Projected effects of anthropogenic CO_2 emissions on eutrophication-induced hypoxia and acidification in the northern Gulf of Mexico

Arnaud Laurent [1], Katja Fennel [1], Dong Ko [2] and John Lehrter [3]. Correspondence to A. Laurent (arnaud.laurent@dal.ca)

OC44A-0507

1. Rationale

The northern Gulf of Mexico (NGOM) receives excessive nutrients from the Mississippi-Atchafalaya River Basin that promote high primary production and high respiration during algal decomposition. In combination with summer stratification, respiration results in hypoxia, high dissolved inorganic carbon concentrations and low pH in bottom waters. Increasing temperatures, atmospheric CO_2 and discharge may further intensify eutrophication-induced hypoxia and acidification in the future.

2. Method

- A coupled physical-biogeochemical model of the northern Gulf of Mexico (ROMS) with the pelagic N-cycle model of Fennel et al. [2011] and O_2 and carbonate chemistry (Fig. 1).
- Two 6-year simulations, present and future.
- Different boundary conditions, discharge, and atmospheric temperature and pCO_2.
- Future biogeochemistry calculated from a future-present bias in MPI-ESM RCP8.5.*

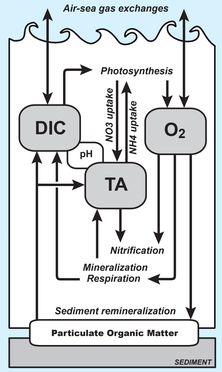


Figure 1. Schematic of the processes controlling O_2 and carbon biogeochemistry in the coupled model.

3. Present state

An extended area of acidified waters develops in summer that coincides spatially with the hypoxic zone (Fig. 2). Acidification and hypoxia are driven by microbial respiration of organic matter (OM) and strong vertical stratification. The largest source of dissolved inorganic carbon (DIC) is from the remineralization of suspended detritus (Table 1). However, when considering the biological fluxes that add DIC to the bottom boundary layer (BBL) where low pH occurs, the sediment is the dominant contributor (Table 1). The contribution of allochthonous dissolved OM is negligible for bottom water acidification. This implies that acidification and hypoxia are linked to autochthonous production driven by river nutrients, that can be mitigated by management of inorganic nutrients in the watershed.

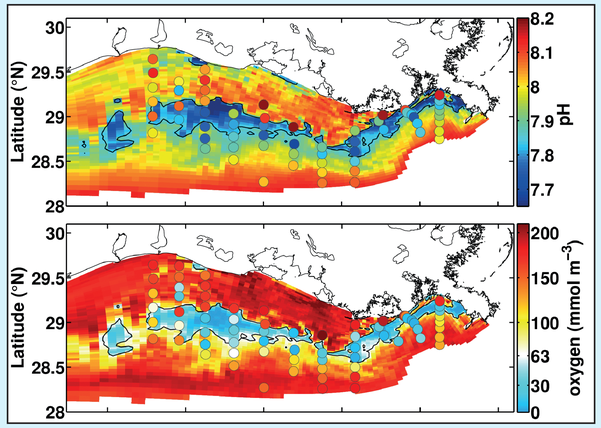


Figure 2. Comparison of simulated bottom water pH and O_2 on 21 August 2007 (maps) with observations (colored circles) from Cai et al. [2011] collected over the period 19-24 August 2007. The figure is reproduced from Laurent et al. [2017].

	DIC Production										Alkalinity Sink			
	Zooplankton Respiration		Remineralization						Sediment DIC Efflux		Nitrification		NH_4^+ Uptake	
			Small Detritus		Large Detritus		River DOM							
Water Column														
Oct–Apr	6.7	14%	**20.3**	**42%**	0.3	< 1%	4.7	12%	8.7	18%	3.4	7%	3.4	7%
May–Sep	**19.8**	**24%**	**28.8**	**34%**	0.5	< 1%	5.5	8%	**16.7**	**21%**	4.9	6%	6.2	7%
Hypoxic	**19.8**	**22%**	**26.2**	**29%**	0.3	< 1%	5.5	8%	**20.9**	**29%**	5.0	6%	6.1	6%
Bottom 5 m														
Oct–Apr	2.1	11%	**5.4**	**27%**	0.1	< 1%	1.6	11%	**8.7**	**42%**	1.1	5%	0.5	3%
May–Sep	4.2	13%	6.1	19%	0.1	< 1%	1.6	7%	**16.7**	**53%**	1.7	5%	0.8	3%
Hypoxic	5.1	12%	7.2	17%	0.1	< 1%	2.7	8%	**20.9**	**55%**	2.7	6%	1.0	2%

[a]Fluxes are averaged for the periods from October to April, from May to September, and for hypoxic locations only. The percentages indicate the contribution of each process to the decrease in pH (see section 2). The dominant contribution for each period/region is given in bold.

