Future projections of the combined impacts of acidification and deoxygenation in eutrophic waters: a case study of Tokyo Bay, Japan

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Objective

- To use modeling approaches to simulate present and future ocean acidification and deoxygenation in eutrophic coasts of Japan
- To provide scientific guidelines for measures to local stakeholders, especially in the fisheries and tourism sectors

Tokyo Bay, as representative of eutrophic coasts

- Surrounded by large urban areas and highly eutrophic
- Hypoxia and anoxia repeatedly observed in inner bay (Kodama and Horiguchi, 2011, Mar. Pollut. Bull.)
- Large seasonal fluctuations in pH and aragonite saturation state (Ω_{ara}) (Yamamoto-Kawai *et al.*, 2021, Front. Mar. Sci.)
- Ω_{ara} already decreased by 0.6 since preindustrial (Yamamoto-Kawai *et al.*, 2015, J. Oceanogr.)

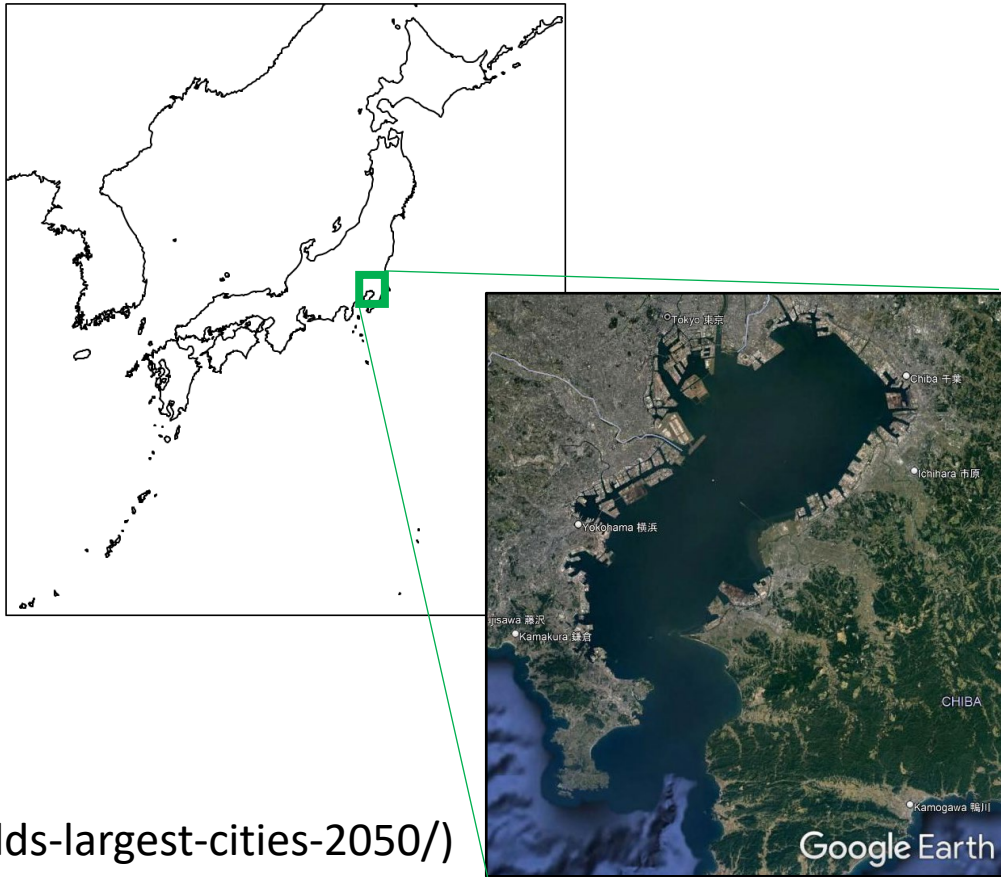
THE 10 MOST POPULATED CITIES IN THE WORLD

(IN MILLIONS OF INHABITANTS)

