1. Introduction

The global Meridional Overturning Circulation (MOC) transports heat, nutrients, carbon and other substances around the globe and connects the surface and atmosphere with the enormous reservoir of the deep sea. As such it is considered an important part of Earth's climate system. However, little is currently known about how and why the MOC has changed in the past (Lynch-Stieglitz 2017), although it has been implicated in abrupt climate and ecosystem changes and variations of atmospheric CO_2 (e.g. McManus et al. 2004; Parsons et al. 2014; Schmittner and Galbraith 2008). One promising period for studying the MOC is the Last Glacial Maximum (LGM, ~20,000 years before the present) because the background climate was much different, providing a large forcing, and previous projects have synthesized a wealth of paleoclimate data (e.g. Curry and Oppo 2005; Skinner et al. 2017). Recent progress in quantitatively reconstructing the LGM MOC has been facilitated by including paleo tracers such as carbon isotopes into models, which allows direct comparison to sediment data (Gu et al. 2020; Menviel et al. 2017; Muglia et al. 2018).

Despite these efforts, important aspects of the LGM MOC remain controversial. Whereas a consensus has emerged that the Atlantic MOC (AMOC) was shallower, its strength remains debated. Some studies suggest a weaker (Menviel et al. 2017) and others a stronger circulation (Kurahashi-Nakamura et al. 2017). Recent results indicate poor constraints from some of the paleo tracers used (Gu et al. 2020), which could explain why AMOC flow rates are more difficult to reconstruct than its geometry.

Diapycnal mixing in the glacial ocean and its effects on the MOC and the carbon cycle is another contentious issue and the focus of this proposal. Several studies imply reduced mixing as a reason for increased deep ocean carbon storage and lower atmospheric CO_2. Ferrari et al. (2014), for example, suggest that, due to the shoaling of the AMOC, the interface between Antarctic Bottom Water (AABW) and North Atlantic Deep Water (NADW) moved away from the bottom-intensified regions of vigorous mixing (Fig. 1). This would have caused a separation of those water masses, increased isolation of AABW and thus increased deep ocean carbon storage, which could explain part of the observed glacial reduction of atmospheric CO_2. Watson and Garabato (2006) and more recently Stein et al. (2020) assert that increased deep ocean stratification would have reduced vertical mixing and thus increased carbon storage. Conversely, sea level lowering and associated effects of changes in basin geometry on tides have been suggested to *increase* mixing during the LGM (Egbert et al. 2004; Schmittner et al. 2015).

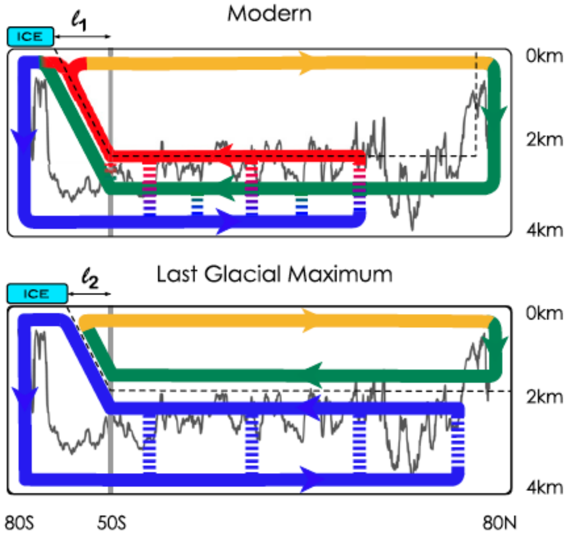

Figure 1: Conceptual model of the MOC from Ferrari et al. (2014). The wiggly line indicates the depth of the mid-ocean ridge below which mixing is enhanced. Shoaling of the MOC in the LGM due to an expansion of Southern Ocean sea ice separates the AABW (blue) circulation from that of NADW (green).

Our own recent work tentatively supports the idea that diapycnal mixing was increased during the LGM with important implications for the MOC (Wilmes et al. 2019). However, as we will discuss in more detail below, those results are based on an incomplete model, one that utilizes only a portion of the energy (the near-field effect) supplied to tidal mixing. Here we propose to extend the study to a comprehensive model of tidal mixing, including far-field effects, which describe the propagation of internal waves, remote dissipation and turbulence (see Diapycnal Mixing section for more detailed definitions of near-field and far-field effects).

The effects of wind changes are not well understood either. Westerly winds in the southern hemisphere have been suggested as an important control on the MOC and deep ocean carbon storage during the LGM (Toggweiler et al. 2006) and last deglaciation (Anderson et al. 2009; Menviel et al. 2018). A recent review of the modeling literature indicates that in most models intensified winds increase atmospheric CO_2 (Fig. 2; Gottschalk et al. 2019). However, to our knowledge, all of the reviewed coarse-resolution models with realistic geometry had used constant (in time and space) isopycnal-layer-thickness diffusivities, which leads to unrealistic physical responses because those models neglect eddy compensation (Gent 2016). Here we propose to apply a more realistic model with variable isopycnal-layer-thickness diffusivities, which accounts for eddy compensation, to better quantify effects of westerly winds on the MOC, the carbon cycle and atmospheric CO_2.

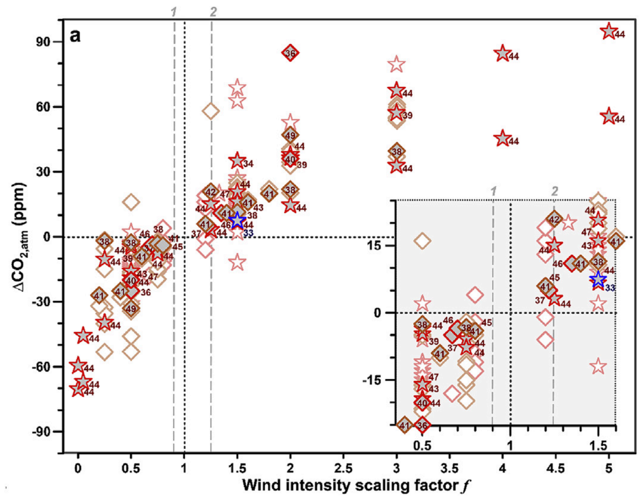

Figure 2: Model atmospheric CO_2 responses to a change of southern hemisphere westerly winds. From Gottschalk et al. (2019).

