Response to reviewer comments

We would like to thank the reviewer for their thorough evaluation of our manuscript and for the constructive comments and suggestions. We have carefully revised the manuscript according to the comments. In the following, we provide a detailed, point-by-point response to all the comments. All changes made in the manuscript are highlighted in the revised version.

Reviewer comment 1: Insufficient literature survey/failure to acknowledge MESMO 3c, MESMO 3c includes processes not represented in cGENIE-MCP (e.g., hydrothermal DOC degradation). The novelty of this study relative to MESMO 3 / MESMO 3c is unclear, as these models already include a recalcitrant DOC pool.

Response:

We thank the reviewer pointing out that the novelty of our work was not described clearly. MESMO 3 and MESMO 3c represent important advances in global marine DOC modeling by explicitly resolving semi-labile and refractory DOC pools within an Earth system modeling framework. **MESMO 3** explicitly resolves semi-labile (DOM_{SL}) and refractory DOM (DOM_R) pools, representing DOM_R production as a fixed fraction ($fDOM_r$:~1%) of DOM production routed from NPP or via the deep particulate organic matter (POM) split pathway (same $fDOM_r$:~1%). DOM_R remineralization rate is governed by prescribed additive sink terms, including slow background decay, photodegradation, and hydrothermal vent circulation. **MESMO 3c** further refines this formulation by recalibrating DOM production relative to net primary production, introducing environmental dependencies such as temperature and mixed layer depth, and splitting DOM into DOM_{SL} and DOM_R fractions at a ratio of 1000:7. The "deep POM split" pathway of MESMO 3 is carried forward in MESMO 3c, whereby sinking POM is split or broken down into smaller POM and DOM. The newly formed total DOM at depth is further partitioned into DOM_{SL} and DOM_R at the same 1,000:7 ratio that occurs in the surface ocean. The rate of POM splitting into DOM depends on the availability of dissolved oxygen and temperature. The three pathways of DOM_R remineralization in MESMO 3 are carried forward in MESMO 3c: slow background decay, photodegradation, and hydrothermal vent circulation, but these characteristic timescales of decay are calibrated. MESMO 3c reproduces distributions and inventories of total dissolved organic carbon (DOC_T) that are broadly consistent with observationally derived products.

In **MESMO 3 and MESMO 3c**, newly produced DOM—whether generated from NPP or through deep POM splitting—is partitioned into semi-labile and recalcitrant fractions using fixed allocation ratios (e.g., $fDOM_r$: ~1% or DOM_{SL}: DOM_R = 1000:7). As a result, DOM_R is designated as recalcitrant at the moment of production, rather than emerging through subsequent transformation.

By contrast, the **Microbial Carbon Pump (MCP)** framework emphasizes the progressive reworking of labile and semi-labile DOC into recalcitrant compounds that accumulate over long timescales (Jiao et al., 2010; Jiao et al., 2024; Legendre et al., 2015). In **cGENIE-MCP**, the transformation from SLDOC to RDOC is implemented as an explicit, process-based pathway that is dynamically coupled to remineralization fluxes. Although a constant yield is prescribed, RDOC production depends on the time-evolving processing of semi-labile DOC. RDOC accumulation in cGENIE-MCP emerges from the time-integrated transformation of semi-labile DOC. The parameters governing this semi-labile–to–refractory DOC conversion are adopted from the observational data-constrained inverse modeling framework of Wang et al. (2023). These parameters were optimized using a Bayesian inversion approach that jointly assimilates global observations, yielding a model state that reproduces the observed large-scale DOC distribution with high fidelity. We have incorporated this observation-based, inverse-derived DOC transformation parameter into cGENIE-MCP. This process-based and data-informed representation distinguishes cGENIE-MCP from MESMO 3/3c schemes.

We note that MESMO 3c includes several DOC-related processes that are not yet represented in cGENIE-MCP, such as DOC degradation in hydrothermal vent systems. These differences reflect complementary modeling objectives. Our study is specifically designed to isolate and quantify the role of labile DOC transformation pathways emphasized by MCP theory. Additionally, the data and descriptions regarding cGENIE-MCP and MESMO3 in the manuscript have also been replaced with the updated version of MESMO3c. The main modifications in the revised manuscript are as follows:

