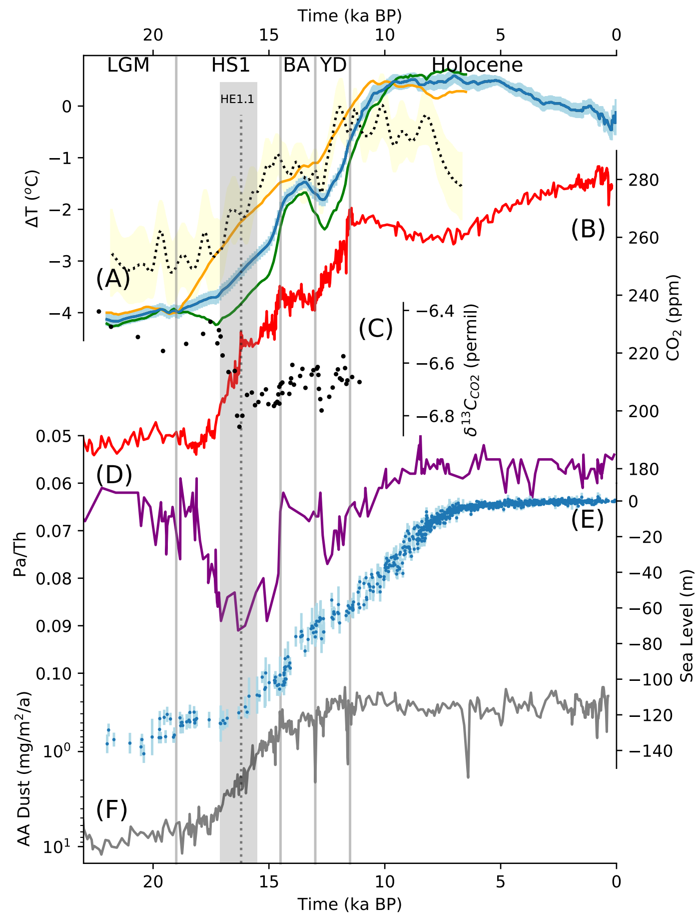

Figure 1: Key paleoclimate reconstructions during the last deglaciation. (A) global (blue), southern hemisphere (orange), and northern hemisphere (green) surface air [1, 2] and whole ocean (black dotted with yellow shading) [5] temperature, (B) atmospheric CO_2 [11], (C) $\delta^{13}C_{CO2}$ [16], (D) $^{231}Pa/^{230}Th$ a proxy for AMOC strength [17, 18], (D) sea level [19], and Antarctic dust flux [23]. Note the inverted axes for dust and Pa/Th (lower $^{231}Pa/^{230}Th$ indicates stronger AMOC). Records (A), (B), (C) and (F) are from Antarctic ice cores. Ice rafting during Heinrich Event 1.1 (HE1.1)[21] is indicated by the grey bar.

Paleoclimate data suggest that such interactions have played important roles in past climate change (Fig. 1). Global temperatures, atmospheric CO_2 concentrations and sea level were low during the Last Glacial Maximum (LGM, ~26-19 ka BP) and rose during the subsequent deglaciation, whereas dust fluxes were high during the LGM and decreased afterward [20]. During Heinrich Stadial 1 (HS1; ~19-14.5 ka BP), air temperatures started to increase in the southern hemisphere whereas temperatures in the north stayed cool or even decreased. The Atlantic Meridional Overturning Circulation (AMOC) decreased during HS1 approximately at the same time as dust fluxes decreased and Southern Ocean temperature and atmospheric CO_2 increased [1], followed by northern hemisphere ice sheet surging [21, 22]. The initial deglacial CO_2 rise and corresponding $\delta^{13}C_{CO2}$ drop has been attributed to a decrease in the ocean's biological pump [16], changes in AMOC [24], southern hemisphere westerly winds [25, 26], and decreased iron fertilization [27]. Sea-level rise accelerated during Meltwater Pulse (MWP) 1A, approximately coincident with an AMOC resumption, rapid warming in the northern hemisphere and a jump in CO_2 during the transition from HS1 to the Bølling/Allerød (BA) warm interval. Temperatures in Antarctica and CO_2 stabilized or even declined slightly during the BA, which corresponds to the

Antarctic Cold Reversal. The subsequent AMOC decrease during the Younger Dryas (YD) was associated with cooling in the North Atlantic, warming in Antarctica and an increase in CO_2.

The AIS is thought to have contributed to the deglacial CO_2 rise through ice-ocean interactions [28-30]. It remains difficult, however, to assess effects of AIS-ocean interactions on atmospheric CO_2 since most climate-carbon cycle models are not coupled with interactive ice-sheet components [31, 32]. Such coupling, however, is now possible due to recent developments and improvements of parameterizations for associated processes such as sub-ice melting. It is thus timely to work towards developing fully coupled ice sheet–climate–carbon cycle models that are suitable for long-term simulations to address these outstanding problems. Here we propose an ambitious but feasible project to create a unique, computationally efficient Earth System Model (ESM) that will combine existing, well-tested oceanic, atmospheric and biogeochemical components with state-of-the-science AIS and solid-Earth models. Model simulations will be designed to assess critical ice sheet-ocean-carbon cycle feedbacks that are missing in most existing models. Simulations of the LGM and last deglaciation will be assessed by a large array of existing paleoclimate records. **A key outcome will be to assess the role of AIS-ocean-carbon cycle interactions on the evolution of atmospheric CO_2.**

2 Background

Atmospheric CO_2 variations are essential to explain the amplitude of glacial cycles in climate and sea level [33, 34]. Various processes have been proposed to account for the observed glacial-interglacial variability in atmospheric CO_2 of ~90 ppm, but no consensus has emerged. Noting a tight correlation between CO_2 and Antarctic temperature many investigators have pursued Southern Ocean processes [35, 36]. The direct effect of ocean temperature on the solubility of CO_2 has long been dismissed as small (<25 ppm) [37-40], but new evidence described below has challenged that assertion. Increased iron fertilization has been suggested to strengthen the biological pump and sequester more carbon in the deep ocean [41], an idea supported by observations of higher dust fluxes in Antarctic ice [42] and in Southern Ocean sediments [27], but models estimate it is a small effect [23]. Expanded sea-ice cover has been suggested to restrict outgassing of CO_2 from the ocean [43] and increase the salinity of Antarctic Bottom Water [44], which would lead to a more-stratified, less-mixed, carbon-rich deep ocean [45-47] or an expansion and isolation of Antarctic Bottom Water [48]. Changes in westerly winds [26, 49] and Southern Ocean buoyancy fluxes [50] have also been invoked to force a more sluggish deep ocean circulation and enhanced carbon storage there.