Global, coarse-resolution ocean models require parameterizations of processes on scales smaller than the grid-box size. But although subgrid-scale parameterizations of mixing processes are known to affect both the simulated large-scale circulation (Bryan 1987), many ocean components of coupled climate models still use highly simplified parameterizations, often with constant in time and/or space diffusivity parameter values, which questions the reliability of their responses (Gent, 2016). However, much progress has been made recently to develop more physically based parameterizations, implement them in models, and evaluate their performances. The Climate Process Team (CPT) on Internal Wave-Driven Ocean Mixing, for example, compiled observational estimates of diapycnal diffusivities and developed and tested new internal wave-driven mixing parameterizations (MacKinnon et al. 2017). Spatially and temporally variable parameterizations of mesoscale eddies and internal wave-driven mixing have been developed and combined in a unified, energetically consistent scheme that includes all major energy sources and transfers, and that integrates isopycnal and diapycnal mixing (Eden et al., 2014). Here it is proposed to evaluate this scheme, referred to in the following as the Internal Wave Dissipation, Energy and Mixing (IDEMIX) model, and apply it to the LGM in order to test hypotheses regarding diapycnal mixing and the ocean's response to southern hemisphere wind changes, two key uncertainties in paleoceanography as outlined above.

The study proposed here would be complementary to the new CPT on Ocean Transport and Eddy Energy effort (Zanna et al. 2020), which will test scale-aware mesoscale eddy parameterizations in global models (mostly MOM6) at high resolution (grid box sizes between ¼° and 1°. Models at this resolution reproduce more details but they are computationally more expensive, which limits the number and lengths of possible simulations. Thus, they are ideal for short-term (decadal to centennial) simulations that require a high degree of realism. However, for many applications such as paleoclimate studies, uncertainty estimates, long-term (multi-millennial) future projections, or carbon cycle investigations multiple long simulations are required. Here we focus on coarse resolution (non-eddy-resolving) global models for long-term simulations. We note a link between this project and the Eddy CPT in that there is likely energy transfer from the mesoscale to the internal wave field (e.g. Stanley and Saenko 2014). This effect, which will be discussed in more detail below, will be included in our model.

In summary, we argue here that a comprehensive study of innovative mixing schemes would be a timely exercise with potentially transformative implications for understanding the paleo ocean. Such a study is now possible because the parameterizations have been fully developed and preliminary evaluations with a limited number of observations have been conducted with encouraging results (Pollmann et al. 2017). We have partially implemented the schemes already in the Oregon State University (OSU) version of the University of Victoria (UVic) climate model (OSU-UVic). Therefore, only a limited amount of new code development work will be required. Moreover, the OSU-UVic model is equipped with tracer components including biogeochemistry and isotopes and has already been applied to the LGM. We proceed by stating our hypotheses, after which we provide more background information followed by a detailed work plan.

2. Hypotheses

H10: (Null Hypothesis) Diapycnal mixing in the LGM ocean was not considerably different from that in the modern ocean.

H1A: (Alternative Hypothesis) Diapycnal mixing was considerably reduced in the LGM ocean due to increased stratification and/or shoaling of the AMOC.

H1B: (Alternative Hypothesis) Diapycnal mixing was considerably greater in the LGM ocean due to enhanced tidal energy dissipation in the deep ocean and increased propagation and dissipation of internal wave energy.

H20: (Null Hypothesis) Eddy compensation does not considerably affect the response of the carbon cycle and atmospheric CO_2 to changes in southern hemisphere westerly winds in realistic geometry models.

H2A: (Alternative Hypothesis) Eddy compensation considerably reduces the response of the carbon cycle and atmospheric CO_2 to changes in southern hemisphere westerly winds.

Given the preliminary results regarding tidal mixing presented below and studies examining the effects of eddy compensation on the modern carbon cycle (Lovenduski et al. 2013; Swart et al. 2014) and in idealized geometry models (Munday et al., 2014), we expect both null hypotheses to be false and the alternative hypotheses H1B and H2A to be true. If confirmed, this would represent a transformational advance in our understanding of the glacial ocean and highlight the role of mixing processes. It would suggest that impacts of LGM tides on the MOC are larger than hitherto thought and its effects need to be considered as first-order effects in future modeling. If H2A turns out to be true it would imply that the effect of wind changes on atmospheric CO_2 is much smaller than previously thought.

Our strategy to test these hypotheses is to implement IDEMIX in a process-based global realistic-geometry model that includes biogeochemistry and isotopes and compare model results to modern and paleo observations. Our preliminary results (section 4a) include evidence that sediment data provide constraints on paleo ocean mixing rates. However, proper consideration of uncertainties in surface forcing, tidal energy input and limitations in determining the MOC from paleo data requires a relatively large number of paleo simulations.

Models typically implement subgrid-scale mixing as diffusion processes. This proposal is concerned with calculations of diapycnal (K_ρ), isopycnal (K_i) and isopycnal-layer-thickness diffusivities (K_GM). It is generally thought that K_i and K_GM are closely related because they are mostly due to mesoscale eddy activity (Gent and McWilliams, 1990) although this idea has been questioned (Gnanadesikan et al., 2015), which is why we will consider them separately.

3. Diapycnal Mixing

Mixing of interior waters with different densities directly powers the diabatic part of the MOC (Munk, 1966; Gnanadesikan, 1999; Kuhlbrodt et al., 2007). The most important energy sources for diapycnal mixing are tides and the wind (Munk and Wunsch, 1998; Wunsch and Ferrari, 2004). Barotropic tides loose energy through interactions of tidally-driven flow with bathymetry. This creates turbulence and mixing locally especially around rough topography (Polzin et al., 1997) and on continental shelves. It also generates internal waves that propagate away from generation sites, which leads to mixing elsewhere (Simmons et al., 2004b; Nash et al., 2004). Only about one third of the energy dissipated from the barotropic tide contributes to local mixing. This locally dissipated portion, referred to as **near-field** tidal mixing by the CPT, is relatively well understood and parameterized in models. Both the OSU-UVic model and the Community Earth System Model (CESM) use a formulation based on the works of Jayne and St. Laurent (2001), St. Laurent et al. (2002) and Simmons et al. (2004), in which the diapycnal diffusivity $K_\rho = K_\mathrm{bg} + \Gamma\varepsilon/N^2$ is calculated as the sum of a background diffusivity K_bg plus the locally dissipated tidal mixing, which depends on the mixing efficiency Γ, the rate of turbulent kinetic energy (TKE) dissipation ε, and the buoyancy frequency N. The buoyancy frequency squared $N^2 \sim \partial\rho/\partial z$ is proportional to the vertical gradient of locally referenced potential density and thus stratification. Dissipation of TKE $\varepsilon = qE(x, y)F(z, H)/\rho$ depends on the local energy flux from the barotropic tide $E(x, y)$ calculated by a barotropic tide model, where x and y denote longitude and latitude, the fraction $q = 1/3$ of this flux that is locally dissipated, density ρ, and a function F of depth in the water column z above the seafloor H, which distributes the mixing vertically. OSU-UVic uses a variable mixing efficiency (Mashayek et al., 2017).