"Despite recent advances in global marine DOC modeling, the explicit representation of MCP processes responsible for RDOC production in cGENIE remains limited. The Minnesota Earth System Model for Ocean biogeochemistry (MESMO 3) represents an important development, explicitly resolving semi-labile and refractory DOC pools. MESMO 3, developed based on the GENIE-1 framework, represents RDOC production diagnostically as a fixed fraction of organic matter production or via deep particulate organic matter (POM) partitioning, with RDOC removal governed by additive sink terms including slow background decay, surface photodegradation, and hydrothermal vent circulation (Matsumoto et al., 2021). Subsequent developments in MESMO 3c further refined this formulation by recalibrating DOC production relative to net primary production, introducing environmental dependencies such as temperature-dependent degradation rates, and constraining parameter values using global DOC observations (Gilchrist and Matsumoto, 2023). These refinements substantially improved agreement with observed DOC inventories and spatial patterns and represent an important advance in the simulation of large-scale DOC distributions. However, in both MESMO 3 and MESMO 3c, the assignment of organic matter to refractory DOC occurs at the point of production through prescribed allocation ratios, rather than emerging through an explicit representation of MCP-driven RDOC accumulation arising from the progressive transformation of more labile DOC pools.

Here, we introduce cGENIE-MCP, an extension of the cGENIE model that explicitly represents MCP-driven DOC transformations. The framework partitions total DOC into three fractions—labile (LDOC), semi-labile (SLDOC), and refractory (RDOC)—and implements a process-based conversion of SLDOC into RDOC that is directly coupled to the remineralization process. In this formulation, RDOC accumulation emerges dynamically as a function of SLDOC remineralization processing rates and ocean circulation. We evaluate the performance of cGENIE-MCP against global observational datasets and compare its behavior with that of the standard cGENIE configuration. Finally, we analyze the spatial distribution and production of LDOC, SLDOC, and RDOC in relation to primary production to assess the model's ability to capture essential features of the MCP."

'a is a dimensionless conversion coefficient that represents the transformation of SLDOC into RDOC. The parameters governing the conversion from SLDOC to RDOC are derived from the observation-constrained inverse modeling framework of Wang et al. (2023). '

'4.3 Model performance for DOC

The statistical evaluation indicates that cGENIE-MCP reproduces observed DOC distributions with skill comparable to that of the well-established MESMO3c model across the major ocean basins (Table 32 and Fig. S12). The cGENIE-MCP yields low CRMSE in the Atlantic (3.63 μmol kg^{-1}), Pacific (3.84 μmol kg^{-1}), and Indian (2.56 μmol kg^{-1}) Oceans, MESMO3c shows similarly good performance in the Atlantic and Indian Oceans (Atlantic 4.03, Pacific 8.77, Indian 3.80 μmol kg^{-1}). When errors are weighted by model grid cell volumes (RMSE_vw), cGENIE-MCP achieves realistic basin-integrated DOC concentrations, with volume-weighted RMSE values ranging from 4-5 μmol kg^{-1} across all major ocean basins. These results indicate that cGENIE-MCP provides a plausible representation of DOC when the volumetric contribution of different ocean layers is taken into account. Among all basins, the Indian Ocean shows the best performance for cGENIE-MCP, characterized by the lowest CRMSE and RMSE_vw values, possibly reflecting the model's enhanced representation of low-latitude processes. Taylor diagrams shows show the bias of modeled DOC from the MESMO3c and cGENIE-MCP models with observations (Figure 10). cGENIE-MCP exhibits a relatively high correlation coefficient and a smaller standard deviation comparable to the observed value in the Atlantic, Pacific and Indian Oceans.

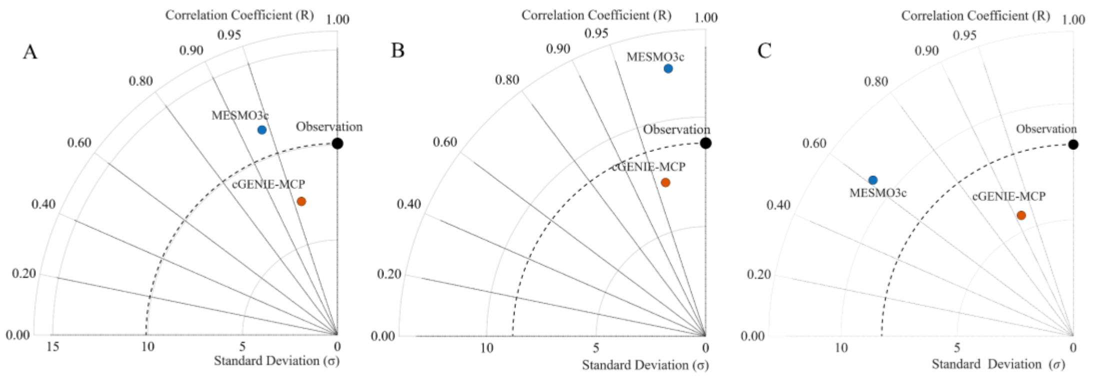

Figure 10. Taylor diagrams comparing simulated DOC concentration from cGENIE-MCP and MESMO3c against observed values from Hansell's laboratory (https://hansell-lab.earth.miami.edu/research/data-collection/) for (A) Atlantic, (B) Indian, and (C) Pacific.

