

1 Scientific Progress Achieved During the Previous Allocation Period

The previous allocation enabled substantial progress in the implementation and evaluation of an extended marine nitrogen cycle (ExtN) in HAMOCC within the ICON-XPP Earth system model. The work completed so far has advanced the model from a simplified nitrogen-cycle formulation towards a process-based framework that explicitly represents key redox-sensitive nitrogen transformations and their coupling to marine N_2O production. This now provides the foundation for the next phase of parameter tuning, long spin-up integrations, and production simulations.

A central achievement is the successful activation of the ExtN in a tuned ICON-XPP-HAMOCC configuration at approximately 80 km atmospheric and 20 km ocean resolution (R2B5/R2B7). In contrast to the standard HAMOCC formulation, the extended framework explicitly resolves NH_4^+ , NO_2^- , NO_3^- , N_2O , and N_2 , and includes two-step nitrification, denitrification, DNRA, DNRN, and anammox. Together with the M4AGO sinking scheme, this framework enables a more mechanistic representation of nitrogen turnover across oxic, suboxic, and hypoxic conditions, and strengthens the connection between organic matter remineralisation, oxygen consumption, and low-oxygen nitrogen cycling. The overall process structure is summarised in Fig. 1.

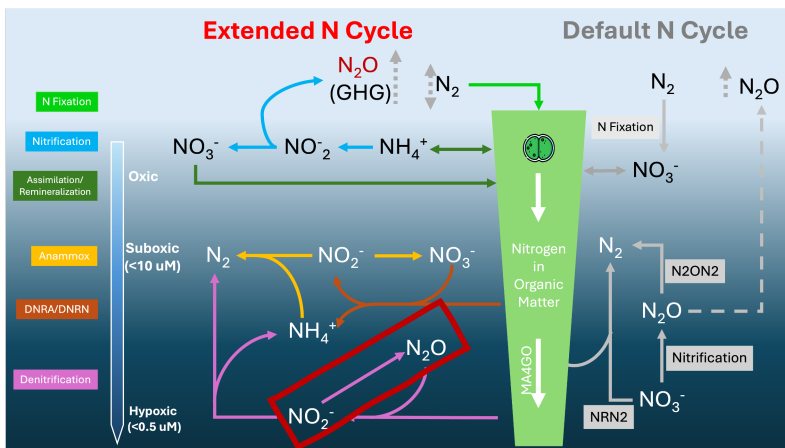


Figure 1: Schematic of the extended marine nitrogen cycle (ExtN) implemented in HAMOCC, contrasted with the default nitrogen-cycle representation. The red box highlights the newly completed process representation for N_2O production during denitrification under hypoxic conditions.

A further key advance is the completion of the code development for N_2O production during denitrification under anoxic conditions. This newly implemented pathway, highlighted in red in Fig. 1, addresses an important gap in the previous model structure by representing N_2O as an intermediate product of nitrogen loss in low-oxygen waters. This process is particularly relevant near the oxic-hypoxic transition, where marine N_2O production is highly sensitive to oxygen availability and to the interaction of multiple microbial pathways. Its implementation therefore represents a scientifically important step towards a more realistic simulation of marine greenhouse-gas production.

The first model evaluation confirms that the ExtN framework is dynamically active in the expected

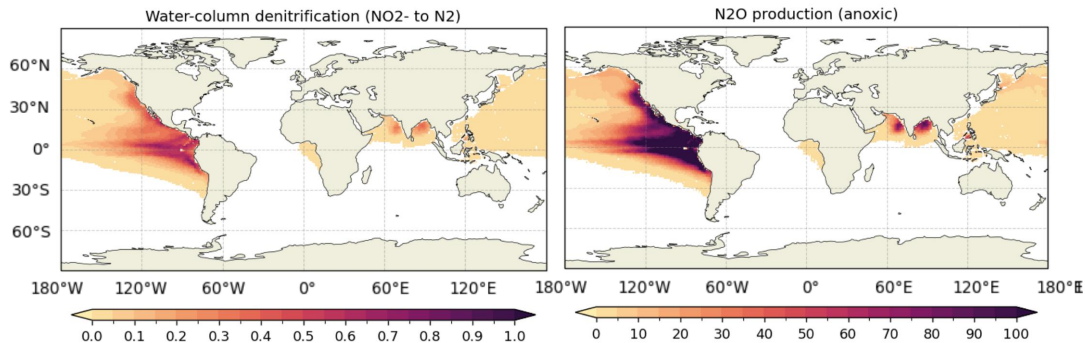


Figure 2: Preliminary spatial patterns of depth-integrated tendencies associated with the newly implemented denitrification-linked N_2O production pathway. Shown are the regional distributions of water-column denitrification (NO_2^- to N_2) and anoxic N_2O production. The strongest activity occurs in the oxygen-deficient eastern tropical Pacific, where other low-oxygen nitrogen transformations, including anammox, DNRA, and DNRN, also co-occur.

low-oxygen environments. The model reproduces the major regions of marine denitrification associated with oxygen-deficient zones, particularly in the eastern tropical Pacific and other major oxygen minimum regions. The simulated annual marine denitrification rate is about 98 Tg N yr^{-1} , which lies within the broad range reported in the literature. The simulated global ocean N_2O flux is about 3.7 Tg N yr^{-1} , slightly lower than central observation-based estimates ($\sim 4.2 \text{ Tg N yr}^{-1}$), but still within both the spread of current Earth system models and the CMIP6 range ($1.9\text{--}9.4 \text{ Tg N yr}^{-1}$). These results indicate that the extended framework provides a plausible first-order representation of marine nitrogen loss and N_2O emissions.

Additional diagnostics suggest that the newly implemented N_2O -producing denitrification pathway behaves in a physically consistent manner. As shown in Fig. 2, denitrification-related pathways (shown here as denitrification, but also including anammox, DNRA, and DNRN) and anoxic N_2O production are concentrated primarily in the eastern tropical Pacific oxygen-deficient zone, whereas oxic N_2O production is distributed much more broadly across the global ocean. The preliminary diagnostics further show a clear vertical separation among the newly implemented pathways, with oxygen-deficient processes concentrated in subsurface low-oxygen waters and oxic N_2O production strongest in the upper ocean. These patterns provide a first process-oriented confirmation of the new implementation.

The main priorities for the next phase are now clear. Oxygen-deficient waters remain too extensive and too deep in the current configuration, affecting the magnitude and distribution of denitrification and N_2O production. In addition, the simulated global marine N_2O outflux remains below observational estimates and requires further tuning. The next step is therefore a systematic comparison of the new process diagnostics with observational constraints, combined with targeted calibration of oxygen-sensitive pathways. Initial tuning can be performed in a lower-resolution ocean setup (40 km, R2B6) before transfer to the production configuration. A further practical bottleneck is the long queue waiting time on bu1507, which noticeably reduces workflow efficiency. Continued access to DKRZ resources is therefore essential for efficient model calibration and robust process-based evaluation.