Recent improvements to this scheme consider differences in q for diurnal (q_d) and semi-diurnal (q_s) tides and subgrid-scale bathymetry, which results in a three-dimensional flux E in the coarse-resolution model and the above formulation for ε is modified accordingly into a double sum over all tidal constituents and all depths (Schmittner and Egbert, 2014). The subgrid-scale bathymetry scheme improves agreement with microstructure data in coarse resolution models with a smoothed bathymetry such as the OSU-UVic model. The CPT tested different formulations for the vertical decay function F, which had modest effects (Melet et al., 2013). The vertical decay is the basis of the before-mentioned hypothesis by Ferrari et al. (2014).

Although some additional uncertainties remain, we conclude that the near-field tidal mixing scheme is relatively well established and tested. Much less is known about the **far-field**, that is the propagation of internal waves and their interactions with each other, with mesoscale eddies, the mean flow and with topography. For this reason, many global coarse-resolution models hitherto have simply used a constant background diffusivity K_{bg} to account for the remotely dissipated tidal energy. Recently, however, progress has been made by developing the IDEMIX model that consists of a single prognostic equation for total internal wave energy suitable for implementation in coarse resolution ocean general circulation models (Olbers and Eden, 2013). It includes energy input at the surface from near-inertial waves generated by wind fluctuations (Jochum et al., 2013) and at the bottom from barotropic tides. The propagation of internal wave energy is treated as a diffusive process both in the vertical and in the horizontal, which arises from integration of the radiative transfer equation over all wavenumbers. The dissipation of internal wave energy $\varepsilon_{\mathrm{iw}}$ becomes the source for TKE, which leads to mixing such that $K_\rho = \Gamma\varepsilon_{\mathrm{iw}}/N^2$. Note that in the equation for K_ρ the background diffusivity K_{bg} is no longer required since $\varepsilon_{\mathrm{iw}}$ includes both near and far-field contributions. The $\sim N^{-2}$ dependency of K_ρ is the basis of the afore-mentioned hypothesis by Stein et al. (2020).

It is argued here that despite the many assumptions that go into IDEMIX (Olbers and Eden 2013) it is based on well-established concepts and presents a major advancement in ocean modeling. In contrast to existing near-field tidal mixing schemes it is energetically consistent such that all energy that produces internal waves is converted to turbulent kinetic energy, which leads to mixing. IDEMIX has four independent tunable parameters: τ_v, τ_h, j^* and μ_0. j^* controls both horizontal and vertical propagation speed of internal wave energy, whereas τ_v and τ_h impacts them separately, and μ_0 controls the amount of dissipation.

IDEMIX has only been evaluated with a limited set of modern observations. Pollmann et al. (2017) showed encouraging agreement of turbulent kinetic energy (TKE) dissipation rates and internal gravity wave energy between the model and observational estimates of the upper ocean based on Argo floats. However, the scheme has not been evaluated against microstructure observations, which are sparser in spatial coverage but include deeper depths and are more precise than the Argo-based estimates. We hypothesize here that a careful evaluation against the microstructure data assembled by the Internal Wave CPT will provide an assessment of the model's vertical and horizontal propagation of internal wave energy in the deep ocean.

In the modern ocean most of the tidal energy removed from the barotropic tide dissipates on shallow continental shelves, where its contribution to mixing and the MOC are minor (Egbert and Ray 2001; Schmittner and Egbert 2014). Since the shallow dissipation was largely removed during the LGM due to the lower sea levels, tides got bigger and dissipated more energy in the deep ocean, which contributes strongly to mixing and the MOC (Egbert et al. 2004). And since semi-diurnal tides in the Atlantic are close to resonance, and move even closer during the LGM, they can respond strongly and non-linearly to relatively small perturbations of basin geometry (Egbert et al., 2004). As a result, simulated LGM tides are sensitive to changes in glacial land ice extent, as it modifies basin geometry (Wilmes and Green, 2014; Wilmes et al., 2019).

4. Results from Prior NSF Support

(a) "Collaborative Research: Assessing the Impact of Tidal Mixing on the Meridional Overturning Circulation of the Last Glacial Maximum" (NSF 1559153, 02/2016 - 01/2018, \$275,964) PI **Schmittner**, Co-PI **Danabasoglu**.

Intellectual Merit: The goal of the project was to estimate ***near-field*** tidal mixing and its effect on the LGM MOC. Sensitivity tests with a high-resolution barotropic tide model and with the OSU-UVic climate model were performed. The tide model simulations have shown little sensitivity to realistic changes in stratification, model resolution and internal wave drag parameterization. However, the modeled tides are sensitive to differences in ice sheet extent between ICE-5G (Peltier, 2004) and ICE-6G (Peltier et al., 2015) reconstructions. The results suggest that the energy supply to the internal wave field was 1.8 (ICE-6G) to 3 (ICE-5G) times larger during the LGM than at present day, mostly in the Atlantic. Using the near-field parameterization of tidal mixing described above this leads to a large increase in Atlantic diapycnal diffusivities by between a factor of 2 (ICE-6G) and 4 (ICE-5G) and strengthens the AMOC (by 14-64%) and AABW. These results are published (Wilmes et al. 2019), whereas the results described next are currently prepared for submission.

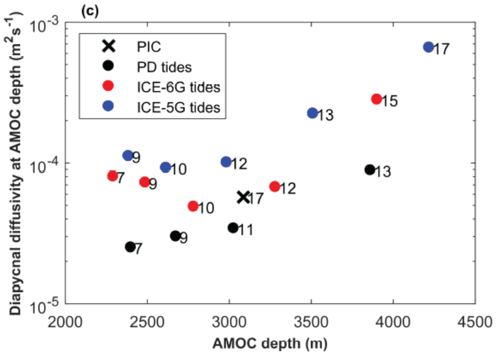

Figure 3: Diapycnal diffusivity in the Atlantic on the NADW/AABW interface (AMOC depth determined by the zero streamfunction contour). Labels indicate AMOC strength at 25 °N, which decreases as the AMOC shoals.