Paleoceanographic data such as carbon isotopes ($\delta^{13}C$) clearly show that the water mass geometry of the deep ocean was different during glacial times, with greater influence of Southern Ocean waters and a shallower North Atlantic Deep Water cell [51, 52], but reconstructing flow rates remains a challenge [53]. An observed increase in whole-ocean radiocarbon age by about 700 c14-years, which has been interpreted as a more sluggish circulation [54, 55], but our recent work has shown that higher preformed radiocarbon ages, particularly in the Southern Ocean, due to sea-ice expansion can account for the observations without the need for slower circulation or increased ideal age [56, herein K19]. Reduced dissolved oxygen reconstructions in the deep glacial ocean have also been interpreted as a slower circulation and an increase in the efficiency of the biological pump [57, 58], but these data are also affected by reduced air-sea gas exchange due to enhanced sea-ice cover and do not necessarily reflect a global increase in export production and the biological pump, nor do they require slower circulation rates [K19]. Higher nitrogen isotope

($\delta^{15}N$) values in the glacial Subantarctic Zone, a measure of increased nutrient utilization there, and their correlation with iron and dust fluxes support the iron fertilization hypothesis [27].

We have recently made progress in reconstructing the glacial ocean by combining a process-based, isotope-enabled model with sediment data from the LGM. The strategy is to use complementary constraints from different proxies [59]. For example, $\delta^{13}C$ is influenced by both iron fertilization and circulation and thus unique attribution of any observed changes in $\delta^{13}C$ to one mechanism is difficult. However, when combined with $\delta^{15}N$, which provides constraints on iron fertilization, $\delta^{13}C$ can be used more reliably to reconstruct circulation changes. The first application of this strategy to the LGM has led to a model state that fits a large number of physical, biogeochemical and isotope data from the glacial ocean [60, herein M18]. The state is characterized by enhanced soluble iron fluxes to the Southern Ocean and a weaker and shallower AMOC (Fig. 2). Note that the carbon isotope data used by M18 only constrain well AMOC depth, whereas its strength remains more uncertain [53].

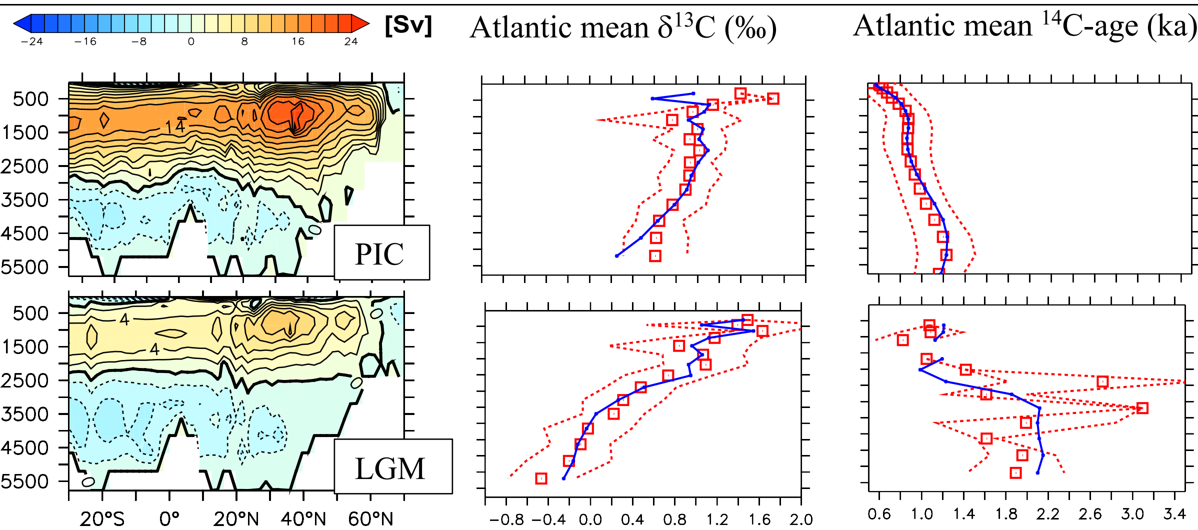

Figure 2: Left: AMOC streamfunction as a function of depth (m) and latitude. Center and right: Horizontally averaged $\delta^{13}C$ (center) and radiocarbon age (right) as a function of depth. Top: Pre-industrial control. Bottom: Best-fitting LGM simulation. Observations/reconstructions [red; 61, 62] with the spatial standard deviation given as the dotted line. Model results (blue) sampled at the data locations. Reconstructed LGM ^{14}C-ages are mostly from benthic-planktic pairs of foraminfera [54], which are sparser and noisier than estimated preindustrial values, which are based on water-column measurements. Modified from K19.

Figure 2 only shows a subset of data averaged over the Atlantic basin. More detailed comparisons including spatial distributions are available in M18 and K19. Compared with the relatively homogenous vertical distribution of $\delta^{13}C$ and radiocarbon age in the preindustrial ocean, the LGM state shows larger vertical gradients in the sediment data and in the model. Increased iron fertilization contributes to the larger gradient in $\delta^{13}C$ by decreasing $\delta^{13}C$ in Antarctic Bottom Water, but AMOC shoaling (by ~700 m in the model) is also important (Fig. 5 in M18). Similarly, increased sea-ice cover and AMOC changes contribute both about equally to the higher radiocarbon ages in the deep Atlantic (Fig. S6 in K19). This model also reproduces the reconstructions of whole ocean cooling [5], decreases in deep ocean oxygen concentrations and the increase in Southern Ocean $\delta^{15}N$ (Figs. S2, S10 in K19). However, the deep deoxygenation is dominated by sea-ice expansion and associated stronger air-sea disequilibrium and not due to a more sluggish circulation.

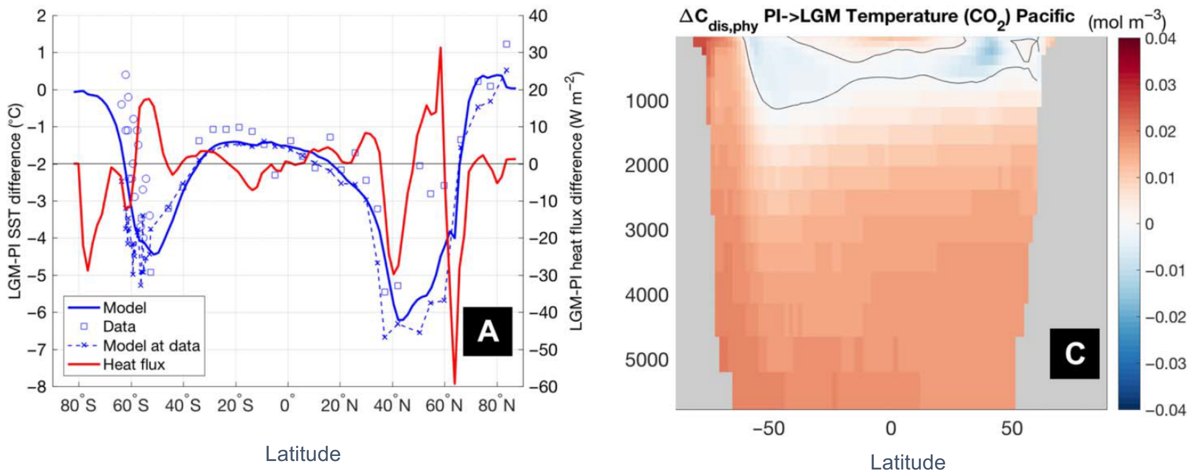

Figure 3: Left: Zonally-averaged difference LGM minus pre-industrial (PI) as a function of latitude of sea surface temperature (blue, left axis) from the model (solid line) and reconstructions (squares [63] and circles [64]) and sea-air heat flux (red, right axis). Right: Zonally-averaged response in physical disequilibrium carbon storage due to LGM cooling as a function of latitude and depth (m). From K19.