Table 1. Simulated, vertically integrated DIC production (mmol m^{-2} d^{-1}) due to various biological processes throughout the whole water column and for the 5-m thick bottom layer, and alkalinity sink (mmol m^{-2} d^{-1}) due to nitrification and NH_4^+ uptake. The Table is reproduced from Laurent et al. [2017].

2006

pCO_2 = 380.81µatm

Atmospheric pCO_2

Sea surface pCO_2

2100

pCO_2 = 935.85µatm

+3°C air temperature

+10% river discharge

Constant

Nutrient load

Wind forcing

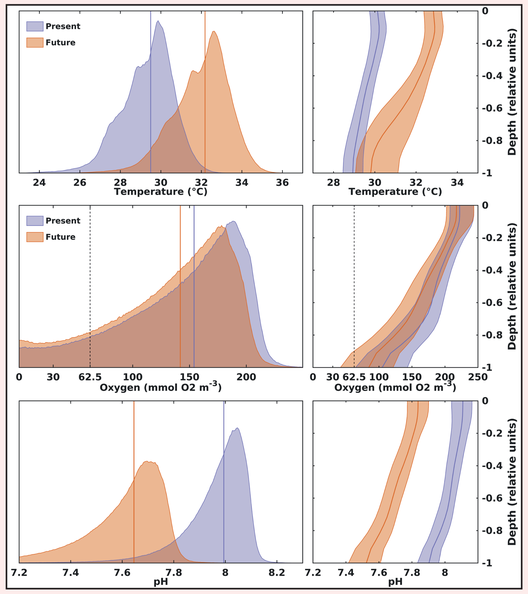
Forcing variability

4. Projected changes in NGOM

Warmer and fresher surface waters result in stronger summer stratification (+12.35 J m^{-3} in potential energy anomaly). Warmer water has lower O_2 saturation concentrations and thus less O_2 (ΔO_2 = -9.4% in bottom waters, Fig. 3). Time-integrated hypoxic area increases by 26% and hypoxic volume by 39% on average. Hypoxia occurs over longer periods (Fig. 4); continuous hypoxia > 2 weeks occurs over 14.1x10^3 km^2 (+44%).

A major difference between O_2 and inorganic carbon variables is the drastic change in the mean of the latter (Figs. 3 & 5). Bottom water pH decreases to 7.58 (ΔpH = -0.37) and to 7.39 in hypoxic waters. The carbonate saturation state near the bottom drops significantly but remains well above the saturation limit for aragonite Ω_{Ar} = 1.82 (-44%) and calcite Ω_{Ca} = 2.73 (-45%). However, in hypoxic waters Ω_{Ar} gets close to the saturation limit (Ω_{Ar} = 1.05).

Figure 3. Summer frequency distribution (left) and median vertical profiles (right) of surface temperature and bottom O_2 and pH on the shelf. Vertical profiles are restricted to the region 0-20m, 91.2-89.0°W.

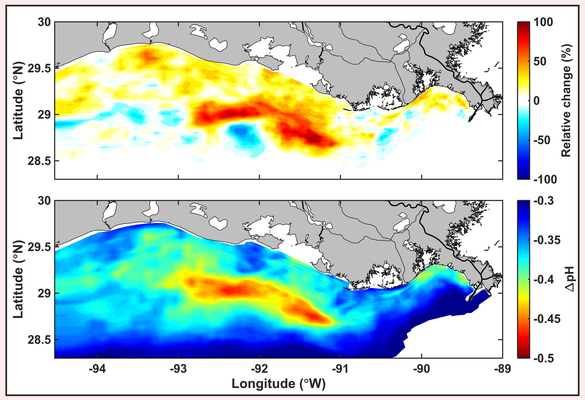


5. Underlying mechanisms

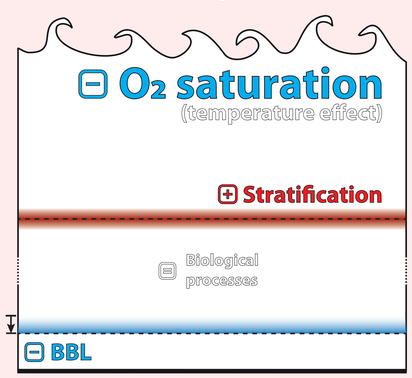
60-74% of bottom ΔO_2 (-9.4%) is explained by lower O_2 saturation concentrations. The remainder is due to stronger stratification and thinner BBL. Biological processes have marginal effects.