Data constraints from LGM sediments suggest that the AMOC was shallower (and possibly weaker) than at present. Muglia et al. (2018), who used present day tidal energy dissipation, achieved a shallow and weak AMOC by reducing atmospheric meridional moisture transport in the Southern Hemisphere in a series of experiments with the OSU-UVic model (by changing atmospheric diffusivities for water vapor), which causes saltier AABW and reduces the AMOC. (Similar effects on Southern Ocean buoyancy fluxes could have been caused by highly uncertain ice-ocean interactions.) The same set of experiments was repeated here with ICE-5G and ICE-6G based tides. Results show that models with a shallower AMOC generally have less mixing on the NADW/AABW interface (Fig. 3), supporting the idea of Ferrari et al. (2014). However, increased tidal energy dissipation can counter this effect such that mixing between NADW and AABW is increased despite AMOC shoaling. E.g. in the LGM model with ICE-5G tides, an AMOC strength of 9 Sv and an AMOC depth of 2,400 m diapycnal mixing is larger than in the pre-industrial control (PIC) simulation with an AMOC strength of 17 Sv and an AMOC depth of 3,100 m. Since we only consider near-field effects, diffusivities are likely underestimated in the LGM tide models.

These experiments confirm the results from Muglia et al. (2018) that lowest errors in both $\delta^{13}C$ and radiocarbon age are found for simulated weak and shallow LGM AMOC states (Fig. 4). Both independent sediment data sets agree in favoring an AMOC state with a strength (at 25°N) of between 8 and 10 Sv and a depth (averaged between 30°S-30°N) of 2.4-2.7 km. Note that the model underestimates the present day AMOC depth, so that AMOC depth changes were likely larger in reality than in the model. However, subsequent work has shown that these data only constrain AMOC depth effectively, so that AMOC strength estimates remain more uncertain (Gu et al. 2020). We will discuss this point more below.

Interestingly, all experiments collapse almost perfectly onto one curve for the global RMSE as a function of the AMOC for both $\delta^{13}C$ and radiocarbon (top row in Fig. 4). This suggests that the main impact on the RMSE is the AMOC and not the differences in tidal mixing. However,

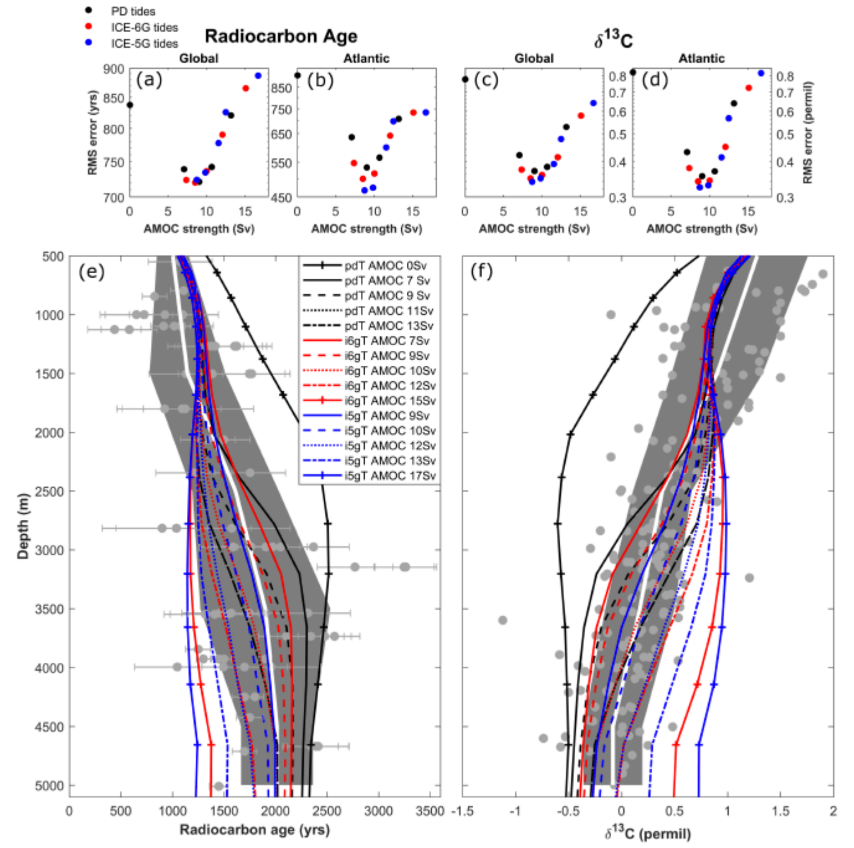

Figure 4: Data constraints on LGM MOC and mixing. Top row: Root-mean-squared error (RMSE) for radiocarbon age (a,b) and $\delta^{13}C$ (c,d) globally (a,c) and in the Atlantic only (b,d) as a function of AMOC at 25°N. Three sets of experiments were performed. LGM models with present day (PD) tidal mixing are compared with models with LGM tidal mixing using the ICE-5G (blue) and ICE-6G (red) reconstructions of ice extent. The panels (e,f) show horizontally averaged profiles in the Atlantic for the full set of experiments (lines) and the sediment data (grey points and white line with grey shading indicating the ±1 standard deviation).

experiments with LGM tidal mixing and similar AMOC show slightly better agreement with Atlantic (Fig. 4 b,d) and global $\delta^{13}C$ (Fig. 4 c) data due to reduced vertical gradients around 3 km depth in the higher mixing models (Fig. 4 e,f). This is recognized by comparing models with a similar AMOC (9 Sv) and weaker (present day) mixing (black dashed lines) with stronger mixing models (i5g, blue solid line). Though subtle, these results indicate, for the first time to our knowledge, that sediment data contain information on paleo ocean mixing rates.

Moreover, because in these experiments only changes in locally dissipated tidal energy (near-field) were considered (K_{bg} was kept the same in PD and LGM experiments) the effects of stronger LGM tides is likely underestimated. Thus, we hypothesize that the remotely dissipated tidal energy (far-field effect) would have contributed to an additional increase in mixing and thus a further strengthening of the MOC. A logical next step will be to test this idea using IDEMIX because it provides an energetically consistent formulation of both near- and far-field tidal mixing.

Broader Impacts: A female early career scientist (Dr. S.-B. Wilmes) was trained in tide and climate modeling and biogeochemistry. International and interdisciplinary collaboration was fostered between the US and the UK and between tide experts Green and Wilmes and climate modelers Schmittner and Danabasoglu. Updated tidal mixing schemes were implemented in two climate models (OSU-UVic and CESM) with a large user community.

Publications: Wilmes et al. (2019)

(b) “Collaborative Research: Ocean Transport and Eddy Energy” (NSF 1912420; 09/2019 – 08/2022, $372,194) NCAR PIs **Bachman** and **Danabasoglu**.

Intellectual Merit: The focus of this project is on the theory and transport of mesoscale eddy energy in the world ocean and its representation in global climate models. This project will use a combination of theory, modeling, and observations to “singletrack” mesoscale eddy parameterizations in next-generation ocean models.

Broader Impacts: This project is part of the Climate Process Team initiative co-funded by NOAA, representing a multi-institution collaboration between six universities and three climate modeling centers in the USA that aims to significantly advance the science of ocean macroturbulence. All simulation data, parameterizations, and models are freely available to the community.

