Phosphorus limitation reduces hypoxia in the northern Gulf of Mexico: results from a physical-biogeochemical model

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Summary

In the northern Gulf of Mexico, excess dissolved inorganic nitrogen (N) and phosphorus (P) loads from the Mississippi-Achafalaya River system promote high primary production and contribute to the seasonal development of hypoxic bottom waters on the Louisiana Shelf. While phytoplankton growth is controlled by light, nutrient limitation has been observed in this region during peak river discharge in spring and summer. River-induced P limitation is a common phenomenon in coastal hypoxic systems. Although a key aspect of nutrient load reduction strategies for hypoxia mitigation, there is still limited direct evidence for the effect of P limitation on hypoxia. Here we present a synthesis of recent developments that quantitatively assessed, using a realistic physical-biogeochemical model, the effect of P limitation on primary production and hypoxia development on the Louisiana Shelf.

Model description

The Regional Ocean Modelling System (ROMS) is configured to simulate the circulation over the Louisiana continental shelf.

Circulation model

The Ocean Multiple Model Intercomparison Project (OMMIP) is used to set-up the model and therefore the dilution in primary production results in an over-estimation of part of primary production. Since this relocation occurs over a large area, (i.e., westward, Fig. 4), where it fuels primary production in otherwise N-limited regions.

Results

1. Nutrient limitation

The simulated annual cycle of nutrient limitation is as follows: no nutrient limitation in winter (Fig. 3g), P limitation in the mid-salinity waters of the Mississippi River plume in early summer (Fig. 3b) and N limitation over the shelf in late summer and fall (Fig. 3i). Open ocean waters are always N-limited. These patterns agreed well with the observations (Fig. 3j) and biosurveys of Sylvan et al. (2006). Interestingly, P limitation does not occur in the Atchafalaya River plume, primarily due to high P concentrations and the rapid river P turnover and N loss through denitrification, which limits the potential for P limitation.

2. Shift in primary production

P limitation reduces primary production by 16% near the Mississippi delta between May and July (Fig. 4b). The excess DIP load and a westward relocation of part of primary production. Since this relocation occurs over a large area, the overall primary production is dilluted over the shelf (see conceptual framework). POM deposition is a quadratic function of primary production in the model and therefore the dilution in primary production results in an overall reduction of POM deposition flux.

Conceptual framework

The effect of P limitation on phytoplankton is similar among river-induced eutrophicated systems; P limitation displaces phytoplankton biomasses toward downstream due to the transport of the N (Fig. 5). However, there is currently no consensus on whether this displacement amplifies or weakens hypoxia. P limitation is generally viewed as a mechanism that relocates or spreads hypoxia and thereby considered detrimental. Any relocation of primary production due to P limitation will also relocate DIP sinks, which could potentially lead to the development of hypoxic conditions in waters that would be normoxic without P limitation.

In flow-through systems, which are characterized by strong freshwater-induced transport and stratification akin to a simple translation along their upstream-downstream axis, a shift of primary production along this axis may well result in a linear effect on hypoxia.

However, excess nutrients in river plumes are being diluted when plumes interact with coastal circulation forced by topography, winds and tides. In these open systems, a “downstream” relocation may spread elevated primary production over a larger area while lowering the maxima of primary production in the affected area, in effect “diluting” the impact of a westward transport of P. This spread of nutrients does not promote a westward expansion or relocation of hypoxia. Rather, the onset of hypoxia is delayed and the size of the hypoxic zone reduced. In other words, P limitation dilutes the effects of eutrophication on the Louisiana Shelf. Two additive effects explain this reduction, namely the westward shift of organic matter respiration against the backdrop of weak vertical stratification and the net shift of respiration from the sediments to the water column.

3. The dilution effect

Changes in bottom-water O2 associated with P limitation are asymmetrical over the Louisiana Shelf with a significant increase on the eastern shelf, but only a small decrease on the western shelf (Fig. 3). This spatial asymmetry is explained by two additive effects, namely the westward shift of organic matter respiration against the backdrop of weak vertical stratification and the net shift of respiration from the sediments to the water column.

The intensity of water column stratification varies along the freshwater gradient of the Mississippi River plume. Water column stratification is strongest on the eastern shelf and decreases towards the western shelf. Weak stratification on the western shelf (Fig. 4) results in lower hypoxic areas and longer hypoxia duration on the west compared to the east (Laurent & Fennel 2014). How does the character of oxygen demand control the structure of hypoxia on the Texas–Louisiana continental shelf? Journal of Marine Systems, 70, 49–62.

Additional simulations with ±50% DIP and/or DIN to determine the effect of P limitation.

30.5 29.5 29 28 27.5 27.0 26.5 26.0 25.5 25.0 24.5 24.0 23.5 23.0 22.5 22.0 21.5 21.0 20.5 20.0 19.5 19.0 18.5 18.0 17.5 17.0 16.5 16.0 15.5 15.0 14.5 14.0 13.5 13.0 12.5 12.0 11.5 11.0 10.5 10.0 9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0

4. N and P load mitigation

Four nutrient reduction scenarios were tested to assess their effect on summer hypoxia (Laurent & Fennel 2014). (1) 50% decrease of river DIN (−N), (2) 50% decrease of river DIP (−P), (3) 50% decrease of river DIN and DIP (−NP) and (4) a 50% increase in river DIN with a simultaneous 50% reduction of river DIN (−NP+P). The dual −N and −P load mitigation decreases the hypoxic area and hypoxia duration (Fig. 5). However, this dual load mitigation does not promote a westward expansion or relocation of hypoxia. Rather, the onset of hypoxia is delayed and the size of the hypoxic zone reduced. In other words, P limitation dilutes the effects of eutrophication on the Louisiana Shelf. With P limitation only, hypoxia is reduced in the northern Gulf of Mexico from a physical-biogeochemical model

Maritime Canada: results from a physical-biogeochemical model

Summary

In summary, the mean difference in O2 concentration due to P limitation on the Louisiana Shelf is (−2.0 ± 1.5) mol kg−1. The results of the simulation with −NP results in a significant increase in O2 concentration downstream of the Atchafalaya River system and a significant decrease in O2 concentration at the Louisiana shelf station, associated with a modification in nutrient concentration and nitrate-plankton growth (μ; d−1) and by either dissolved inorganic nitrogen (DIN) or DIP as follows:

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