91% of bottom ΔpH is due to biogeochemical boundary conditions (atmospheric pCO_2, acidified offshore waters), 5% to temperature and 4% to stratification and BBL. The increasing slope in the future O_2 vs. pH (Fig. 5) indicates an increased effect of respiration on pH due to a lower buffering capacity (the Revelle factor increases from 9.4 to 12.7). See Laurent et al. [2018] for details. The main drivers of O_2 and pH changes are summarized below.

Figure 4. Change in the average number of hypoxia days per year (top) and in bottom water pH in summer (bottom). The change is calculated as the difference between future and present.



Oxygen



Carbon

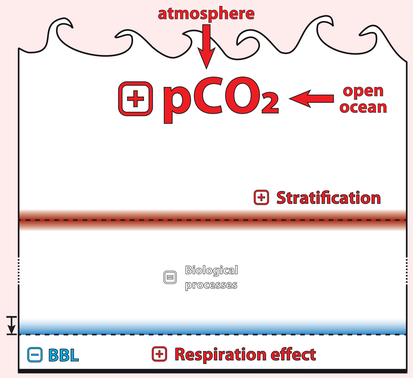
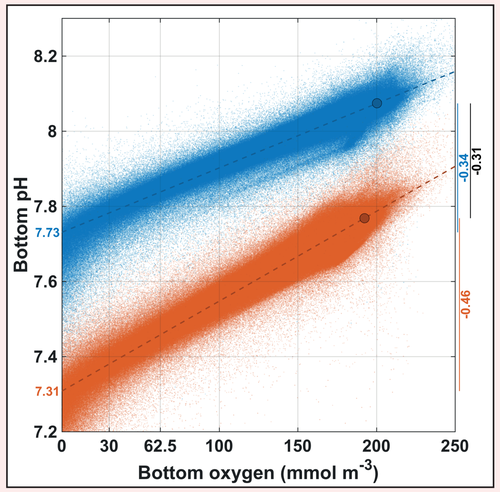


Figure 5. Relationships between O_2 and pH in bottom waters in summer. Relationships are calculated for the present (blue) and future (orange) simulations. Dashed lines are the fit for each relationship. The scattered dots are the model data points. The dots on the dashed lines are the values for O_2-saturated surface waters in summer. Numbers on the left axis indicate the values in anoxic conditions. Numbers on the right axis indicate the future – present difference at surface O_2 saturation (black), the difference between O_2 saturation and anoxia for the present (blue) and future (orange) simulations.



6. Conclusions

- Climate change will exacerbate hypoxia and acidification in the northern Gulf of Mexico; current hypoxia mitigation strategies will need to be adapted.
- Changes in O_2 and inorganic carbon are driven by lower O_2 saturation in warmer waters and biogeochemical boundary conditions, respectively.
- Changes in stratification and BBL contribute 26–40% of ΔO_2 but <10% of ΔpH in bottom waters.
- Climate-driven acidification will ultimately overwhelm the present eutrophication-induced acidification, but eutrophication will remain an important issue that adds to the climate signal.
- A more frequent exposure to hypoxia, in conjunction with lower aragonite saturation and hypercapnia will have an impact on a number of calcifying and non-calcifying species and therefore on the ecology of the northern Gulf.

*The time series is from the "business as usual" RCP8.5 scenario of the Max-Planck-Institute Earth System Model (MPI-ESM) [Giorgetta et al., 2013] which was used to calculate the forcing in the future simulation.

Cai et al. [2011], Acidification of subsurface coastal waters enhanced by eutrophication, Nat. Geosci., 4(11), 766–770.
Fennel et al. [2011], A coupled physical-biological model of the Northern Gulf of Mexico shelf: model description, validation and analysis of phytoplankton variability, Biogeosciences, 8(7), 1881–1899.
Giorgetta et al. [2013], Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the Coupled Model Intercomparison Project phase 5, J. Adv. Model. Earth Syst., 5(3), 572–597.
Laurent et al. [2017], Eutrophication-induced acidification of coastal waters in the northern Gulf of Mexico: insights into origin and processes from a coupled physical-biogeochemical model, Geophys. Res. Lett., 44(2), 946–956.
Laurent et al. [2018], Climate change projected to exacerbate impacts of coastal eutrophication in the northern Gulf of Mexico, J. Geophys. Res. Oceans, in review.

[1] Department of oceanography, Dalhousie University, Halifax, Canada
[2] Naval Research Laboratory, Stennis Space Center, USA
[3] Dauphin Island Sea Laboratory, Dauphin Island, Alabama, USA

Link to pdf: http://memg.ocean.dal.ca/memg/presentations/Laurent_OSM2018.pdf