Table 2. RMSE of modeled DOC for cGENIE-MCP and MESMO3 compared to observations

Tracers	cGENIE-MCP			MESMO3c		
	CRMSE	RMSE_vw	R	CRMSE	RMSE_vw	R
Atlantic DOC (μmol kg^{-1})	3.63	4.48	0.966	4.03	2.13	0.938
Pacific DOC (μmol kg^{-1})	3.84	5.33	0.919	8.77	5.37	0.614
Indian DOC (μmol kg^{-1})	2.56	4.16	0.968	3.80	2.39	0.990

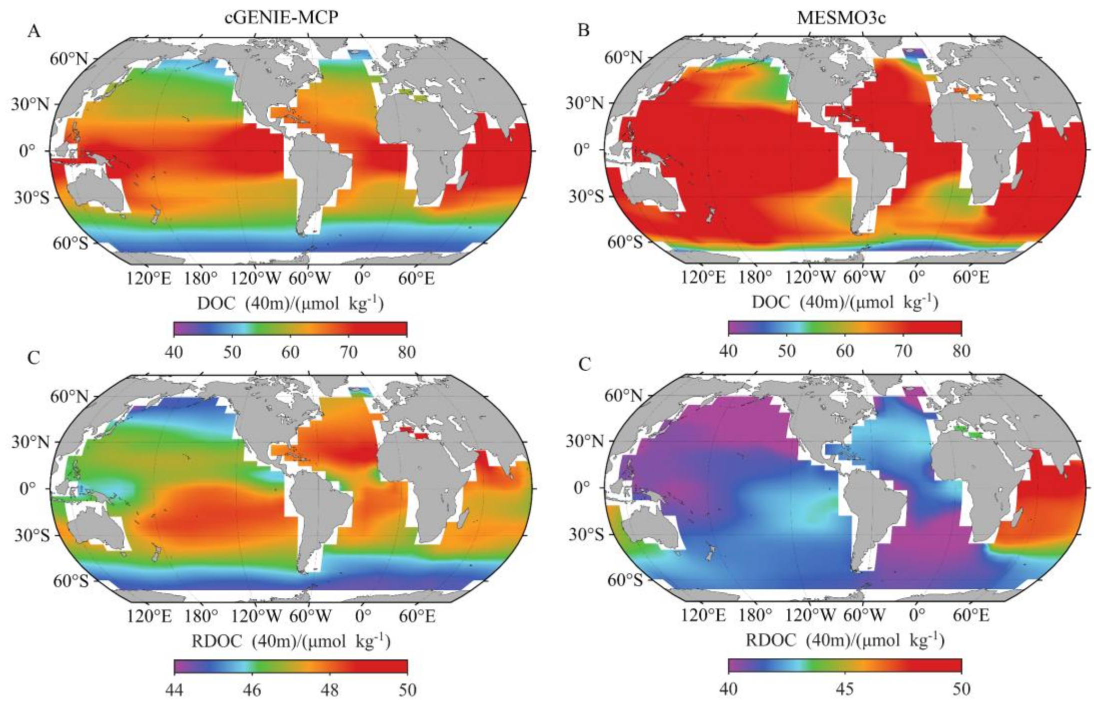

Figure S12. Global distributions of surface (A-B) DOC, (C-D) RDOC concentration (μmol kg^{-1}), (A,C) the results of cGENIE-MCP, (B,D) the results of MESMO3c.

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Reviewer comment 2: Gilchrist & Matsumoto (2023) have even carried out a glacial DOC cycle study, a long-term study that the authors of this submission hope to do.

Response:

We did not intend to imply that glacial-scale or long-term DOC cycle studies have not been conducted previously. Indeed, Gilchrist & Matsumoto (2023) have already presented an important and comprehensive investigation of the glacial DOC cycle, and we fully acknowledge their contribution. Our intention was to indicate that the cGENIE-MCP framework developed in this study provides a basis for future applications of long-term DOC cycle simulations that explicitly incorporate MCP-driven DOC transformations within the cGENIE modeling framework. The primary objective of the present study is to investigate the relationship between MCP and other carbon pumps in Snowball Earth periods or the future. We have therefore revised the manuscript, and the main modifications are as follows:

‘Several "Snowball Earth" events occurred throughout geological history. According to the Snowball Earth hypothesis, the biogeochemical cycle and the PP have severely slowed down or even stagnated under global freezing conditions. However, previous studies have found PP and DOC reservoirs still exist during glaciations (Jiao et al., 2024a; Man et al., 2024). These results suggest that organic matter produced in the surface ocean may have been degraded into DOC or RDOC in the water column. Therefore, understanding the changes of the DOC pools during Snowball Earth periods is of great significance (Hoffman and Schrag, 2002; Hoffman et al., 2017; Sansjofre et al., 2011). Indeed, previous studies in the glacial DOC cycle of Gilchrist and Matsumoto (2023) have demonstrated the importance of DOC dynamics during glacial climates. Building on these advances, a mechanistic characterization of the storage, spatial distribution, and source-sink processes of MCP-driven RDOC pools, as well as a quantitative assessment of their interactions with other carbon pumps during “Snowball Earth” periods, remains limited. The cGENIE-MCP model proposed in this study provides a process-based framework to simulate MCP-driven RDOC production and its large-scale spatial distribution over geological timescales. It is possible to analyze the relationship between $\delta^{13}C$ negative excursion and carbon pumps in geological records on a global scale, quantify the efficiency of MCP, and evaluate the impact of ocean environmental changes on the distribution of DOC.

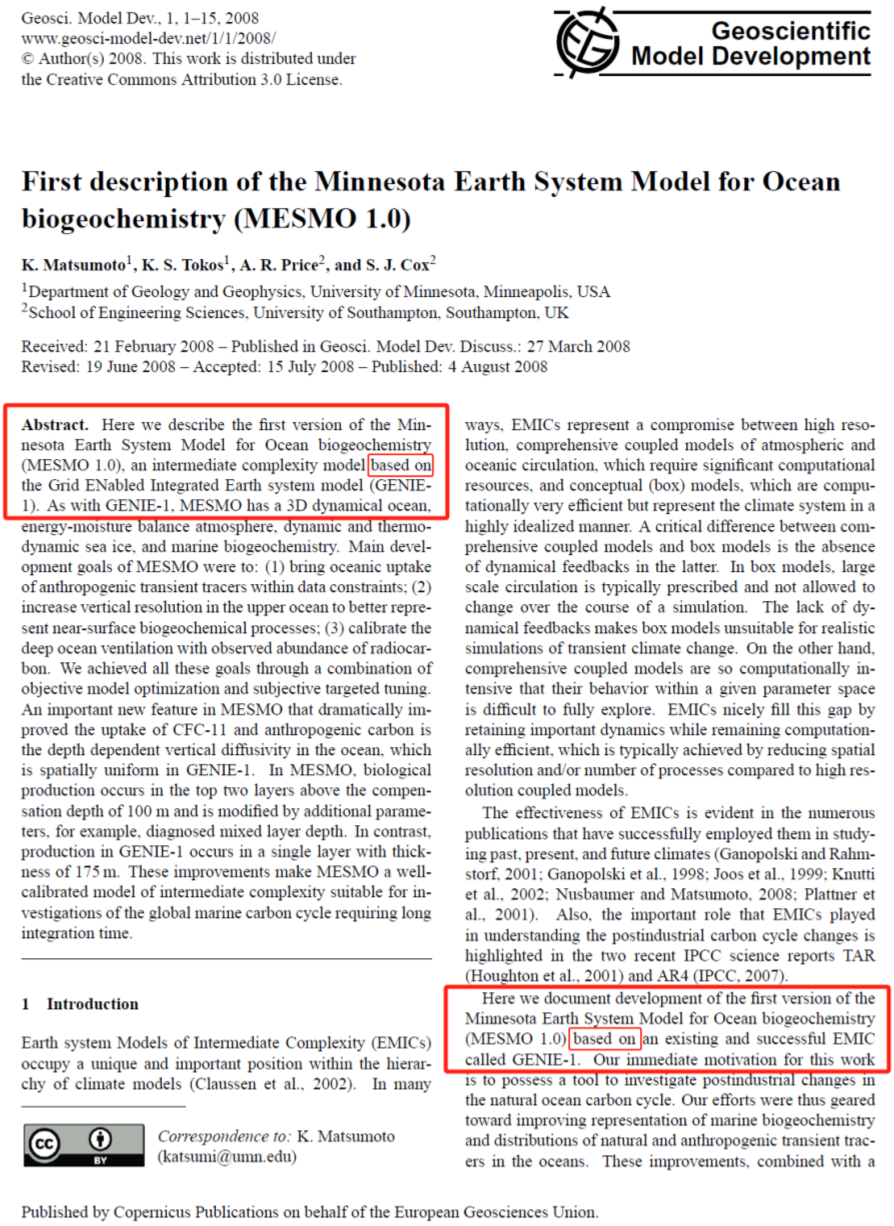
Furthermore, reducing emissions and enhancing carbon sinks have become a global consensus in response to global warming, with ocean carbon sinks playing a vital role in achieving this goal. Previous studies have pointed out that both "Snowball Earth" events and glacial-interglacial cycles are not only driven by orbital forcing but are also influenced by the ocean carbon cycle (Hoffman et al., 2017; Jiao et al., 2024a). The global ocean DOC reservoir is estimated to contain approximately 700 Pg C (Hansell, 2013). Although this accounts for only about 40% of the regenerated DIC reservoir (~1700 Pg C), it nonetheless represents a significant and long-lived carbon pool in the ocean. Its importance lies in its connection to SLDOC through the MCP process, allowing RDOC to vary in response to physical and biogeochemical perturbations. This dynamic behavior underscores the critical role of MCP-driven RDOC formation in regulating long-term ocean carbon storage and climate feedbacks. Therefore, evaluating the efficiency of the MCP is crucial for understanding of long-term climate regulation. The cGENIE-MCP model provides a flexible, modular framework that is well suited for long-term climate research. For example, by coupling the model with Shared Socioeconomic Pathway (SSP) scenarios, the response of MCP to rising atmospheric CO2 concentration can be investigated to reveal the feedback between climate change and the ocean carbon cycle. Future the model can be used to assess the potential of ocean negative carbon emission technologies (e.g., ocean alkalinization enhancement) under different climate scenarios. By simulating alternative implementation pathways, the long-term environmental impacts of these technologies can be quantified, enabling a comprehensive evaluation of optimal deployment strategies for sustainable carbon sequestration.’

