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Viewpoint

Inland Waters Are Not Exempt from the Human-Driven Multidecadal Increases in Greenhouse Gas Emissions

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Estimating inland-water greenhouse gas emissions has been challenging. For the potent greenhouse gas nitrous oxide (N_2O, >200 times stronger than carbon dioxide), observations in inland waters are scarce and unevenly distributed, and span a nearly 50-year period (Figure 1). Most existing studies have tried to produce more robust estimates by reducing uncertainties related to spatial heterogeneity or variabilities at sub-annual or interannual scales.[4] The long-term temporal dimension, beyond variabilities at sub-annual or interannual scales, is rather flattened, due to temporal limitations in observational data.

A recent study suggests that this compromised use of observational data spanning decades as a "static" state for current inland-water N_2O emission may be debatable. Wang et al.[1] conclude that global inland-water N_2O emissions have overall increased >3-fold since 1900. Inland-water N_2O observations became available from the 1970s onward; since then, global inland-water N_2O emissions have increased 1.6-fold (Figure 1). This long-term increase occurred in multiple systems: groundwater, streams, rivers, lakes, and reservoirs.[1] Such a multidecadal increase was also captured by another recent process-based study on N_2O from streams and rivers.[5] It is thus highly imperative to account for long-term changes in inland-water N_2O emissions if we are to advance our ability to project future atmospheric N_2O levels.

The use of observations that cover decades to represent a "static" current state of inland-water N_2O emissions, is inconsistent with the documented long-term changes in factors governing N_2O cycling, such as hydrology, climate, land use, nitrogen release from agriculture, wastewater, and aquaculture, as well as atmospheric N_2O concentrations.[1] These conspiring long-term changes driven by human activities interact with natural ecosystems in a complex manner, pushing inland-water N_2O cycling and emissions away from the "static state". Wang et al.[1] show that the construction of reservoirs and the steadily increasing nitrogen loading primarily caused the long-term increase in N_2O production and emissions from inland water bodies. As the importance of groundwater N_2O input becomes increasingly recognized,[4] consideration of its temporal change is necessary, as is reflected by the large and evolving nitrogen legacy arising from historical changes in agricultural activities.[6] Moreover, reservoirs have become the major site of N_2O production, not only because of an increase in their number

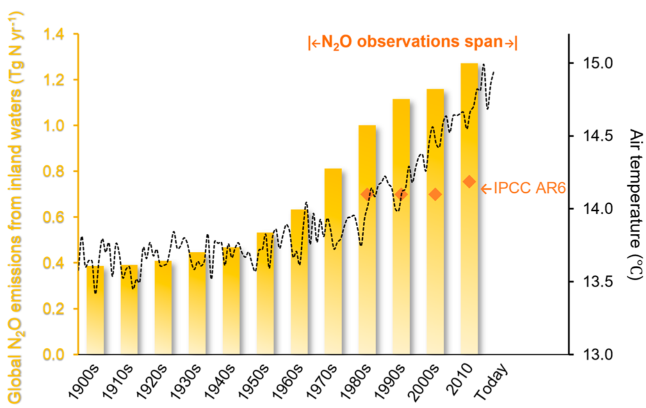

Figure 1. Long-term changes in global inland-water nitrous oxide (N_2O) emissions and global average air temperature. N_2O data from ref 1 and the latest IPCC Assessment Report[2] and near-surface air temperature data from CMIP6.[3]

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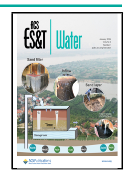

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and volume, but also because of aging and consequent changes in their biogeochemical conditions.[1] The use of observations that span decades without proper temporal (yearly/decadal) binning may weaken our ability to retrospect the historical trajectory, project future pathways, capture critical tipping points, and thereby develop and implement timely adaptation and/or mitigation strategies for greenhouse gas emissions and climate change.

The scarcity of data may pose challenges to not only conventional upscaling but also new approaches, such as machine learning, for gaining a better estimate of global inland-water N_2O emissions. N_2O observations started later than those for major nitrogen forms, and the number of observational data of N_2O is several orders of magnitude smaller than that of dissolved inorganic nitrogen or total nitrogen. In addition, a robust reproduction of the highly variable N_2O emissions from inland waters requires more environmental data with their spatial and temporal information being consistent with that of N_2O data, for example, for factors of land use, groundwater and soil properties, hydro-climate characteristics, nutrients, oxygen conditions, and organic carbon availability, which have been proven to be important in inland-water N_2O cycling,[4] but their data that are consistent with the spatiotemporal information on N_2O observations are rather limited. Moreover, available monitoring data are unevenly distributed spatially and temporally, which has to be compromised with the limitations in overall data availability. Nevertheless, the number of N_2O observations is steadily increasing and the data quality is improving, which makes machine learning a promising approach. A future combination of the recent dynamic process-based perspectives (e.g., in refs 1 and 5) with machine learning that utilizes both N_2O data and key governing factors, may significantly improve our understanding of inland-water N_2O cycling and associated emissions in the time dimension of multidecadal changes.

Mitigating greenhouse gas emissions and their associated effects on climate requires more than "static state" emission estimates for the current era; it also requires their long-term evolution and understanding of the underlying mechanisms in the face of unprecedented human perturbations. Evidently, it is imperative to advance our knowledge on N_2O cycling (production, consumption, transport, and interactions at interfaces) through observational (e.g., isotope measurements, rate measurements, microbial community characterization, and simultaneous monitoring of N_2O and ambient environmental factors) and modeling (process-based and machine learning) approaches; this will require in-depth transdisciplinary collaborations of observational scientists, experimentalists, and modellers.

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Notes

The authors declare no competing financial interest.

Biographies

Dr. Junjie Wang is an environmental biogeochemist working in the Department of Earth Sciences at Utrecht University. Her research interests include the nutrient (nitrogen, phosphorus, and silicon) and related element (carbon and oxygen) cycles in the Anthropocene's inland and coastal waters. She develops numerical models and uses *in situ* observations and large databases to understand how natural and anthropogenic sources from the land, perturbance of hydrology, and climate change regulate freshwater biogeochemistry cycles, water quality, greenhouse gas emissions, land-to-sea transport, and coastal ecosystems at multiple temporal and spatial scales. Her most recent research uses integrated, spatially explicit, mechanistic, coupled biogeochemistry−hydrology modeling approaches to quantify the fate (source, transport, transformations, and interactions at interfaces) of greenhouse gases [nitrous oxide (N_2O) and carbon dioxide (CO_2)] and nutrients in global inland waters.

Dr. Xiaochen Liu, serving as an advisor and researcher in Deltares, specializes in the design, development, evaluation, and implementation of sophisticated environmental computer models. His expertise spans a wide range of scales, from an individual grid cell to a global scale, with a focus on analyzing water and nutrient fluxes and processes on the Earth's surface and their responses to historical and future human pressures. His latest research delves into the global groundwater nitrogen legacy dynamics, nutrient (nitrogen, phosphorus, and silicon) fluxes from the land to seas and eutrophication risk in global coastal areas, emissions of greenhouse gases from inland waters, and nitrogen and phosphorus fluxes in wastewater systems.

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