A surprising finding of the K19 study was that the pattern of sea surface temperature change in the Southern Ocean (Fig. 3) is important for CO_2 drawdown by increasing carbon storage from physical disequilibrium. This pattern, which is characterized by maximum cooling of ~4-5°C at mid latitudes and essentially no cooling at high latitudes, where waters are already at the freezing point in the modern ocean, is consistent with temperature reconstructions. Thus, the meridional temperature gradient between mid and high latitudes and the ocean-atmosphere heat flux are decreased. In the modern ocean the air-sea heat flux cools southward-moving surface waters and creates a large negative physical carbon disequilibrium ($C_{dis,phy} < 0$) because carbon uptake is slower than heat loss [65]. Reduction of heat flux in the glacial ocean decreases the magnitude of negative disequilibrium, thus increasing deep ocean carbon storage ($\Delta C_{dis,phy} > 0$; Fig. 3). This mechanism amplifies the temperature effect on atmospheric CO_2 drawdown from 25 ppm as estimated previously from equilibrium changes alone [37-40] to 45 ppm when including the disequilibrium effect, suggesting temperature was the dominate process in glacial CO_2 lowering. This offers a new explanation for the tight correlation between observed Antarctic temperatures and CO_2.

The second largest contribution (26-39 ppm) to glacial CO_2 lowering in K19's analysis was iron fertilization. This is more than previous modeling studies suggested (11-25 ppm) that were not constrained by nitrogen isotopes [66, 67]. Together, temperature and iron fertilization thus account for 67-87 ppm or >75% of the observed CO_2 reduction, whereas sea-ice and circulation changes contributed little. Another surprising result was that the biological pump, defined as the amount of respired organic carbon and dissolved calcium carbonate, was not increased globally, consistent with a slight reduction in modeled global export production. Rather, an increase in disequilibrium carbon storage explains the transfer of carbon from the atmosphere to the ocean.

While promising and illustrating our methods, it is important to stress the limitations of these initial studies. *First,* the number of circulation states tested in M18 was limited and in those that were tested, the strength and depth of the AMOC were strongly correlated, i.e. a stronger AMOC was also deeper and vice versa. Thus the alternative state of a shallow and strong AMOC [68] was not tested. Moreover, the proxies used ($\delta^{13}C$ and radiocarbon) do not provide good constraints on circulation rates [53] and biases remain (e.g., deep Pacific deoxygenation in the model is only about half that reconstructed by Anderson et al. [2019]). We thus propose to use additional circulation rates and more proxy constraints in an effort to improve AMOC reconstructions. *Second*, the mechanism used in M18 to perturb the AMOC was a reduction of meridional moisture transport by modifying the atmospheric diffusivity. This causes less precipitation at high latitudes, increased salinities and flow rates of AABW, and a weakening and shoaling of the AMOC [69, 70]. Here we suggest that a different mechanism, ice-ocean interactions, may be more likely and would have had a similar effect. *Third*, M18 considered the LGM equilibrium state only. The proposed mechanisms have not been tested in transient simulations. We thus propose to test them in coupled ice-ocean simulations of the last deglaciation.

3 Hypotheses

We propose to study the effects of AIS-ocean-carbon cycle interactions in data-constrained simulations of the LGM and the subsequent deglaciation. We will test the following hypotheses.

H1: A colder LGM ocean caused reduced ice melt around Antarctica, saltier Antarctic Bottom Water, more ocean carbon storage, and lower atmospheric CO_2.

H2: AMOC variations during the last deglaciation affected the Antarctic Ice Sheet through Southern Ocean subsurface temperatures.

H3: Antarctic ice sheet-ocean interactions and feedbacks during the last deglaciation modulated atmospheric CO_2 variability.

We will address these hypotheses through modeling and comparison with paleoclimate data as outlined in more detail in the next section. The last deglaciation is chosen due to the availability of a large number of well-dated paleoclimate data. In the remainder of this section, we elaborate on each of these hypotheses to provide more context.

3.1 H1: Effects of Ice-Ocean Interactions on AABW and Ocean Carbon Storage

Bottom water reconstructions based on sediment pore-water measurements indicate a colder (close to the freezing point), saltier (in excess of the one salinity unit increase due to sea-level lowering) and salt-stratified abyssal ocean during the LGM, in contrast to the modern temperature-dominated stratification [44]. We suggest that different processes conspired to produce this high-salinity bottom water. A colder atmosphere would have transported less moisture poleward, which would have reduced precipitation at high latitudes [71]. In addition to this purely thermodynamic effect, an equatorward shift in the storm track could also have reduced moisture transport to high southern latitudes. Moreover, increased equatorward transport of sea ice would have caused salinification of Antarctic Bottom Water [72, 73]. Reproducing the observed glacial salinification of bottom waters could be important for carbon storage. Models without ice sheet-ocean interactions typically enhance the salinity of AABW artificially to force a more stratified, carbon-rich abyssal ocean [46, 60, 74].

These mechanisms (colder atmosphere, changes in storm tracks, sea ice) are already included in most climate models, but the following two, associated with ice-ocean interactions, are not, which may be why most models struggle to reproduce observed glacial ocean features [75]. *First*, in the modern ocean, freshwater input from basal melting of ice shelves contributes to freshening and stratification of polar surface waters [76]. The large heat capacity of water can lead to substantial changes in basal melting due to relatively small variations in circulation or ocean temperature, with a general sensitivity of ~1 m yr^{-1} of ice melt for ~0.1°C of warming [77, 78]. This indicates an important role for oceanic forcing in AIS mass loss [6-8, 79], which has been confirmed in ice-sheet only simulations of the last deglaciation [80, 81] and the penultimate deglaciation [82]. Cooling of polar subsurface waters such as Circumpolar Deep Water that flowed into sub-ice cavities during the LGM would have reduced basal melting of ice shelves. As a result of reduced freshwater input, the salinity, density and perhaps also the flow of Antarctic Bottom Water would have increased [28, 29, 76]. This mechanism has never been tested in a coupled global ice-ocean model of the glacial ocean.