	2000		2025		2050 (PROJECTIONS)	
1	Tokyo	30,3	Jakarta	41,9	Dhaka	52,1
2	Jakarta	25,6	Dhaka	36,6	Jakarta	51,8
3	Guanghzou	19	Tokyo	33,4	Shanghai	34,9
4	Seoul	19	New Delhi	30,2	New Delhi	33,9
5	Kolkata	18,4	Shanghai	29,6	Karachi	32,6
6	New Delhi	18	Guangzhou	27,6	Cairo	32,4
7	Manila	17,8	Cairo	25,6	Tokyo	30,7
8	Mexico	17,6	Manila	24,7	Guangzhou	29,2
9	Dhaka	17,4	Kolkata	22,5	Manila	27,1
10	São Paulo	16,7	Seoul	22,5	Kolkata	23,8

Source: United Nations Population Division

(United Nations Regional Information Centre website https://unric.org/en/worlds-largest-cities-2050/)



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Model configuration

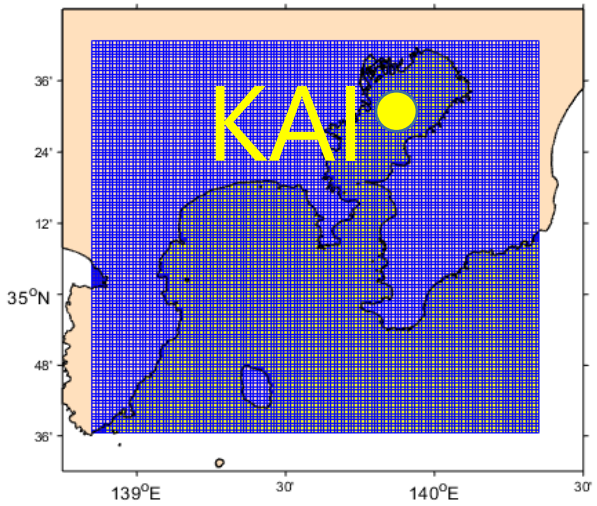
- We developed a high-resolution coupled ocean physical and biogeochemical model (Coupled Regional Ocean Modeling System (ROMS)-based Croco modeling system (Jullien et al., 2019) with Pelagic Interaction Scheme for Carbon and Ecosystem Studies (PISCES) biogeochemical model (Aumont et al., 2005))
- ~1.0 km grid cell size, 32 vertical layers, 6-hour output
- River freshwater and nutrient inflow is considered
- Present simulation period: July 2020 to August 2021
- Future projection period: July 2099 to August 2100 with Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report RCP 2.6 and 8.5 scenarios (van Vuuren *et al.*, 2011)
- Present simulation results were compared to time-series observations from Kawasaki Artificial Island (KAI) monitoring station (https://www.tbeic.go.jp/MonitoringPost/ViewGraph/ViewGraph?buoyId=02)

CROCO
Coastal and Regional Ocean COmmunity model

https://www.croco-ocean.org



(https://ja.wikipedia.org/wiki/川崎人工島)



Boundary condition (ocean)

Boundary condition	Dataset	Source
Bathymetry	General Bathymetric Chart of the Ocean (GEBCO) 15 arc-second	GEBCO website
Tide	TPXO Global Tidal Models (TPXO7.0)	Egbert and Erofeeva (2002)
Ocean physics (daily intervals) (water temperature (T), salinity (S), current velocity, water level)	Present: Hybrid Coordinate Modeling System Global Ocean Forecasting System (HYCOM-GOFS) 3.1 Analysis Future: Future Ocean Regional Projection (FORP)-JPN02 (MRI-GCM3)	GOFS 3.1 website van Vuuren *et al.* (2011) Tsujino *et al.* (2017) Nishikawa *et al.* (2021)
Atmospheric forcing (hourly intervals) (irradiation, air temperature, sea level pressure, relative humidity, precipitation, wind velocity)	GPV/JMA Meso-scale Spectral Model (MSM)	Japan Meteorological Agency website
Atmospheric CO_2 concentration	Present: 370 ppm Future: 420 ppm (RCP 2.6 scenario), 900 ppm (RCP 8.5 scenario)	van Vuuren *et al.* (2011)
Dissolved oxygen (DO) Nutrients (NO_3, PO_4, Si)	World Ocean Atlas 2009	Garcia *et al.* (2010a) Garcia *et al.* (2010b)
Dissolved organic carbon (DOC) Fe		Aumont and Bopp (2006)
Total alkalinity (TA)	TA = 2319 + 0.5155 T – 0.2367 DO	Watanabe *et al.* (2020)
Dissolved inorganic carbon (DIC)	Present: DIC = 2407 – 12.20 T – 0.7851 DO Future: Outputs from Model description and results of CMIP5-20c3m experiments (MIROC-ESM) (2086-2095)	Lewis *et al.* (1998) Watanabe *et al.* (2020) Watanabe *et al.* (2011)