Publications: Bachman et al. (2020), Bachman (2020)

5. Isopycnal and Thickness Diffusivities

Mesoscale eddies are the dominant mechanism for mixing along isopycnal surfaces. Gent and McWilliams (1990) proposed the first parameterization of mesoscale eddy effects. Variants of their scheme, which assumes that baroclinic instability acts to flatten isopycnal surfaces and can be described as diffusion of isopycnal-layer thickness, are still used in most global coarse-resolution models today. Whereas some models have used variable thickness diffusivities for some time, many other models still use a constant in time and space value for K_{GM} of around 10^3 m^2/s. As argued by Gent (2016) the results from modeling studies exploring changes in southern hemisphere westerly winds that use a constant K_{GM} do not correctly simulate eddy compensation, which describes the compensating effect of increased eddy activity due to increased winds on the MOC and occurs in eddy-resolving models and presumably also in the real ocean (Farneti et al. 2015; Gent and Danabasoglu 2011; Hallberg and Gnanadesikan 2006). Eddy compensation leads to a greatly muted response of the residual MOC in the Southern Ocean and the AMOC. This is a serious issue that affects many coarse resolution model results with constant K_{GM} that have examined effects of southern hemisphere westerly wind changes on atmospheric CO_2 (Winguth et al., 1999; Parekh et al., 2006; Toggweiler et al., 2006; Schmittner et al., 2007; Marinov et al., 2008a, 2008b; Menviel et al., 2008; Tschumi et al., 2008, 2011; d’Orgeville et al., 2010; Lee et al., 2011; Lauderdale et al., 2013; Huiskamp et al., 2016). However, eddy compensation can be captured in models that employ a variable K_{GM} (Gent, 2016).

Here it is proposed to investigate the effects of different schemes. Eden and Greatbatch (2008) and Stanley and Saenko (2014) have proposed $K_{GM} = c_E L^2 \sigma$, where c_E is a constant tunable parameter, L is the eddy lengthscale and $\sigma = fRi^{-0.5}$ is the Eady growth rate, $Ri = N^2/|\partial u_h/\partial z|^2$ is the Richardson number and u_h is the horizontal velocity. The two studies mentioned above differ in their choice of length scales. We have implemented both schemes already in the OSU-UVic model and performed a preliminary parameter variation study. We may also test structurally different schemes such as the one proposed by Bates et al., (2014), which has been implemented in POP2 by Co-PI Danabasoglu.

Including a prognostic (or diagnostic) equation for total (kinetic plus available potential) mesoscale eddy energy E_{eddy} it is possible to calculate the dissipation of mesoscale eddy energy ε_{eddy}. Two different parameterizations have been proposed $\varepsilon_{eddy} = (E_{eddy})^{3/2}/L_d$, where L_d is a dissipation length scale (Eden and Greatbatch, 2008) and $\varepsilon_{eddy} = rE_{eddy}$ (Marshall and Adcroft, 2010). As discussed in more detail in Eden et al. (2014) various processes of mesoscale eddy energy dissipation have been proposed, which would transfer energy either to the internal wave field or directly to TKE. But whereas all proposed processes lead to mixing, the location of that mixing is different. Whereas lee wave generation by mesoscale flow over topography (Marshall and Naveira Garabato, 2008; Nikurashin and Ferrari, 2011; Stanley and Saenko, 2014) would lead to bottom enhanced mixing, Lighthill radiation of gravity waves would lead to mixing in the interior and the generation of ageostrophic instabilities or a direct energy cascade to smaller scales would lead to mixing near the surface. This uncertainty will be considered in our research plan, which will explore if the observations provide constraints on the depth of energy conversion and by inference the possible mechanism. No matter where the dissipation occurs it becomes a source for the internal wave energy equation and thus couples the mesoscale with the TKE equation (Eden et al., 2014, eqs. 8-11).

6. Evaluation with Observations

Microstrucure- and Argo-based estimates of K_ρ compiled by the Internal Wave CPT (Waterhouse et al. 2014; Whalen et al., 2015) will be used here to evaluate IDEMIX. Figures 9-12 in Schmittner and Egbert (2014) provide examples of using microstructure estimates of K_ρ to test models. We hypothesize that those data will constrain IDEMIX parameters. Vertical profiles of diffusivities can be expected to provide constraints on model parameters related to vertical transport of internal wave energy such as τ_v, which was not well constrained by Argo data (Pollmann et al., 2017). Horizontal differences between K_ρ profiles will provide constraints on horizontal transport parameters such as τ_h. Since parameter j^* affects both vertical and horizontal propagation of wave energy we expect that it affects the ratio of energy that is dissipated locally. Thus, the smaller j^* and the smaller the fraction of locally dissipated energy, the more smoothed out K_ρ will be. We also expect smaller j^* to increase the impact of stratification on internal wave energy propagation, since the ratio N/j^* affects group velocities. Therefore, examining K_ρ profiles in regions with strong and weak stratification may provide constraints on j^*.

Temperature and salinity climatologies from Gouretski and Koltermann (2004) and the World Ocean Atlas will be used to evaluate those variables in the model. Modern water column observations of physical and biogeochemical tracers such as radiocarbon ($\Delta^{14}C$), chlorofluorocarbons (CFCs) and dissolved oxygen have long been used to evaluate ocean models including their subgrid-scale parameterizations (e.g. Gnanadesikan et al., 2004). Natural radiocarbon distributions provide information on centennial to millennial time-scale ocean ventilation (e.g. Khatiwala et al., 2012), whereas anthropogenic CFCs and nuclear bomb-produced radiocarbon provide information on decadal scales (e.g. Saenko et al., 2002). Simulated oxygen distributions are known to be sensitive to both diapycnal and isopycnal diffusivities (e.g. Gnanadesikan et al., 2004). However, to our knowledge IDEMIX has not been evaluated against these tracers yet. Radiocarbon and CFC climatologies available from the Global Ocean Data Analysis Project will be used here.

Mesoscale eddy parameterizations in OSU-UVic have not been evaluated. Recently published observational estimates of horizontal diffusivities and length scales on a global scale (Cole et al., 2015) provide a timely opportunity for such an analysis. However, the Argo-based Cole et al. (2015) dataset only covers the upper 2 km of the water column and results from tracer release experiments, satellites and drifter observations are even more limited. For this reason, we will also use tracers such as oxygen and radiocarbon, for which much more data are available.

Those tracers, with interior sinks, are useful for the evaluation of isopycnal diffusivities because they exhibit larger variations along isopycnals than temperature and salinity (Gnanadesikan et al., 2013). The Eddy CPT will evaluate parameterizations for high-resolution models used for centennial projections, whereas here we target coarse-resolution models used for longer simulations. Thus, our project will be complementary to the CPT.