Second, reduced melting of icebergs close to Antarctica would have increased AABW salinities. Due to colder temperatures during the LGM we would expect icebergs to drift further north before melting. In the contemporary ocean, most ice loss from the AIS is due to roughly equal contributions from basal melting of ice shelves and calving of icebergs into the ocean [77, 83]. Icebergs account for about 1,300 Gt yr^{-1} of AIS mass loss about equally distributed between small and giant bergs [83, 84]. Most calved bergs are advected in the Antarctic coastal current westward around the continent. Some escape the current and drift north, whereas almost all small and most (~65%) giant bergs melt close to Antarctica, where they contribute up to half of the total freshwater input [85]. Currently only about 35% of giant icebergs melt north of 63°S, most of which move through Iceberg Alley in the western part of the Weddell gyre. Iceberg Alley provides a conduit for icebergs to exit the coastal current and enter the eastward flowing Antarctic Circumpolar Current (ACC). Reconstructions from iceberg rafted debris suggest that increased fluxes of icebergs through Iceberg Alley occurred several times during the last deglaciation [86]. Colder temperatures around Antarctica suggest that during the LGM, melting of icebergs there was reduced, while more bergs were transported into the ACC and melted further north than today, with the associated increased freshwater export likely increasing AABW salinity.

3.2 H2: Effects of AMOC variability on AIS

It is well established that the AMOC influences Southern Hemisphere surface temperatures through interhemispheric heat transport [87, 88]. This mechanism is thought to have caused the observed anti-phasing of air temperatures in Greenland and Antarctic ice cores at millennial timescales during the last ice age [89-91]. However, AMOC variability may also affect AIS mass balance through subsurface temperatures. A hypothesis based on uncoupled ice-sheet modeling [80] suggests an AMOC recovery around 14.5 ka would have reduced Southern Ocean overturning circulation and caused enhanced intrusion of warmer North Atlantic Deep Water into the subpolar ocean surrounding Antarctica. This would have warmed Circumpolar Deep Water and increased its flow into ice-shelf cavities. The resulting enhanced basal melting of ice shelves, potentially amplified by ice-ocean feedbacks (see following section) and reduced buttressing of grounded ice, would have caused grounding line retreat and enhanced ice flow into the ocean, contributing to meltwater pulses during the last deglaciation. These pulses have been recorded as rapid sea-level rise in tropical corals [92] and by ice-rafted debris in Southern Ocean sediments [86]. More recently, climate modeling suggested that a prolonged AMOC shutdown during the penultimate deglaciation caused subsurface warming around Antarctica, which one ice-sheet model found led to collapse of the West Antarctic Ice Sheet and associated sea-level rise [82]. Note that these two hypotheses identify opposite AIS responses to changes in the AMOC, whereby [80] suggest an AMOC increase causes AIS melting, while [82] suggest an AMOC reduction causes AIS melting.

In either case, climate model simulations suggest that freshwater fluxes into the Southern Ocean affect the AMOC [e.g. 93], which implies the potential for a feedback. *However, this feedback and the impacts of AMOC changes on the AIS have never been investigated in a fully coupled ice-climate model.*

3.3 H3: AIS-Ocean Feedbacks

One proposed positive feedback involves ice-mass loss and an associated freshwater flux to the ocean. A number of modeling studies suggest that freshwater input to the Southern Ocean can lead to subsurface ocean warming, basal melting of ice shelves, and thus an increased freshwater flux [12, 80, 86, 94-99]. Because subsurface waters in the Southern Ocean are warmer than surface waters, convection and mixing along steeply sloping isopycnals causes upward heat transport there. As a response to surface freshening, stratification increases, isopycnals flatten, and convection and vertical mixing decrease. This reduces upward heat flux and leads to cooling at the surface and warming of the subsurface [100-103]. This is a qualitatively robust effect across a variety of models and has been suggested to play a role in rapid sea-level rise during MWP 1A [80]. *However, it has never been tested in a coupled ice-ocean model and its effect on deglacial sea-level and CO_2 variations remains unknown.*

AIS freshwater fluxes and associated surface cooling and sea-ice expansion may strongly influence biogeochemical cycles by (1) causing an intensification of Southern Hemisphere westerly winds [102], which affects upwelling of subsurface nutrients and carbon and may impact atmospheric CO_2 [94], or (2) increasing stratification. Increased stratification may have reduced vertical mixing and outgassing of CO_2 from the Southern Ocean and thus contributed to the observed pause in the deglacial CO_2 rise during the Antarctic Cold Reversal (~14.5-13 ka BP; Fig. 1) [104]. Moreover, atmospheric teleconnections shift the Intertropical Convergence Zone (ITCZ) in response to Southern Ocean cooling and sea-ice expansion [13, 98, 100]. Such a shift affects tropical precipitation patterns and thus land vegetation and carbon storage there [94]. To our knowledge, however, the only modeling study that has investigated effects of AIS meltwater on biogeochemical cycles [94] used pre-industrial and constant $2\times CO_2$ background conditions. *Thus, it is currently unknown how AIS freshwater fluxes would affect biogeochemical cycles in more realistic simulations of the last deglaciation.*

4 Methods

We propose to test the above hypotheses through a combination of modeling and paleoclimate data analysis. A new Earth System Model will be developed by coupling two existing, well-tested models: the Oregon State University version of the University of Victoria climate model (OSU-UVic) and the Pennsylvania State University Ice sheet model (PSUI). We will assess ice sheet–ocean feedbacks by using this model to perform simulations with and without ice sheet–ocean coupling. The intermediate-complexity climate model includes a three-dimensional ocean component and is computationally efficient enough for a series of simulations over 10's of thousands of years. This allows exploration of uncertainties such as those associated with the ocean state mentioned above, or ice-ocean coupling. The model is well-tested and includes isotopes that can be directly compared against paleoclimate data. Biogeochemistry and carbon cycling are included. Atmospheric impacts and feedbacks will be estimated by using a model version with atmospheric dynamics. The ice-sheet model includes ice shelves, is coupled to the solid Earth, and is well-tested for both modern and paleo applications. The proposed coupling will involve challenging model development work such as implementing parameterizations of the unresolved flow in small ice cavities and basal melting of ice shelves. The resulting model will be limited by its resolution. While we cannot expect this project to provide final quantitative answers, we expect qualitative, perhaps semi-quantitative (order-of-magnitude) estimates that will provide important new insights that will directly address our hypotheses. We also expect that this project will lay the essential groundwork for further model development that will lead to quantitative answers. Our coupled AIS-climate simulations of the last deglaciation will thus be a major advance over the present state of knowledge, which is based on uncoupled and separate ice-sheet and climate simulations.