Different physical conditions, atmospheric CO_2 concentration, and DIC between present and future

Boundary condition (river inflow)

Boundary condition	Values	Source
River flow (m^3 s^{-1})	Variable among months and rivers	River Discharges Yearbook of Japan (2005), This study
Temperature (℃)	Variable among months	Kurasige (1934, J. Meteor. Soc. Japan)
Salinity	2	This study
Total alkalinity (μmol kg^{-1})	950 (Arakawa, Naka, Sumida and Edo Rivers) 1094 (Tama and Tsurumi Rivers)	Yamamoto-Kawai *et al.* (2015, Front. Mar. Sci.)
Dissolved inorganic carbon (μmol kg^{-1})	1050	Yamamoto-Kawai *et al.* (2015, Front. Mar. Sci.)
Dissolved organic carbon (μmol kg^{-1})	71	Kubo *et al.* (2015, Biogeosci.)
Particulate organic carbon (μmol kg^{-1})	71	Kubo *et al.* (2015, Biogeosci.)
Phosphate (μmol kg^{-1})	Variable among months and rivers	River Discharges Yearbook of Japan (2005), Sakai *et al.* (2008, Proceedings of hydraulic engineering), this study
Nitrate (μmol kg^{-1})	Variable among months and rivers	River Discharges Yearbook of Japan (2005), Sakai *et al.* (2008, Proceedings of Hydraulic Engineering), this study
Ammonium (μmol kg^{-1})	166	Kubo *et al.* (2015, Biogeosci.)
Silicate (μmol kg^{-1})	227.6	Kubo *et al.* (2015, Biogeosci.)
Dissolved oxygen (μmol kg^{-1})	144 - 252	Ministry of Land, Infrastructure, Transport and Tourism Water Information System (http://www1.river.go.jp/)