443 δ^{13}C and 246 radiocarbon data from LGM sediments will be used as in Muglia et al. (2018). Data from more recent publications will be added as they emerge. Existing and emerging temperature reconstructions will also be used (MARGO, 2009; Tierney et al., 2020).

7. Work Plan

Here it is proposed to use mainly the OSU-UVic global climate model of intermediate complexity because it is well tested, computationally efficient, suited for many long-term simulations, includes the Model of Biogeochemistry and Isotopes (MOBI) and it is already set-up for LGM simulations. A large number of model experiments is necessary to explore the parametric and structural uncertainties of the parameterizations and the uncertainties in LGM forcing, MOC state and tidal energy fluxes. The OSU-UVic model is well suited for the extensive sensitivity tests, tuning and many long LGM experiments necessary for this project. To broaden the impact and benefit a larger modeling community, we will also port our tested and tuned code to the new ocean component MOM6 of the widely used state-of-the-science CESM model. However, we do not plan extensive tuning, testing and evaluation with CESM. Nevertheless, we believe that this project will benefit CESM and other complex model development by not-only providing working code but also a test of the parameterizations and a set of estimated parameters. Since MOM6 is also the ocean component of the GFDL model our project may also benefit that community. The work will be supported by collaborators Drs. Scott Bachmann and Gokhan Danabasoglu, both at NCAR, who will assist with implementation in MOM6, Dr. Carsten Eden at U. Hamburg, who will provide IDEMIX code and expertise, and Dr. Markus Jochum at U. Copenhagen, who will provide expertise and data on the wind energy input to the near inertial wind field (see letters of collaboration). The work will be performed by the PI (AS) and a postdoctoral researcher (PR), who will be hired and supervised by AS. The team will communicate via email and schedule bi-monthly telecon meetings (via Zoom).

The OSU-UVic model uses a simple, one-layer atmospheric energy-moisture balance model, which makes it computationally efficient, but also limits atmospheric feedbacks. Its ocean component solves the primitive equations at coarse resolution (1.8°×3.6°, 19 vertical levels) and is coupled to a dynamic-thermodynamic sea ice model (Weaver et al., 2000). Here, we will use version 2.10 (Mengis et al. 2020), which is equipped with the most recent IPCC scenarios. However, most of our recent innovations in ocean physics and biogeochemistry are at this point only available in version 2.9. Thus, a first step will be to merge all the latest code into version 2.10. The main UVic model developers have recently agreed to use the code-development and versioning software git and the code-sharing site gitlab (similar to github) in the future for collaborative model development and to make the code available to the public. This project would support this effort and provide all new code developments to the broader UVic user community. As part of this project we will also write a user guide and documentation, which will be useful particularly for new users and serve as a wiki page on gitlab. The UVic model has been applied to many future projections and paleoclimate studies and is well tested. Both the physics and the biogeochemistry have been extensively validated and found to be consistent with contemporary observations (e.g. Mengis et al., 2020).

Our strategy for model evaluation involves three steps:

First, a series of equilibrium simulations with the physics-only model but including radiocarbon and CFCs will be performed in which a range for the parameter values is scanned. For radiocarbon to equilibrate the simulations will need to run for 5,000 years with forcing corresponding the past 5,000 years. These simulations will be driven by observed CO_2 and other well-known forcings including isolation from Earth's orbital changes and observed atmospheric radiocarbon and CFC concentrations. Such a long transient spinup is preferable to a spinup with constant pre-industrial forcing as is commonly used because of the long memory of the deep ocean, which currently still feels the impacts of the Little Ice Age cooling (Gebbie and Huybers 2019). Comparison with observed physical variables such as temperature, salinity, isopycnal slopes, diffusivities, TKE dissipation rates, radiocarbon and CFCs will be performed to narrow the parameter space. Based on previous experience we expect that about one third of the initial ensemble will survive the first step.

Second, the full biogeochemistry (MOBI) calculations will be switched on and a subset of the parameter space that passed the physics evaluation will be repeated. These simulations, which will also need to be integrated for 5,000 years due to the long equilibration time of the ocean's nitrogen inventory and $\delta^{13}C$, will be compared with the full suite of observed biogeochemical variables and isotopes available (PO_4, NO_3, dFe, DIC, ALK, O_2, $\delta^{13}C$, $\delta^{15}N$, radiocarbon, CFCs). The resulting best fitting model will be identified.

Third, the best fitting model will be applied to the LGM. We will use our standard LGM set-up, which includes radiative forcings from changes in greenhouse gas concentrations estimated from ice cores, prescribed ice sheets, increased global salinity, solar irradiance according to changes in Earth's orbital parameters, dust, wind stress from the Paleoclimate Model Intercomparison Project (PMIP; Muglia et al., 2018). As in Muglia et al. (2018) for each model a series of LGM simulations will be performed. This is necessary because of the uncertainties in buoyancy forcing. A caveat of the Muglia et al. (2018) study was that it only explored a limited set of circulation states forced with changes in southern hemisphere meridional water vapor transport. The resulting AMOC states were either weak and shallow or strong and deep, but a strong and shallow state was not tested although it has been suggested as a viable LGM state by Kurahashi-Naramura et al. (2017). Extending the experimental set-up by including experiments with additional (negative) freshwater forcing in the North Atlantic, we have now completed a first set of 15 experiments spanning the AMOC depth vs strengths phase space (Fig. 5).

We plan to repeat this set with both ICE-5G and ICE-6G tidal energy fluxes and present-day tides such that a total number of 45 LGM simulations will be performed. Note that it will not be necessary to vary the dust fluxes, which were constrained with $\delta^{15}N$ data by Muglia et al. (2018) and are not sensitive to circulation changes. Ongoing NSF funded efforts are underway to include additional tracers ($^{231}Pa/^{230}Th$ and ε_{Nd}) into the model. Both have been suggested to include rate information (Du et al. 2020; McManus et al. 2004), which may improve the observational constraints regarding AMOC strength, which is not well constrained by $\delta^{13}C$ and radiocarbon (Fig. 5). But even if those additional data do not allow to constrain AMOC strength much further, the hypotheses can still be tested considering this uncertainty because our experiments cover the range of possible AMOC states. A table listing all planned experiments is given in the Facilities and Equipment section of the proposal.