4.1 Model Descriptions

The OSU-UVic model [105] includes a three-dimensional, fully non-linear (primitive equations) ocean general circulation component coupled to a dynamic-thermodynamic sea-ice model, a simple, 1-layer energy-moisture balance atmospheric component (EMBM), and a land-surface module with dynamic vegetation, soil carbon and permafrost [106], all at coarse resolution (1.8°×3.6°, 19 ocean levels). The physical ocean model uses state-of-the-science parameterizations of tidal mixing [107] and mesoscale eddies including spatially and temporally variable coefficients for isopycnal thickness and along-isopycnal tracer diffusion [108]. Effects of tidal mixing changes during the LGM due to sea-level lowering can be included [109]. Version 2.9 uses the Model of Ocean Biogeochemistry and Isotopes (MOBI) with a full carbon cycle, nitrogen, phosphorous, and iron as limiting nutrients for phytoplankton, dissolved organic matter, and three isotope systems [110-113]. OSU-UVic-MOBI is well tested for current, past and future applications. In particular, its simulation of mixed-layer depths, chlorofluorocarbons (CFCs), and radiocarbon distributions in the modern ocean indicate that its large-scale circulation and ventilation of subsurface waters on decadal to centennial timescales is consistent with modern observations [105, 114, 115]. Similarly, its large-scale distributions of biogeochemical tracers such as nitrate, phosphate, dissolved oxygen, DIC, alkalinity and surface fluxes of CO_2 are all consistent with observations. Like any model, OSU-UVic-MOBI is imperfect and has biases. However, its biases in large-scale tracer distributions are relatively minor, well documented, and unlikely to have major effects on the results of this study. It resolves the major large-scale features of the Southern Ocean circulation such as the subpolar gyres in the Weddell and Ross Sea sectors, the eastward flowing Antarctic Coastal Current and the westward flowing Antarctic Circumpolar Current. In its current version, the model includes only two resolved (albeit very crudely) ice shelf cavities (Filchner-Ronne and Ross). It is highly computationally efficient and well suited for many long-term simulations. On Schmittner's newest Intel-based Linux cluster, OSU-UVic-MOBI, with all 30 prognostic biogeochemical variables, integrates about 300 model-years per day on a single processor core. A simulation of the last deglaciation (20,000 years) will thus take about two months of runtime. A unique feature of OSU-UVic-MOBI is that it includes radiocarbon ($\Delta^{14}C$), $\delta^{13}C$ and $\delta^{15}N$ isotopes (Fig. 3). $\delta^{13}C$ is included in all carbon cycle components (land, ocean and atmosphere). Thus, *simulated variations of $\delta^{13}C_{CO2}$ can be compared directly to ice-core measurements* (Fig. 1C) and will help in interpreting these data. Ongoing NSF funded projects will implement two additional isotopes in MOBI: $^{231}Pa/^{230}Th$ ratios (award 1924215) and ε_{Nd} (award 2022461), which may improve constraints on the MOC [17, 116]. OSU-UVic can also be run with a dynamic atmosphere (PlaSim) with 10 levels and T42 horizontal resolution that solves the primitive equations and includes prognostic cloud and radiation schemes [117].

PSUI is a state-of-the-science ice-sheet/ice-shelf model based on the shallow-ice and shallow-shelf approximations [118]. It simulates grounding line dynamics and parameterizes sub-ice oceanic melting and shelf-edge calving. The latest version of PSUI [81] includes a solid-Earth and sea-level model [119] which captures the negative sea-level feedback [120] and its effect on marine ice-sheet instability [121]. PSUI has been extensively tested both in paleo and future applications. For example, Pollard et al. [2017] simulated the AIS evolution during the last deglaciation, the Pliocene, and 5,000 years into the future following the high-emission scenario RCP8.5 with an ensemble of models with different parameter values. PSUI includes a number of uncertain parameters, which have been partly constrained by paleo data [81, 122].

We will build upon *Fyke et al.* [2011], who coupled an earlier version of PSUI one-way to the UVic model such that PSUI receives surface climate information that is used to calculate the surface mass balance, but changes in the ice sheet do not affect the climate model. Ablation is calculated by solving the surface energy budget using a sub-grid scale scheme that employs vertical bins, the number of which depends on the sub-grid scale relief. This downscaling method improves calculations in the narrow ablation zone around the margins of the ice sheet and of orographic precipitation over steep topography compared with more simple interpolation schemes. They also included variable snow albedo, refreezing of meltwater in snow, and a correction of surface air temperature biases over ice sheets from the climate model. However, the *Fyke et al.* [2011] study had two shortcomings: prescribed basal ice-shelf ablation and the lack of ice-sheet influences on the ocean. Nevertheless, their LGM simulations were in reasonable agreement with reconstructions, suggesting that the coupled UVic/PSUI model can simulate reasonably well modern and past ice sheets. Here we will include ocean-temperature-dependent basal ice-shelf ablation and add calculated meltwater fluxes to the ocean.

5 Work Plan

Our work plan involves model development and experimentation, paleoclimate data syntheses, model-data comparison and analysis, outreach, education and dissemination. Individual tasks are described in detail below. AS will lead the project and supervise a postdoctoral researcher (PR), who will do most of the modeling work. PUC will supervise graduate student Saray Valdez Hernandez (SVH) and work with her on the paleoclimate data synthesis. Collaborators David Pollard (DP) and Natalya Gomez (NG) will advise with ice-sheet and solid-Earth modeling. Andrew Haight (AH) from the Oregon Museum of Science and Industry will lead the outreach component. Biswanath Dari (BD) from Oregon State University's Klamath Basin Research and Extension Center (KBREC) in Klamath Falls, will collaborate on the outreach component. The science team (AS, PUC, SVH, PR, DP and NG) will participate in the comparison with model results, analysis and writing papers. We will schedule weekly meetings of the OSU team (AS, PUC, SVH, PR) and less frequent (monthly or bi-monthly) meetings including other team members. The outreach team (AS, AH, BD) will communicate as necessary via email and Zoom.

5.1 OSU-UVic-PSUI coupling

In year 1, the OSU-UVic model will be updated to the newest UVic version (2.10 with MOBI2.0). Version 2.10 includes permafrost, which will be important in simulating changes in terrestrial carbon storage and associated impacts on atmospheric CO_2 and $\delta^{13}C_{CO2}$. Next, the ice-sheet model will be updated to the most recent PSUI version [81], which includes a global solid-Earth and sea-level model, a new calving parameterization, and hydrofracturing. The sea-level model includes gravitational and rotational effects and the solid-Earth model employs radially varying lithospheric and mantle properties that affect glacial isostatic adjustment (GIA) [119].

Next we will implement AIS mass loss due to variable ice-shelf basal ablation rates. Due to the ocean model's coarse resolution, the detailed circulation under ice shelves is not simulated. Simple models have been developed that represent a meltwater plume, which flows along the bottom of the ice shelf from the grounding line towards the calving front [123]. The plume is buoyancy driven by the freshwater input from ablation of the ice base and sustained by entrainment of relatively warm and salty ambient sea water [124]. Although influences from bathymetry, Coriolis force, and tidal mixing [125] create a complex sub-shelf circulation that cannot be simulated directly in a coarse-resolution model, several parameterizations of them have recently been developed [126-128]. Idealized tests suggest that a simple parameterization that expresses ablation rates as a quadratic function of the thermal forcing shows similar skill as more complex schemes based on multiple boxes or meltwater plume theory [127]. This has led the Ice Sheet Model Intercomparison Project (ISMIP6) to recommend this parameterization, which is also easier to implement than the more complex box or plume-based parameterizations [129] and which we propose to use here as our default scheme. Ablation rates in this parameterization depend quadratically on the difference between the pressure-dependent freezing temperature and the ambient ocean temperature. This non-linearity arises from the fact that this temperature difference drives the overturning circulation below the ice shelf [130]. The above-mentioned alternative and more complex formulations will be tested if time permits. A significant effort will be required for a preliminary tuning of the parameters.