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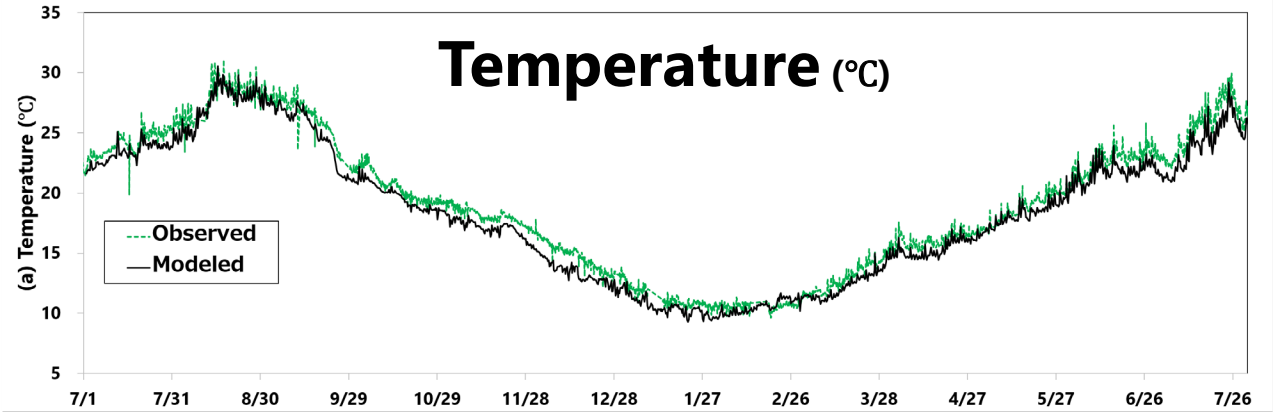
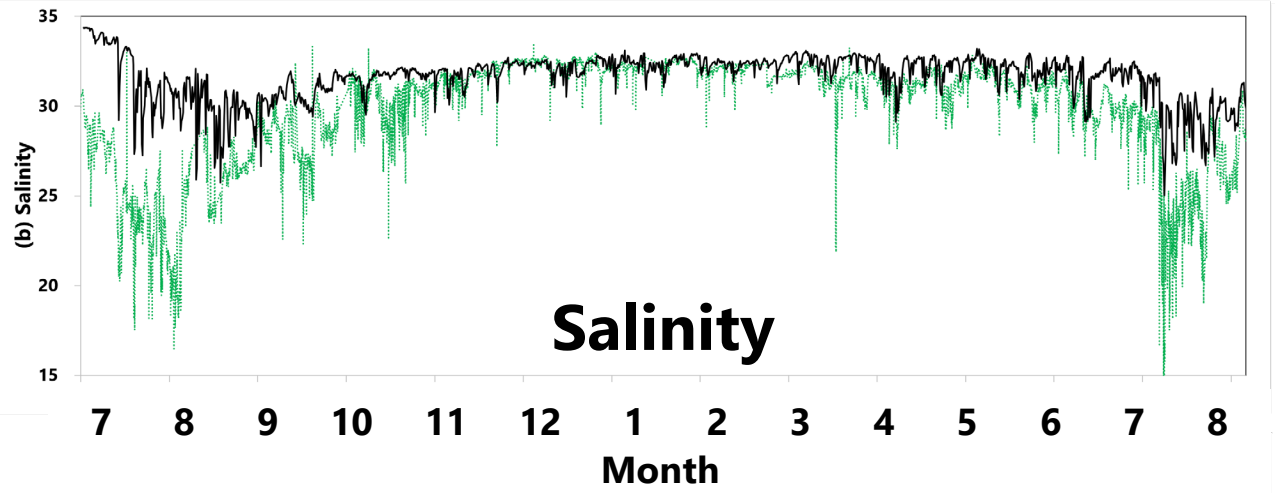
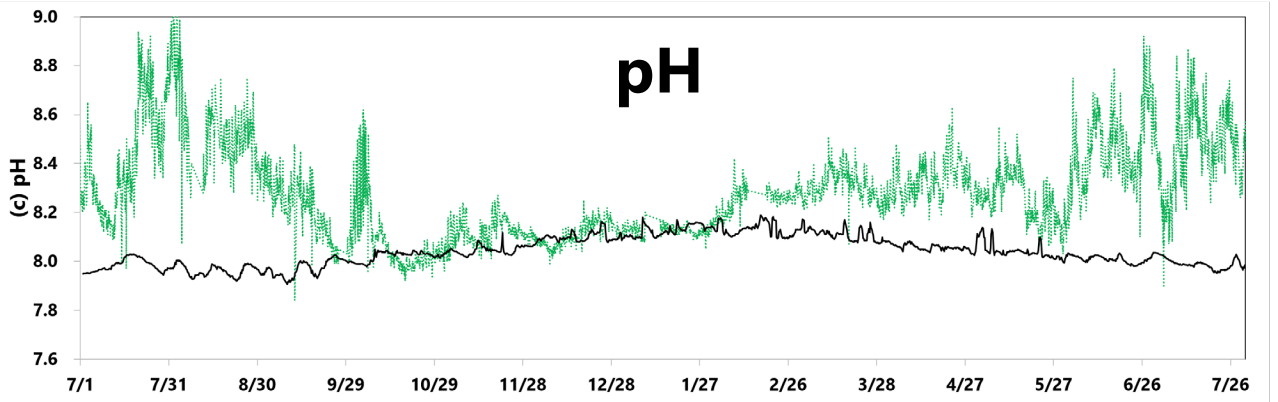