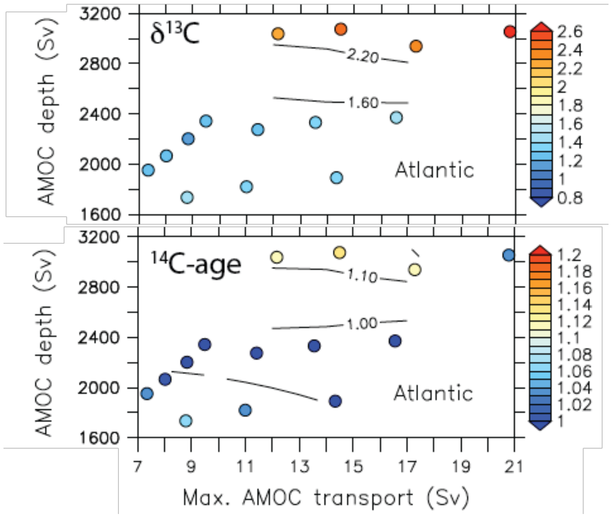

Figure 5: Normalized RMS errors for $\delta^{13}C$ (top) and radiocarbon age (bottom) in AMOC depth vs AMOC strength space. From Muglia and Schmittner (submitted manuscript). The mostly horizontal orientation of the isolines indicate that AMOC depth is much better constrained than AMOC strength confirming earlier results with a more limited number of experiments by Gu et al. (2020).

In **year 1** AS & PR will complete the evaluation of the diagnostic mesoscale eddy energy models, which are already implemented. However, so far, we have only run the physics evaluation (step 1) but not the biogeochemistry and LGM. Observational K_i estimates based on tracer release experiments will be compiled from the literature and compared to the Argo-based estimates of Cole et al. (2015) and the model results. A handful of the best fitting models from the physics evaluation will be used for the biogeochemistry experiments. The best fitting version of those will be used for LGM and wind sensitivity experiments. Comparisons with the default model and sediment data will provide an assessment of variable K_{GM} and K_i parameterizations.

Once calibrated, the model's ability to simulate eddy compensation will be tested by performing idealized experiments with increased southern hemisphere westerly winds and comparing its response of the Southern Ocean MOC and the AMOC with that from high-resolution, eddy permitting models (Farneti and Delworth 2010). This is important since the degree of eddy compensation can depend on the parameterization used or choices within a scheme (Farneti and Gent 2011; Jochum and Eden 2015). The test will be passed if the coarse resolution model with variable K_{GM} shows a considerably muted response of the residual SOMOC and AMOC compared with constant K_{GM} models and more similar to eddy permitting models, suggesting considerable eddy compensation. After this test, the role of eddy compensation on the response of the carbon cycle and atmospheric CO_2 to southern hemisphere wind changes will be examined. This will be achieved through idealized simulations in which southern hemisphere winds are multiplied by different factors (0, 0.5, 0.8, 1, 1.2, 1.5, 2, 5) in two models, one with variable K_{GM} and one with constant K_{GM}. The results will deliver the test of hypotheses **H20** and **H2A**. If for most of those simulations the differences in atmospheric CO_2 concentrations between the two sets is less that 15% H20 will be true, otherwise it will be false. If the atmospheric CO_2 response in the set with variable K_{GM} is more than 15% smaller than that in the set with constant K_{GM} then H2A is true. If H2A is found to be true, this would imply that southern hemisphere wind changes had a much smaller effect on past atmospheric CO_2 changes than previously thought. A series of more realistic LGM experiments with different southern hemisphere westerly wind changes from PMIP models will also be conducted with both the variable and fixed K_{GM} model following (Muglia and Schmittner, 2015). Results from the most recent PMIP4 iteration will be downloaded and added to those from PMIP3.

In year 1 AS, PR & CE will start working on the implementation of the prognostic equation for the internal wave energy (IDEMIX, eq. 10 in Eden et al., 2014). IDEMIX code is available in

CVmix, a community online code repository for ocean mixing parameterizations on github, which should facilitate the implementation. The PI is very familiar with the OSU-UVic code and has implemented many physical and biogeochemical components. One complication of this scheme is that the internal wave energy transport uses different diffusivities than the other tracers. However, we believe that with support from CE the scheme can be implemented. Each summer, starting in year 1, we will offer public seminars and facilitated discussions on climate science (see Broader Impacts section).

In **years 2 and 3** AS & PR will perform a parameter variation study of IDEMIX. For the four independent tunable parameters τ_v, τ_h, j^* and μ_0 we will start from a default parameter setting based on Pollmann et al. (2017) ($\tau_v = 2$ days, $\tau_h = 15$ days, $j^* = 5$, $\mu_0 = 1/3$ and vary each parameter while keeping all others at their default setting. The range of values will be: $\tau_v = 0.2$, 1, 2, 5, 10, 20, 30 days; $\tau_h = 5$, 10, 15, 20, 30, 50 days; $j^* = 3$, 5, 8, 10, 12, 15; $\mu_0 = 1/6$, 1/3, 2/3, 1, 4/3, 5/3, 2. Thus, our minimum ensemble size is 26. Models with additional parameter combinations and/or different assumptions, e.g. the fraction of mesoscale eddy energy injected at the bottom (representing lee-wave generation) or the fraction of near-inertial energy that leaves the mixed layer, may be included, with the goal to keep the ensemble size < 50. Those should be narrowed down to about 10 experiments for the experiments with biogeochemistry and one for the LGM runs. This IDEMIX LGM version will be used to simulate the AMOC depth/strength matrix of 15 experiments each with two LGM tidal energy input estimates (ICE-5G & ICE-6G) and one with present-day tides (pdT). These experiments will test hypotheses **H10, H1A and H1B**. Models with present-day tides will quantify effects of stratification and AMOC shoaling on diapycnal diffusivities and thus address H1A. Stratification and AMOC depth effects can be separated in the diagnostics by re-calculating diffusivity changes that would result from each factor separately. Differences in the results from IDEMIX with those from the default model with only near-field tidal mixing considered will allow us to determine the effects of the far-field tidal mixing on LGM MOC and tracer distributions and thus evaluate H1B. If a model with present day tides fits the sediment data best, which we think is unlikely, then H10 or H1A could be true, while H1B would be false. Conversely, if a model with ICE-5G or ICE-6G tides fits the data best H1B would be true. The results could also indicate different features of the LGM MOC such as increased AABW and or a strong and shallow AMOC being more or less consistent with the sediment data.

With the help and guidance of our NCAR Scientist and Software Engineer collaborators, the PR will implement IDEMIX in MOM6. NCAR collaborators will also help with the setup of the model simulations needed for testing and evaluation. In addition, NCAR will prepare the model with this parameterization included for a functional release in a future CESM version. Priority will be given to ocean – sea ice coupled hindcast simulations. Fully coupled ocean-sea ice-atmosphere simulations will be considered and performed if time permits. In year 2 the PR is expected to write one manuscript about the results from year 1 and to participate in the Oregon Museum of Science and Industry’s (OMSI) Science Communication Fellowship program. In year 3 the PR will write a second paper describing IDEMIX results from years 2 and 3. The public seminars on climate science will be repeated in the summers of years 2 and 3.