Next we will include ice loss as a freshwater flux to the ocean by routing surface runoff and basal ablation to the corresponding ocean grid point. Calving will produce icebergs, which will be allowed to drift with the ocean currents and melt considering the local ocean temperature [85]. Three model versions will be created: (1) a control version (CTR) in which ice dynamics does not affect freshwater fluxes to the ocean, (2) a version with ice-shelf (IS) basal ablation only (without the iceberg model), and (3) a version with ablation from both ice shelves and ice bergs (ISIB) that provides freshwater fluxes to the ocean. The differences between models ISIB and CTR will quantify the full ice-ocean feedback, whereas the difference between models ISIB and IS quantifies the contributions of iceberg dynamics on the full feedback. These models will be used to test hypothesis **H1**.

5.2 Paleoclimate Data Synthesis

In years 1 and 2 we will compile existing and emerging paleoclimate data focusing on records of high temporal resolution (~1 ka) and taking advantage of several recent synthesis efforts. Reconstructions include surface and subsurface temperatures, sea level, oxygen, carbonate ion, and isotopes ($\delta^{18}O$, $\delta^{13}C$, $\Delta^{14}C$, $\delta^{15}N$, $^{231}Pa/^{230}Th$, ε_{Nd}) from the global ocean and cosmogenic ages, sea level and marine records from Antarctica. Some of these are illustrated in Figs. 1 and 4. **Surface temperature** reconstructions will be updated from [1]. The current database includes 165 records from the global ocean (Fig. 4). For the LGM a recent global SST compilation based on $\delta^{18}O$, alkenones, Mg/Ca, and TEX_{86} will be used [131]. We will investigate if planktic $\delta^{18}O$ data can also be used to derive SSTs for the deglaciation [132]. An existing synthesis of 1,361 subsurface ocean **radiocarbon age** (ventilation age) reconstructions from 173 different sites (Fig. 4) based mostly on paired benthic-planktic foraminifera and deep-sea corals [133] will be supplemented with more recent data [e.g. 134]. **$\delta^{13}C_{DIC}$** reconstructions from the emerging, quality-controlled Ocean Circulation and Carbon Cycling (OC3) database of benthic $\delta^{13}C$ from the last deglaciation currently includes 188 well-dated high-resolution records (Fig. 4). The community developed OC3 database structure will be used here also for all other paleoclimate data. It features separate data and chronology files that are designed to facilitate age-model updates, which may be necessary, as when a new radiocarbon calibration is published. All radiocarbon dates in this project will be updated to the most recent INTCAL20 calibration [135].

Nitrogen isotope ($\delta^{15}N$) data synthesized by [136] and supplemented by additional data [e.g. 27, 137, 138] currently amount to 139 records (Fig. 4). We will also update syntheses of **dissolved oxygen** [139] and **carbonate ion** reconstructions [140-142]. Ice-core data of **CO_2** and **$\delta^{13}C_{CO2}$** [16, 104] will be included in our compilation. Recent compilations of **$^{231}Pa/^{230}Th$** [143] and **ε_{Nd}** [116] data will be used. Our current dataset from Antarctica includes 104 terrestrial **cosmogenic age** estimates, 27 **marine** ice sheet extent records [144], and 8 **sea level** records (Fig. 4), which will provide constraints on modeled local ice-elevation changes and GIA responses [145].

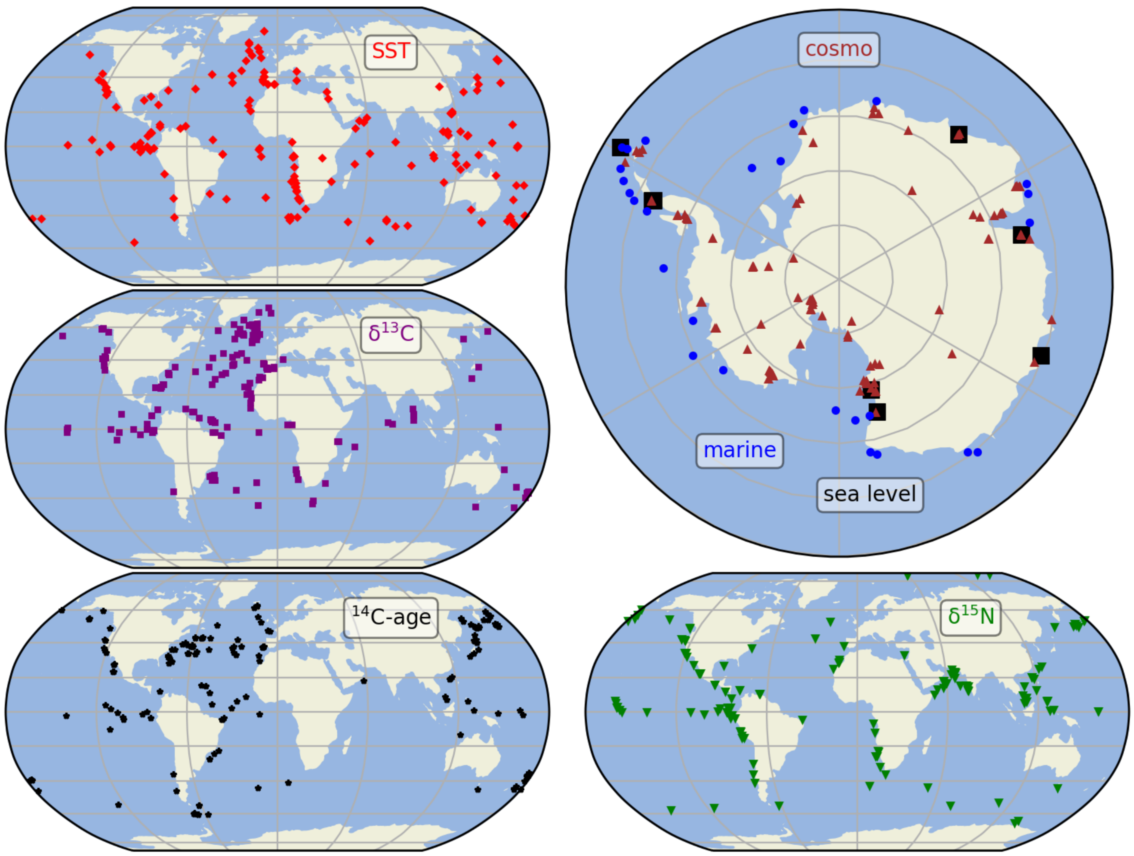

Figure 4: Examples of available paleoclimate data that will be updated and used in this project.