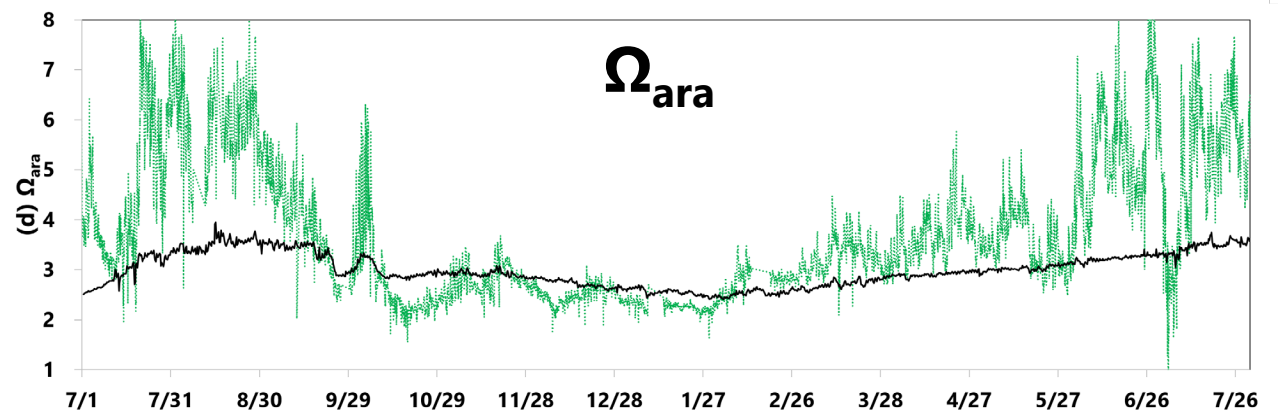
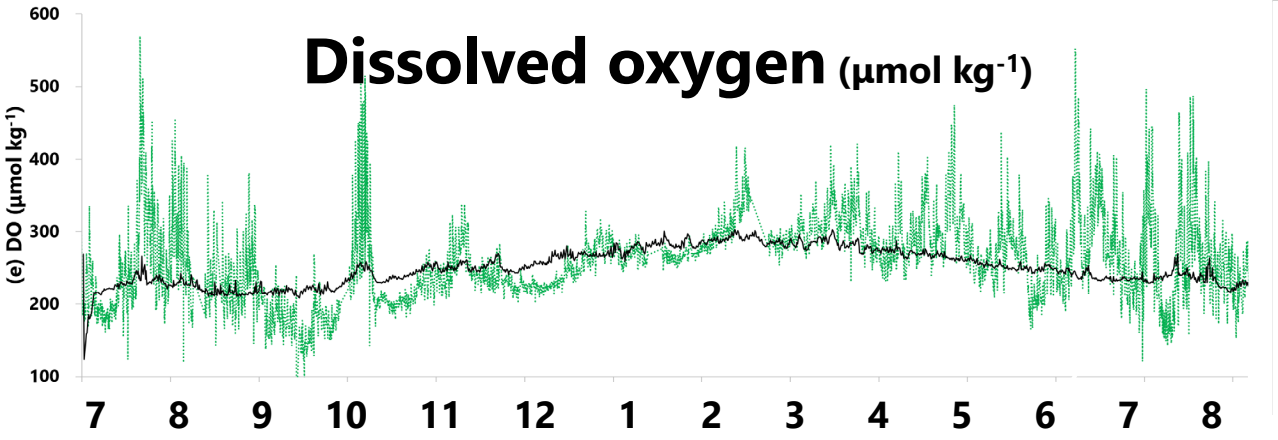
Present simulation (surface layer; July 2020 – August 2021)