Reviewer comment 3: MESMO is “derived from cGENIE” is incorrect

Response:

We initially stated that "MESMO is derived from cGENIE" to imply that MESMO is based on GENIE. According to literature review, MESMO is actually based on GENIE and extended its BGC module. While cGENIE represents a carbon-centric version of GENIE. Since throughout the manuscript we have been referring to cGENIE, we wrote "cGENIE" has caused some ambiguity. We have revised the manuscript as follows:

‘The Minnesota Earth System Model for Ocean biogeochemistry (MESMO 3) represents an important development, explicitly resolving semi-labile and refractory DOC pools. MESMO 3 represents RDOC production as a fixed fraction of organic matter production or via deep particulate organic matter (POM) partitioning,…’



Geosci. Model Dev., 1, 1–15, 2008
www.geosci-model-dev.net/1/1/2008/
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Geoscientific
Model Development

First description of the Minnesota Earth System Model for Ocean biogeochemistry (MESMO 1.0)

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Abstract. Here we describe the first version of the Minnesota Earth System Model for Ocean biogeochemistry (MESMO 1.0), an intermediate complexity model based on the Grid ENabled Integrated Earth system model (GENIE-1). As with GENIE-1, MESMO has a 3D dynamical ocean, energy-moisture balance atmosphere, dynamic and thermodynamic sea ice, and marine biogeochemistry. Main development goals of MESMO were to: (1) bring oceanic uptake of anthropogenic transient tracers within data constraints; (2) increase vertical resolution in the upper ocean to better represent near-surface biogeochemical processes; (3) calibrate the deep ocean ventilation with observed abundance of radiocarbon. We achieved all these goals through a combination of objective model optimization and subjective targeted tuning. An important new feature in MESMO that dramatically improved the uptake of CFC-11 and anthropogenic carbon is the depth dependent vertical diffusivity in the ocean, which is spatially uniform in GENIE-1. In MESMO, biological production occurs in the top two layers above the compensation depth of 100 m and is modified by additional parameters, for example, diagnosed mixed layer depth. In contrast, production in GENIE-1 occurs in a single layer with thickness of 175 m. These improvements make MESMO a well-calibrated model of intermediate complexity suitable for investigations of the global marine carbon cycle requiring long integration time.

1 Introduction

Earth system Models of Intermediate Complexity (EMICs) occupy a unique and important position within the hierarchy of climate models (Claussen et al., 2002). In many ways, EMICs represent a compromise between high resolution, comprehensive coupled models of atmospheric and oceanic circulation, which require significant computational resources, and conceptual (box) models, which are computationally very efficient but represent the climate system in a highly idealized manner. A critical difference between comprehensive coupled models and box models is the absence of dynamical feedbacks in the latter. In box models, large scale circulation is typically prescribed and not allowed to change over the course of a simulation. The lack of dynamical feedbacks makes box models unsuitable for realistic simulations of transient climate change. On the other hand, comprehensive coupled models are so computationally intensive that their behavior within a given parameter space is difficult to fully explore. EMICs nicely fill this gap by retaining important dynamics while remaining computationally efficient, which is typically achieved by reducing spatial resolution and/or number of processes compared to high resolution coupled models.