5.3 Experiments with Simple Atmosphere

In year 2, final parameter tuning of the three model versions will be performed followed by a spin-up into the LGM. Northern Hemisphere ice sheets will be prescribed and fixed at their LGM configuration [146]. Orbital parameters and greenhouse gas concentrations will be initialized at 40 ka and the coupled models will be run transiently to the LGM. Three experiments of 20 kyr each amount to 60,000 model years, which will be run in parallel and take about 2 months of runtime. All LGM simulations will be evaluated by comparison to the reconstructions described above. Additional sensitivity experiments in which a range of AMOC states sampling the two-dimensional AMOC-depth vs AMOC-strength space have already been performed [147] and will be applied here to evaluate effects of AMOC depth and AMOC strength on the AIS separately. Simulated changes in meridional water vapor transport, which will be important for the AIS mass balance, will be compared to LGM simulations from the more comprehensive Paleoclimate Model

Intercomparison Project (PMIP) models. Differences between models CTR, BM and BMIB will test hypothesis **H1**. Models with different AMOC states will allow us to diagnose AMOC effects on the AIS, which will inform tests of hypothesis **H2**.

In year 3, transient experiments of the last deglaciation will be performed with the three model versions. The experiments will be initialized from the LGM states described above. Transient forcings will follow the PMIP4 deglaciation experimental protocol [146] with prescribed changes in orbital parameters and corresponding insolation, radiative forcing due to greenhouse gas concentrations, Northern Hemisphere ice sheets, and corresponding freshwater fluxes according to the protocol's "melt-routed" option. Following the PMIP protocol will allow more direct comparison with other PMIP models. Wind-stress variations will be prescribed according to transient simulations with the Community Climate System Model 3 [148]. Soluble iron fluxes will be adjusted based on ice-core [42, 149] and ocean-sediment [150] reconstructions constrained by nitrogen isotopes. Atmospheric CO_2 concentrations will be calculated prognostically, responding to changes in ocean and land carbon stocks and compared to the ice-core data (Fig. 1). They will not impact radiative forcing, which will be prescribed. This de-coupling is necessary to prevent unrealistic changes in radiative forcing and thus climate due to expected errors in the carbon cycle calculations. It ensures that all experiments have the same radiative forcing and that the resulting differences in calculated atmospheric CO_2 are due only to differences in AIS meltwater fluxes. All experiments will use a 100-year output interval for the full 3D model fields. Global variables and indices will be output at annual resolution. Additional sensitivity experiments will explore different North Atlantic freshwater fluxes and how their effects on the AMOC impact the AIS, which will be used to test hypothesis **H2**. Single forcing experiments will be run to investigate impacts of orbital forcing, greenhouse gas radiative forcing and Northern Hemisphere freshwater fluxes separately. Results from those experiments will be compared with the paleoclimate data compilation described in subsection 5.3 above. A global metric of model-data differences will be calculated to rank the models. Differences between the experiments CTRL and BMIB will test hypothesis **H3**.

5.4 Coupling and Experiments with Dynamic Atmosphere

The purpose of using OSU-UVic with a simple dynamic atmospheric component (PlaSim) is to quantify feedbacks associated with changing winds and clouds. Using the identical ocean model but two different atmospheres (one with and one without atmospheric dynamics) will provide a clear separation of these effects. The current version of OSU-UVic with PlaSim at T42 resolution will be updated to exploit the possibility to run PlaSim in parallel. On Schmittner's new Intel-based cluster, PlaSim at T42 resolution simulates ~300 model years per day on 8 processors. However, all other components, including the coupler (OASIS) will need to be re-compiled with the same Intel compiler and Open MPI to achieve a similar performance with the coupled model. In this configuration, OSU-UVic-PlaSim-PSUI would use 11 processors (8 for PlaSim and 1 each for UVic, OASIS and PSUI). Thus, once updated and recompiled, we should be able to perform a 20,000 year-long simulation of the last deglaciation in about two months. This would be a unique, potentially transformative new model for long-term applications such as ensembles of future projections or paleoclimate simulations on orbital timescales. Model development here will not include impacts of ice-topography changes on the atmosphere, which we consider to be small for the cases considered in this project. For example, geological data indicate that, close to the coast, the LGM AIS has been a few hundred meters thicker than at present, with less elevation changes inland [151]. Importantly, however, the model will be able to respond to changes in ocean circulation by changing winds and clouds and thus affect ecosystems and biogeochemistry. This work will start in **year 1** by updating to the newest PlaSim version. Next, OASIS will be updated to its most recent version (OASIS3-MCT). In **year 2**, the UVic model will be updated to its most recent version, which would already include coupling to the ice-sheet model, followed by performing parallel tests without the ice sheet. After this, we will run tests with switched-on ice sheet. We plan to create two model versions, one fully coupled, and one only coupled one-way without meltwater fluxes affecting the climate model. Next, we will develop a new bias correction since OSU-UVic with PlaSim will have different biases than OSU-UVic with the EMBM. Both versions will be spun-up into LGM. Two simulations of 20 kyr amount to 40,000 model years and will take about 2 month of runtime and 22 processors. In **year 3**, experiments of the last deglaciation will be performed with OSU-UVic-PlaSim-PSUI. These simulations will take about 2 month of runtime and consume 22 processors.

6 Intellectual Merit

This project will improve our understanding of AIS-ocean interactions and feedbacks. Specifically, our simulations of the LGM and last deglaciation will address three outstanding paleoclimate questions. (1) Did ice-ocean interactions contribute to the observed high salinity of glacial bottom waters? (2) How did AMOC variations affect the AIS? (3) Did AIS-ocean interactions play a role in the observed atmospheric CO_2 and $\delta^{13}C_{CO2}$ variations? Atmospheric dynamical feedbacks will also be examined. Most of those calculations have never been done before. Thus, the project will contribute to a better understanding of the complex coupled ice-climate-carbon cycle system.

7 Broader Impacts

Results from our project may impact future paleoclimate simulations, which have been struggling to reproduce basic observed properties of the glacial ocean such as a shallower AMOC and saltier abyssal waters [75]. Despite their importance, ice sheets and associated GIA are not included in most Earth System Models. This project will develop a new Earth System Model with an interactive ice-sheet component and thus provide a major infrastructure enhancement for climate and paleoclimate research. Future improvements may include Northern Hemisphere ice sheets, which could then be applied to fully interactive simulations of glacial cycles, a grand challenge in climate modeling. The newly developed code will be available at a code-sharing website (github). An early career scientist will be trained in climate research, model development and application. A female graduate student from a minority background (Hispanic) will be trained in paleoclimate data synthesis and analysis. She intends to become a mentor and advocate for minority participation in science. She is committed to diversity and plans to include minority undergraduate assistants, among other activities, as an integral part of her academic and research career. Therefore, the project will contribute to the development of a diverse work force in Science, Technology, Engineering and Mathematics (STEM).

We will participate in two international projects: OC3 and PMIP. OC3 is focused on reconstructing ocean circulation and carbon cycling during the last deglaciation. Current plans within OC3, encouraged by the PAGES leadership, are to apply for a second phase to extend the database by including Pa/Th, ε_{Nd} and other relevant proxies and to use the database for model-data comparison, analyses and syntheses. The graduate student will provide important contributions to this effort. OC3 supports preferentially early career and developing country scientists. The Last Deglaciation PMIP working group is a model intercomparison project focused on simulating the last deglaciation. This project would directly contribute model output to both of these efforts. The PR would be entrained in the two communities and the associated activities. Thus, this project would contribute to fostering international collaboration in science.