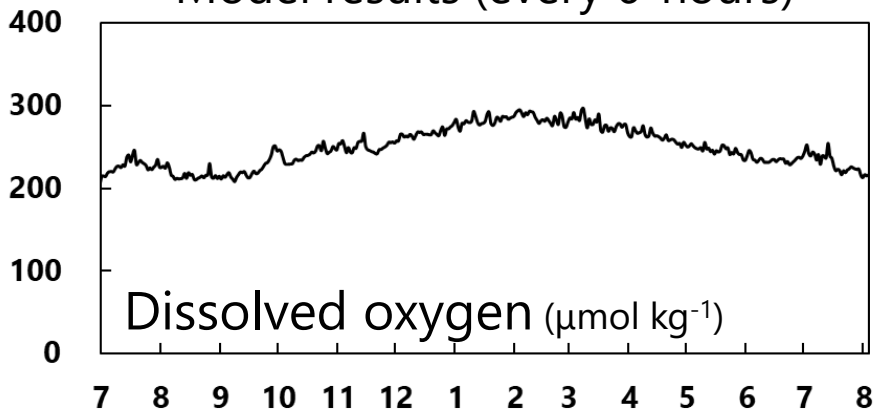
--- Observation (hourly)

— Simulation (every 6-hour)

Consideration of short-term (hourly) fluctuation component

The current model does not adequately reproduce the diurnal variation component

Model results (every 6-hours)