8. Intellectual Merit

This project will advance our knowledge of the role of mixing processes on the MOC, the ocean’s carbon cycle and atmospheric CO_2 in the modern and glacial ocean. It will evaluate a novel, energetically consistent concept of mixing in the ocean with both modern and paleo data. Hypotheses regarding the roles of changes in stratification, AMOC depth and tidal energy input due to sea level lowering on mixing in the LGM ocean will be assessed by considering both near-field and far-field effects of internal wave-driven mixing. The role of eddy compensation in affecting the response of the ocean's carbon cycle and atmospheric CO_2 to southern hemisphere wind changes will be evaluated.

9. Broader Impacts

LGM simulations have long been a staple of PMIP, but none of the previous iterations have considered changes in tidal mixing or the role of eddy compensation. Thus, we expect that if H1B or H2A is true these issues will get the attention of the larger paleoclimate modeling community. The LGM MOC has been hypothesized to affect ocean carbon storage and atmospheric CO_2 (e.g. Sarnthein et al., 2013; Skinner et al., 2017). Thus, improved constraints on the LGM MOC and mixing will aid quantitative understanding of the LGM carbon cycle and the causes for glacial-interglacial variations of atmospheric CO_2, which remain controversial. Preliminary results using the weak and shallow AMOC solution from Muglia et al. (2018) and a precise decomposition of the ocean carbon cycle suggests that this state explains more than three quarters of the observed glacial-interglacial CO_2 changes (Khatiwala et al., 2019). Any improvements to LGM MOC estimates achieved here could be used in a follow-up study using this methodology to quantify effects on the carbon cycle.

This project has the potential to improve two widely used climate models: the UVic model and CESM. The UVic model is used by a number of research groups around the world for long-term (multi-millennial) climate/carbon cycle projections (Clark et al. 2016; Eby et al. 2009; Friedlingstein et al. 2006; Matthews et al. 2009; Meissner et al. 2012; Mengis and Matthews 2020; Oschlies et al. 2008; Schmittner et al. 2008), for paleoclimate (Muglia et al. 2018; Schmittner and Lund 2015; Schmittner and Somes 2016) and many other applications. Newly developed and tested code, as well as a user guide and documentation will be created and shared with the user community via gitlab. A webinar will be provided to the user community including instructions on how to use the new code. CESM is a state-of-the-science climate model used for many different purposes including projections for the Intergovernmental Panel on Climate Change assessment reports. Implementation of IDEMIX in MOM6 will benefit the broader CESM user community and may also be useful for users of the GFDL model, which also uses MOM6. Constraining the parameter range of the parameterizations may also benefit other models with coarse resolution global ocean components such as ongoing efforts in the University of Copenhagen version of CESM with the POP2 ocean model. Therefore, this project has the potential to benefit the broader global climate modeling community.

Large differences remain between the public's view of climate change and that of climate scientists (Funk and Kennedy 2016; Funk and Hefferon 2019). E.g., whereas about 97% of scientists think that global warming is mostly due to humans, only about 53% of the U.S. public think that (Marlon et al. 2019). Here we plan to contribute to a better-informed public by organizing events with presentations by scientists and facilitated discussions with the public. Our target audience are people who have questions about climate science, who may be confused by hearing different things and don't know what to believe. Those are the Cautious, Disengaged, and Doubtful groups described in the "Six Americas" (Roser-Renouf et al. 2015). As shown by these authors (their Fig. 5), those groups are mostly interested in hearing about the scientific evidence, the causes and to a lesser degree the consequences of and solutions to climate change.

Having been involved in the public debate, the PI has realized that there is a thirst for trustworthy scientific information among the public in Oregon. We plan to organize public meetings in which the PI and other climate scientists from OSU will give short presentations followed by discussions and a question and answer session. Information available in an online textbook (Schmittner 2018) will facilitate the Q&A portions. The PI has experience in such public events with the goal to develop true interactions as opposed to one-way information delivery. One impactful learning outcome will be the consensus of climate scientists regarding the causes of climate change (Lewandowsky et al. 2013), which is underestimated in the public (Ballew et al. 2019). Additional goals for these meetings are that participants after the engagement (1) view climate science as more accessible, (2) are more discerning about climate information they access in the media, and (3) are better equipped to search for scientifically valid information or seek out actual scientists to answer their climate related questions. A graduate student enrolled in the Marine Research Management program will design and evaluate the meetings (see letter of collaboration from MRM graduate program director Flaxen Conway). OSU's STEM Research Center will provide consultation on best practices for the evaluation (see letter of collaboration from associate director Julie Risien). If the coronavirus situation prevents in person meetings, we will hold the meetings via Zoom. Sessions will be recorded and made publicly available through OSU servers. They will be broadly announced in newspapers as well as through OSU's press office, Oregon's Climate Change Research Institute, community organizations from across the political spectrum, and social media to ensure maximum participation. CEOAS communications and outreach office, along with the Oregon State Alumni Association, will assist with the programing, promotion and organization of these meetings (see letters of support from Abby Metzger and Desirae Wrathall). We plan at least one meeting each Summer. Depending on the interest, additional meetings could be scheduled. Results from the evaluation of the meetings in year 1 and 2 will be published as part of the student's Masters thesis and used to refine the following meetings.

An early career scientist will be funded and trained in physical oceanography, paleoceanography, climate science, biogeochemistry and modeling. Exposure to different disciplines can broaden the horizon, let a young scientist recognize connections between disciplines, and facilitate the development of a new interdisciplinary workforce. The PR will receive training in science communication through OMSI's Science Communication Fellowship program by participating in a four-part workshop and by developing a hands-on activity that highlights a unique element of the research proposed here. This activity will be presented at OMSI's monthly *Meet a Scientist* public program with an average of 340 visitors at each event. Family groups are chosen as the target audience for two reasons: (i) awareness of and engagement with STEM (science, technology, engineering and mathematics) subjects increases the likelihood of children entering the STEM workforce, and helps people identify as competent science learners (National Research Council, 2009); (ii) science learned in a social environment, alongside family, peers, teachers, and informal science educators, offers greater opportunities for ongoing inquiry (Fenichel and Schweingruber, 2010) and has the potential to efficiently increase public understanding of science (Falk and Dierking, 2010).

Finally, the project will foster a new international collaboration between the PI, Profs. Eden from the University of Hamburg, Germany and Jochum from the University of Copenhagen, Denmark and two scientists from NCAR and new partnerships within OSU and between OSU and community organizations in Oregon.