We will engage undergraduate students from underrepresented groups and colleges through OSU's Research Experiences for Undergraduates (REU) program, which AS and PUC have successfully been involved with previously. Possible projects could be parts of the analysis. This is also a good opportunity for students to learn basic UNIX commands and model analysis software such as ferret or python, as well as become exposed to and involved in high-profile research. Each REU student will deliver a project report at the end of the 10-week internship. Presentations at scientific meetings are also possible.

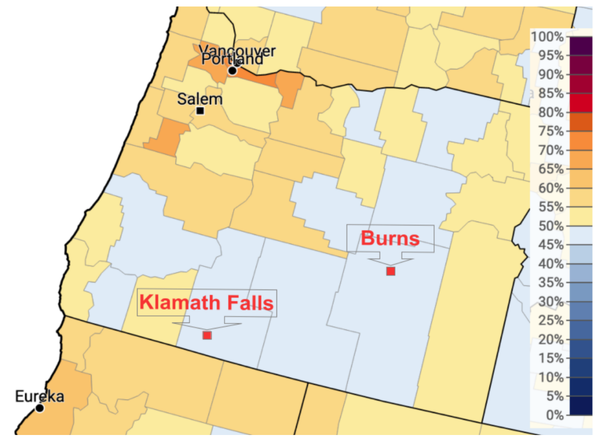

Figure 5: Estimated % of adults in Oregon counties who think global warming is mostly caused by human activities [9]. In contrast, more than 90% of scientists think that humans are the main cause [15].

Climate literacy of the general public remains lacking [152]. Whereas almost all climate scientists think that the current warming is caused by humans, in many rural counties in Oregon less than half of the general population believes that (Fig. 5). Here we plan outreach events for the general public with the goal to improve climate literacy, particularly for underserved rural populations that may be most impacted by climate change. Our target audience are adults in the Cautious, Disengaged, and Doubtful groups as described in the "Six Americas", which are the most interested in learning about the scientific evidence and causes of climate change [153]. Partnering with the Oregon Museum of Science and Industry (OMSI), OSU's Klamath Basin Research and Extension Center and local community-based organizations, we will organize a public forum with the goal to develop a series of questions and topics for a subsequent series of workshops. The topic-selection forum held in Klamath Falls, South Central Oregon (Fig. 5) in year 1 will be guided by the previous NSF-funded "Building Capacity for Co-Created Public Engagement with Science" plan, which was developed by the Museum of Science, Boston, in partnership with OMSI and other science centers. Subsequently, topical meetings will be conducted with different experts from OSU and other regional science institutions. One topic of interest in Oregon could be the effects of climate change on forests. Raging wildfires at the time of writing this proposal have exposed Oregonian's vulnerabilities. However, misinformation about the causes for the recent increases in wildfires in the West persist in the public sphere. For this topic, experts from the College of Forestry at OSU would be suitable. Other possible topics of interest could be paleoclimate, carbon cycle, ocean acidification, extreme events, sea level, impacts on agriculture and solutions. Local experts on all of these topics are available and will be contacted after the set of topics has been determined. The pilot topical workshop will be conducted in year 2 in Klamath Falls and the second topical workshop will be held in Burns, Eastern Oregon (Fig. 5). The meetings will be designed with ample opportunities for discussions and questions from the audience and, depending on COVID, will be conducted virtually or in person. The goal is not simply information delivery, but to establish a real dialogue between the public and climate scientists that builds trust. Participants will learn to (1) locate trustworthy information on climate and distinguish it from misinformation, (2) gauge certainties and uncertainties in climate science, and (3) recognize the scientific consensus about the causes of global warming [154], which is underestimated [155]. Publicly available information such as the PI's online textbook [156] and assessment reports [157, 158] will be utilized to convey the best available and accessible science. The events will be broadly advertised to generate maximum participation. OMSI's Engagement Research and Advancement team will conduct an evaluation study of the public-facing program activities to measure the extent to which the intended public audience impacts have been achieved. Using a mixed-methods approach, the team will collect quantitative and qualitative data regarding satisfaction, engagement, interest, and learning during each of the three public events, and will compile findings into a brief report intended both to describe the public impacts of these activities and to inform and improve the practices of professionals during such events in the future and community needs for additional climate science information.

8 Results from Prior NSF Support

Schmittner Award: 1634719; Period: 09/01/2016 to 08/31/2019; Amount: $497,913. Title: "The Biological Pump During the Last Glacial Maximum and Early Deglaciation"

Intellectual Merit: Results from this project have been presented above. It has improved our understanding of the glacial ocean, its circulation, carbon, nitrogen and iron cycling and led to eleven peer-reviewed publications [56, 59, 60, 110, 159-165].

Broader Impacts: International collaboration has been fostered through OC3, an international working group of the Past Global Changes program. In three meetings (Corvallis, 2017; Cambridge, 2018; San Francisco, 2019), OC3 developed a community-based database for benthic carbon and oxygen isotope data. It also compiled core-top $\delta^{13}C$ data, produced two publications [159, 166] and is currently in the process of finalizing the down-core $\delta^{13}C$ synthesis. The meetings supported many early career scientists and researchers from developing countries. The project supported the PhD and postdoctoral work of Juan Muglia and two undergraduate students. Data and code are available on NOAA Paleoclimate and github.

Clark Award: AGS-1503032; Period: 07/01/2015 to 06/31/2018; Amount: $80,434. Title: "Collaborative Research: Last Interglacial Earth System: testing transient climate and ice-sheet simulations with a proxy-data network."

Intellectual Merit: We developed the first comprehensive reconstructions of regional and global SSTs during the Last Interglaciation (LIG) [167]. We constrained peak LIG SSTs to be ~0.5±0.3°C higher relative to the 1870-1889 mean which is no higher than during peak SSTs during the present interglaciation. We also conducted the first transient simulation with a fully coupled atmosphere-ocean general circulation model from the Penultimate Glacial Maximum 140 ka through the LIG forced by insolation, greenhouse gases, ice sheets, and freshwater forcing. We forced models of the Greenland and Antarctic ice sheets by the climatology from our transient simulation to assess the impact on mass loss, and then used a sea-level model to predict how this mass loss would be recorded at far-field sites with records of relative sea level. Our results show that oceanic forcing played a primary role in explaining the sea-level differences between the two most recent deglacial-interglacial intervals, including causing global mean sea level to rise at least 4 m above modern during the LIG [82].

Broader Impacts: Understanding the cause of higher global sea level under climate conditions similar to or only modestly warmer than present is important for evaluating the impacts of future low-carbon emission scenarios [168, 169]. This study also contributed to human resources by supporting the training, education, and research contributions of a Ph.D. student, Jeremy Hoffman, who is now the Chief Climate and Earth Scientist at the Science Museum of Virginia.