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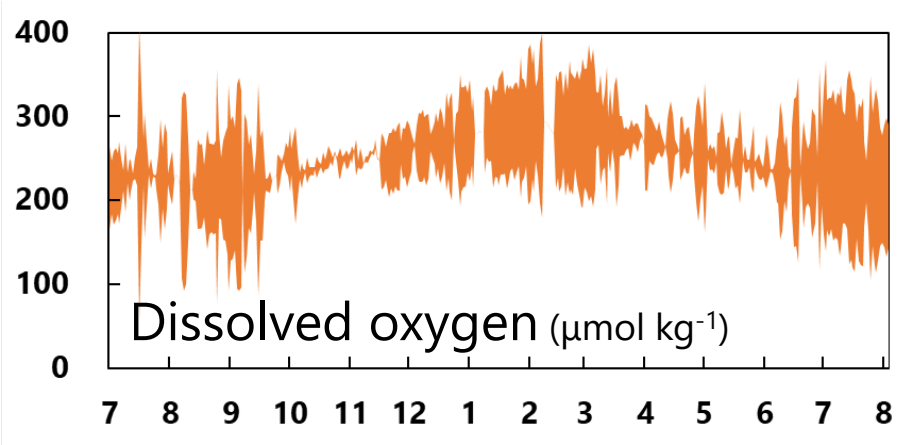
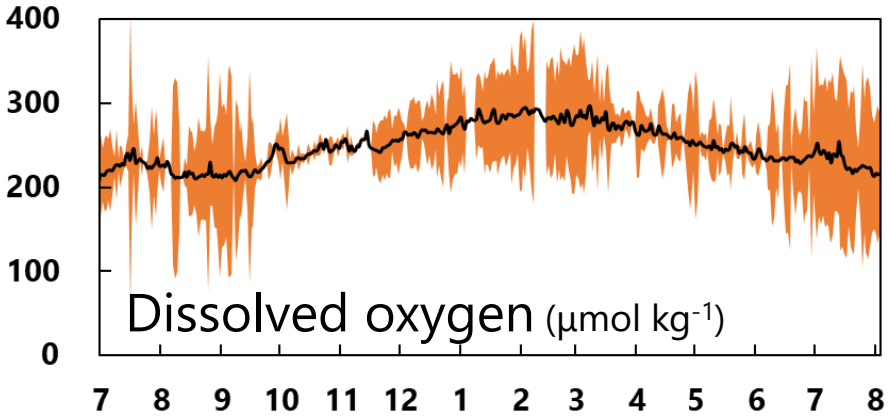
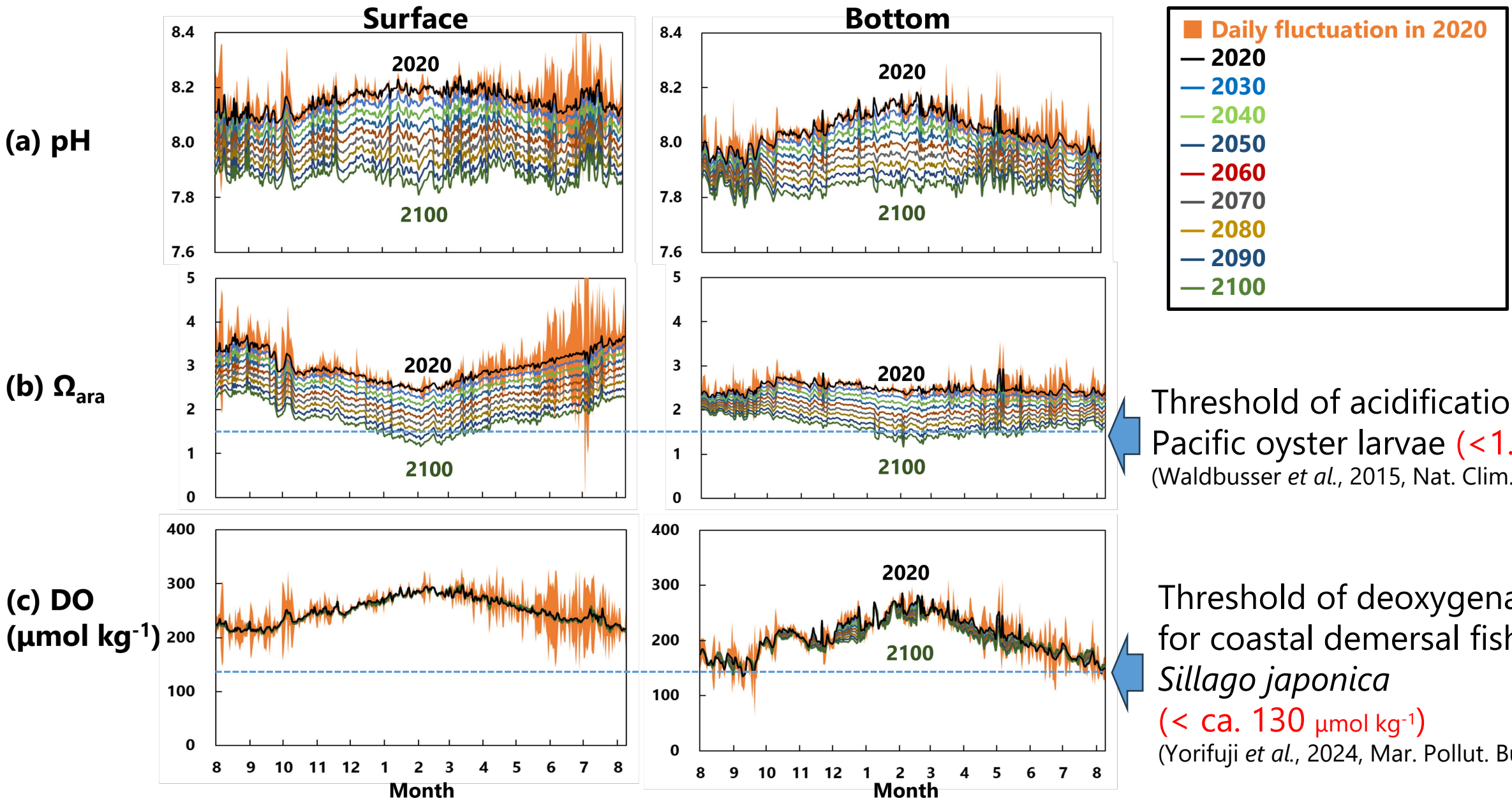
Observed short-term fluctuation derived from the deviation between raw observations and the 11-day running mean