The effectiveness of EMICs is evident in the numerous publications that have successfully employed them in studying past, present, and future climates (Ganopolski and Rahmstorf, 2001; Ganopolski et al., 1998; Joos et al., 1999; Knutti et al., 2002; Nusbaumer and Matsumoto, 2008; Plattner et al., 2001). Also, the important role that EMICs played in understanding the postindustrial carbon cycle changes is highlighted in the two recent IPCC science reports TAR (Houghton et al., 2001) and AR4 (IPCC, 2007).

Here we document development of the first version of the Minnesota Earth System Model for Ocean biogeochemistry (MESMO 1.0) based on an existing and successful EMIC called GENIE-1. Our immediate motivation for this work is to possess a tool to investigate postindustrial changes in the natural ocean carbon cycle. Our efforts were thus geared toward improving representation of marine biogeochemistry and distributions of natural and anthropogenic transient tracers in the oceans. These improvements, combined with a

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Fig. S1 The reference for MESMO1

4 Description of MESMO

The starting point of our model development is Version 6 of CB-GOLDSTEIN (Ridgwell et al., 2007), the non-modular version of GENIE-1. MESMO is identical to Version 6 unless noted otherwise. We decided not to use the word "GENIE" in our model name so as to avoid confusion with the ongoing efforts of the GENIEfy project to develop various flavors of GENIE. The GENIEfy project uses its SVN-controlled code and aims to modularize the different model modules, neither of which applies to our efforts with MESMO. The Bern 3D ocean model is also derived from C-GOLDSTEIN and also does not have the descriptor "GENIE" (Muller et al., 2006).

We describe MESMO's physical climate model (Sect. 4.1) first, followed by its biogeochemistry model (Sect. 4.2). In addition to describing the new features and modifications we adopted in MESMO, we will also briefly note two features that we evaluated but ultimately discarded (Sect. 4.3). Our dead-end efforts may be of some interest in future development efforts by other groups.

4.1 New features in MESMO physical model

First, the vertical resolution in the ocean is increased from 8 layers to 16. To allow biological production to depend on changes in stratification, it is preferable to have at least two layers in the euphotic zone above the critical depth where net production is positive. Therefore, we chose a vertical resolution that contains two complete layers in the top 100 m, which we took as the compensation depth (see Sect. 4.2 below). The midpoints of the 16 layers are: 23, 72, 133, 208, 300, 412, 550, 720, 927, 1182, 1494, 1877, 2347, 2923, 3630, and 4497 m. The increased vertical resolution is concentrated in the upper ocean such that the bottom topography in MESMO is very similar to GENIE-1, as shown in Fig. 1 of Ridgwell et al. (2007).

Reviewer comment 4: Incorrect citation of discussion papers instead of final publications

The reviewer notes that MESMO 3 and Lauvset et al. are cited as discussion papers rather than their final published versions.

Response:

We have re-examined all relevant citations and would like to clarify the following points. The citation to MESMO 3 in the original manuscript refers to the final published version, rather than the discussion paper. For MESMO 1, both the discussion paper and the final published article were cited simultaneously, rather than the discussion paper being cited alone.

Nevertheless, we acknowledge that citing both versions may lead to ambiguity. To avoid any potential confusion, we have removed the discussion paper citation for MESMO 1 and retained only the final peer-reviewed publication. In addition, we have carefully reviewed all references in the manuscript, including Lauvset et al., to ensure that only final published versions are cited and that all references conform to the journal's citation standards.

Despite recent advances, the explicit representation of MCP processes and RDOC cycling within cGENIE has remained limited. The Minnesota Earth System Model for Ocean biogeochemistry (MESMO 3), an Earth system model of intermediate complexity derived from cGENIE, includes an explicit treatment of semi-labile and refractory DOM pools. In MESMO3, the remineralization of refractory DOM is represented by three additive sinks: slow background decay, surface photodegradation, and complete removal through hydrothermal vent circulation (Matsumoto et al., 2021). However, MESMO 3 lacks a mechanistic representation of DOM production pathways associated with MCP processes—specifically, the transformation of semi-labile DOC (SLDOC) into RDOC—and has not been calibrated against global DOM observations. In this study, we propose an extension to the cGENIE model that integrates RDOC and MCP processes to investigate their long-term response to climate change. We introduce a new framework, cGENIE-MCP, which partitions total DOC into three distinct fractions—labile (LDOC), semi-labile (SLDOC), and refractory (RDOC)—enabling improved simulation of DOC production and remineralization based on prior formulations from cGENIE and MESMO 3. We evaluate the performance of the cGENIE-MCP model against global observational datasets and compare its outputs with those from the standard cGENIE model. Finally, we analyze the spatial distribution and production of LDOC, SLDOC, and RDOC in relation to primary production to assess the model's capability in capturing essential features of the MCP.