Assuming short-term fluctuation is unchanged toward the future



Future simulation (High CO_2 emission (RCP 8.5) scenario)



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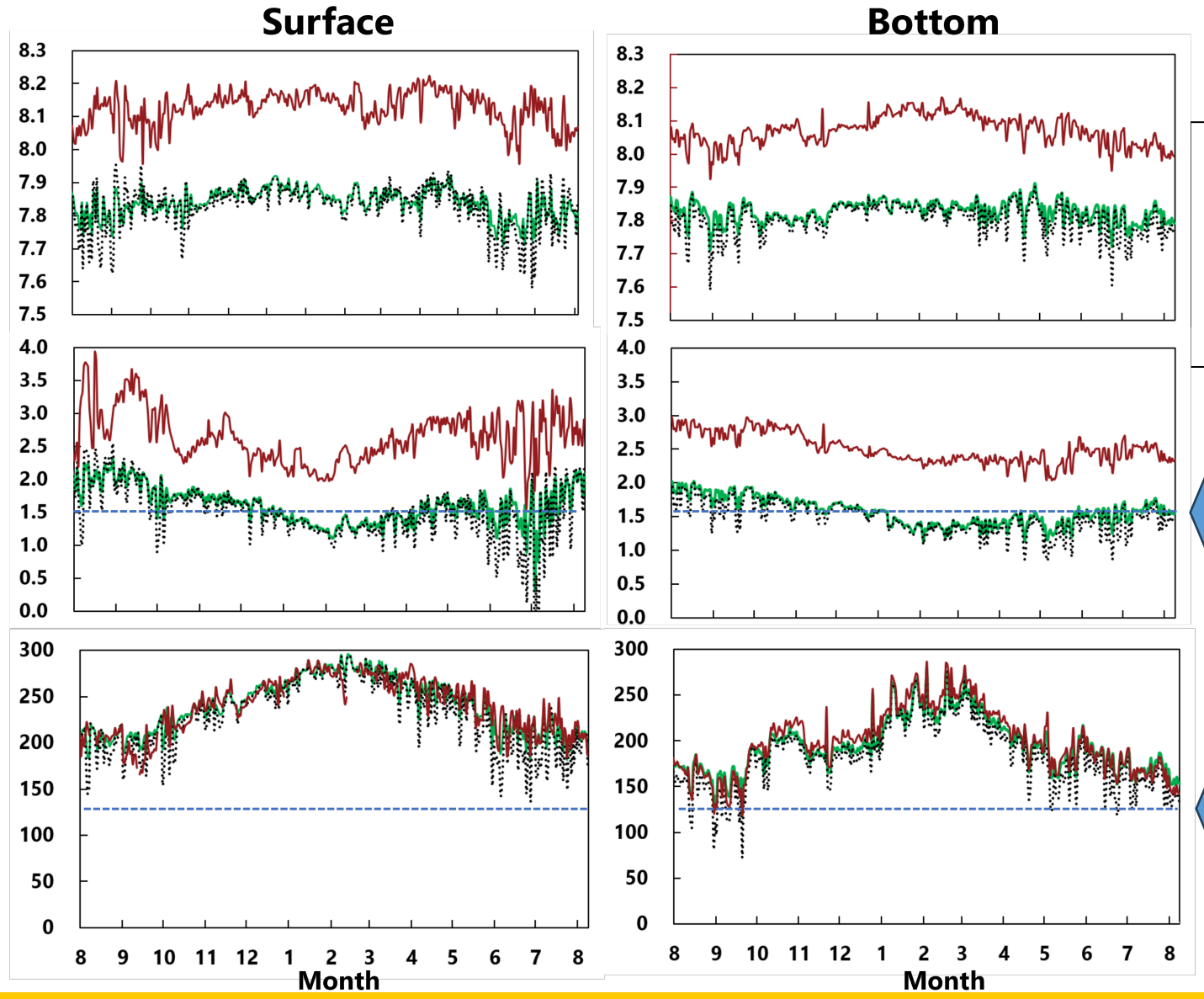
Reduction of CO_2 emission and river nutrient inflow (in 2100)

Daily min. pH

Daily min. Ω_{ara}

Daily min. DO (μmol kg^{-1})



--- High CO_2 emission (RCP 8.5) scenario (Control)

— Low CO_2 emission (RCP 2.6) scenario (Case 1)

— River nutrient inflow halved (Case 2)

Threshold of acidification for Pacific oyster larvae (<1.5)
(Waldbusser *et al.*, 2015, Nat. Clim. Chang.)

Threshold of deoxygenation for coastal demersal fish *Sillago japonica* (< ca. 130 μmol kg^{-1})
(Yorifuji *et al.*, 2024, Mar. Pollut. Bull.)

- Cut CO_2 emission → Mitigate acidification and deoxygenation
- Reduce river nutrient inflow → Mitigate deoxygenation

Summary

We developed a high-resolution coupled physical and biogeochemical model that considers freshwater and nutrient influx processes from rivers.

Model results realistically reproduce seasonal variations in physical and biogeochemical processes observed in Tokyo Bay, a representative eutrophic coastal area in Japan.

Model results suggest:

- Ocean acidification in surface and bottom layers and deoxygenation in bottom layer may have serious impacts on marine organisms by 2100 unless we cut anthropogenic CO_2 emission sufficiently.
- Reduction of river nutrient inflow may also be effective for alleviating impacts of ocean deoxygenation on coastal fisheries species.