Fig. S2 The reference to MESMO3 in the original text

2.2 Ocean biogeochemical module

The ocean biogeochemistry in cGENIE is simulated using the BIOGEM module, which models nutrient-driven biological productivity and the cycling of carbon and associated elements (Van De Velde et al., 2021). BIOGEM includes representations of air-sea gas exchange, nutrient uptake by primary producers, and the remineralization of organic matter in the water column. Phytoplankton are not explicitly represented; instead, primary productivity is calculated diagnostically based on the availability of limiting nutrients (phosphate and dissolved iron), solar radiation, and temperature, following parameterizations from previous studies (Matsumoto et al., 2008a; Matsumoto et al., 2008b; Matsumoto et al., 2021; Crichton et al., 2021). Phosphate (PO_4) and other nutrients are converted to particulate organic matter (POM) in the euphotic zone according to the Redfield stoichiometry. POMs are exported from the

Fig. S3 The reference to MESMO1 in the original text

Matsumoto, K., Rickaby, R., and Tanioka, T.: Carbon export buffering and CO2 drawdown by flexible phytoplankton C:N:P under glacial conditions, Paleoceanography and Paleoclimatology, 35, e2019PA003823, https://doi.org/10.1029/2019PA003823, 2020.

published

Matsumoto, K., Tanioka, T., and Zahn, J.: MESMO 3: Flexible phytoplankton stoichiometry and refractory dissolved organic matter, Geoscientific Model Development, 14, 2265-2288, https://doi.org/10.5194/gmd-14-2265-2021, 2021.

Matsumoto, K., Tokos, K., Price, A., and Cox, S.: First description of the Minnesota Earth System Model for ocean biogeochemistry (MESMO 1.0), Geoscientific Model Development, 1, 1-15, https://doi.org/10.5194/gmd-1-1-2008, 2008a.

MESMO1

Matsumoto, K., Tokos, K., Price, A., and Cox, S.: GENIE-M: a new and improved GENIE-1 developed in Minnesota, Geoscientific Model Development Discussions, 1, 1-37, https://hal.science/hal-00298260v1, 2008b.

Fig. S4 The corresponding list in the references section

Matsumoto, K., Tanioka, T., and Zahn, J.: MESMO 3: Flexible phytoplankton stoichiometry and refractory dissolved organic matter, Geoscientific Model Development, 14, 2265-2288, https://doi.org/10.5194/gmd-14-2265-2021, 2021.

Matsumoto, K., Tokos, K., Price, A., and Cox, S.: First description of the Minnesota Earth System Model for ocean biogeochemistry (MESMO 1.0), Geoscientific Model Development, 1, 1-15, https://doi.org/10.5194/gmd-1-1-2008, 2008.

Fig. S5 The corresponding list in the revised references section

Reviewer comment 5: The reference to CMIP6 sounds like a strawman argument, because as the authors noted, CMIP models are used in "near-term climate projections." It really doesn't matter whether these models have refractory DOC or not.

Response:

We agree that CMIP-class models are optimized for near-term projections. Our reference to CMIP models was intended purely as contextual motivation, highlighting the continued role of EMICs in addressing long-timescale carbon cycle questions. We have made revisions to the manuscript, and the main modifications are as follows:

'The Coupled Model Intercomparison Project Phase 6 (CMIP6) of Earth

System Models has significantly advanced the representation of physical and biogeochemical processes; however, the MCP-driven transformation of labile DOC into recalcitrant DOC remains highly simplified or implicitly represented in most models (Doney et al., 2024; Séférian et al., 2020b; Li et al., 2019). Many ESMs simplify DOC into a single dynamic pool or as multiple pools without explicit differentiation of transformation pathways and timescales (Anderson et al., 2015; Polimene et al., 2018; Ma et al., 2022; Flanjak et al., 2025). These structural simplifications mask the process-based role of MCP in progressively decreasing DOC lability and driving RDOC accumulation over decadal to millennial timescales, leading to underestimation of deep-ocean DOC concentrations and a failure to reproduce the millennial-scale radiocarbon ages observed in deep waters (Yamashita and Tanoue, 2008; Hansell et al., 2012; Follett et al., 2014). While introducing an explicit RDOC pool can improve simulated DOC concentrations and radiocarbon signatures, mechanistic MCP-based formulations provide additional insight into the processes governing RDOC accumulation and persistence (Hansell et al., 2012; Séférian et al., 2020a). '

Reviewer comment 6: Equations are not labeled

Response:
We have already labeled all the formulas in the manuscript.

Reviewer comment 7: Unclear distinction between new developments and legacy code. Section 2.2.1 (air–sea gas exchange) appears unnecessary

Response:
In the revised manuscript, the description of air-sea gas exchange has been moved to the Supporting Information.

Since there was no RDOM (corresponding to the code's URDOM) process in the cGENIE model code, the parts related to RDOM in the code were all newly added by us. The explicit partitioning of DOC into LDOC, SLDOC, and RDOC, and the process-based transformation of SLDOC into RDOC pools have also been added. Therefore, we have included the processes involving RDOM. We have also revised Section 2.2 to explicitly state which components of the biogeochemical model follow the legacy BIOGEM formulation and which aspects are newly developed.

The main modifications in the revised manuscript are as follows:

'Temperature-dependent nutrient uptake process of cGENIE in each surface grid cell is carried forward in cGENIE-MCP and given by'

'The remineralization of POC is modeled as a temperature-dependent process of cGENIE is carried forward in cGENIE-MCP, with separate treatment for labile (POC1) and recalcitrant (POC2) components. The remineralization rate is given by:'

'LDOC is rapidly remineralized in the water column, releasing inorganic carbon and nutrients. The remineralization follows a similar temperature-dependent formulation of cGENIE is carried forward in cGENIE-MCP:'

Reviewer comment 8: Table 1 is not referenced in the text

Response:

We note that Table 1 was cited in the main text at two locations: first at Line 165, where we state "Key parameter values are given in Table 1", and again at Line 246, where we specify that "f_1, f_2, and a are listed in Table 1."

We have revised the surrounding text to more clearly: 'Key parameter values used to define the DOC cycling and MCP-related processes in this study are summarized in Table 1. '

'All other parameters are defined in the preceding equations, with the corresponding parameter values (f_1, f_2, and a) provided in Table 1.'

Reviewer comment 11: Table 2 is not useful. It seems to be a global comparison, but the deep ocean is not highly variable. A global comparison would be biased toward the deep (i.e., global mean) just because of its large volume. Surface and intermediate depth comparisons would be more useful. And why does Table 2 include temperature and salinity? As far as I can tell, cGENIE-MCP has the same model physics as cGENIE.

Response:

We have revised Table 2 and have moved it to the Supporting Information. We agree that a single global metric can be dominated by the large volume of the deep ocean and may obscure model-data differences in the upper and intermediate ocean. Therefore, the surface (0-100 m) and intermediate (100-1000 m) layers comparisons were added. For each tracer, we report both volume-weighted RMSE (RMSE_vw) and centered RMSE (CRMSE) within these depth ranges.

The temperature is included in Table 2 because the cGENIE-MCP configuration involves some temperature-related processes. Salinity is included primarily as a companion physical diagnostic. Although cGENIE-MCP employs the same physical circulation framework as standard cGENIE, this tracer together characterizes the model's water-mass structure and stratification, which indirectly influence biogeochemical tracer distributions through circulation and mixing. These tracers are not included to demonstrate improvements introduced by the MCP formulation, but rather to verify that the introduction of MCP-driven DOC cycling does not introduce unintended degradation of the physical state of the model.

Table 2. RMSE of modeled tracers for cGENIE-MCP and cGENIE and MESMO3c compared to observational data

Tracers		cGENIE-MCP		cGENIE		MESMO3c	
		CRMSE	RMSE_vw	CRMSE	RMSE_vw	CRMSE	RMSE_vw
T (℃)	0-100m	0.00	0.97	0.00	0.98	0.00	0.50
	100-1000m	1.27	1.29	1.27	1.29	0.87	1.11
Salinity	0-100m	0.00	0.07	0.00	0.08	0.00	0.13
	100-1000m	0.12	0.16	0.12	0.16	0.13	0.14
PO_4 (μmol kg^{-1})	0-100m	0.00	0.19	0.00	0.51	0.00	0.03
	100-1000m	0.13	0.37	0.10	0.56	0.10	0.36
DO (μmol kg^{-1})	0-100m	0.00	2.87	0.00	2.79	0.00	3.81
	100-1000m	4.32	7.35	3.88	12.57	9.87	20.31
DIC (μmol kg^{-1})	0-100m	0.00	18.04	0.00	18.79	0.00	47.82
	100-1000m	52.84	12.19	50.22	13.17	53.70	13.70

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