MINJIANG University

21st-Century Maritime Cooperation Committee
21世纪海上合作委员会
UCLG ASPAC

Ocean Hypoxia and Ecological Effects under Global Climate Change

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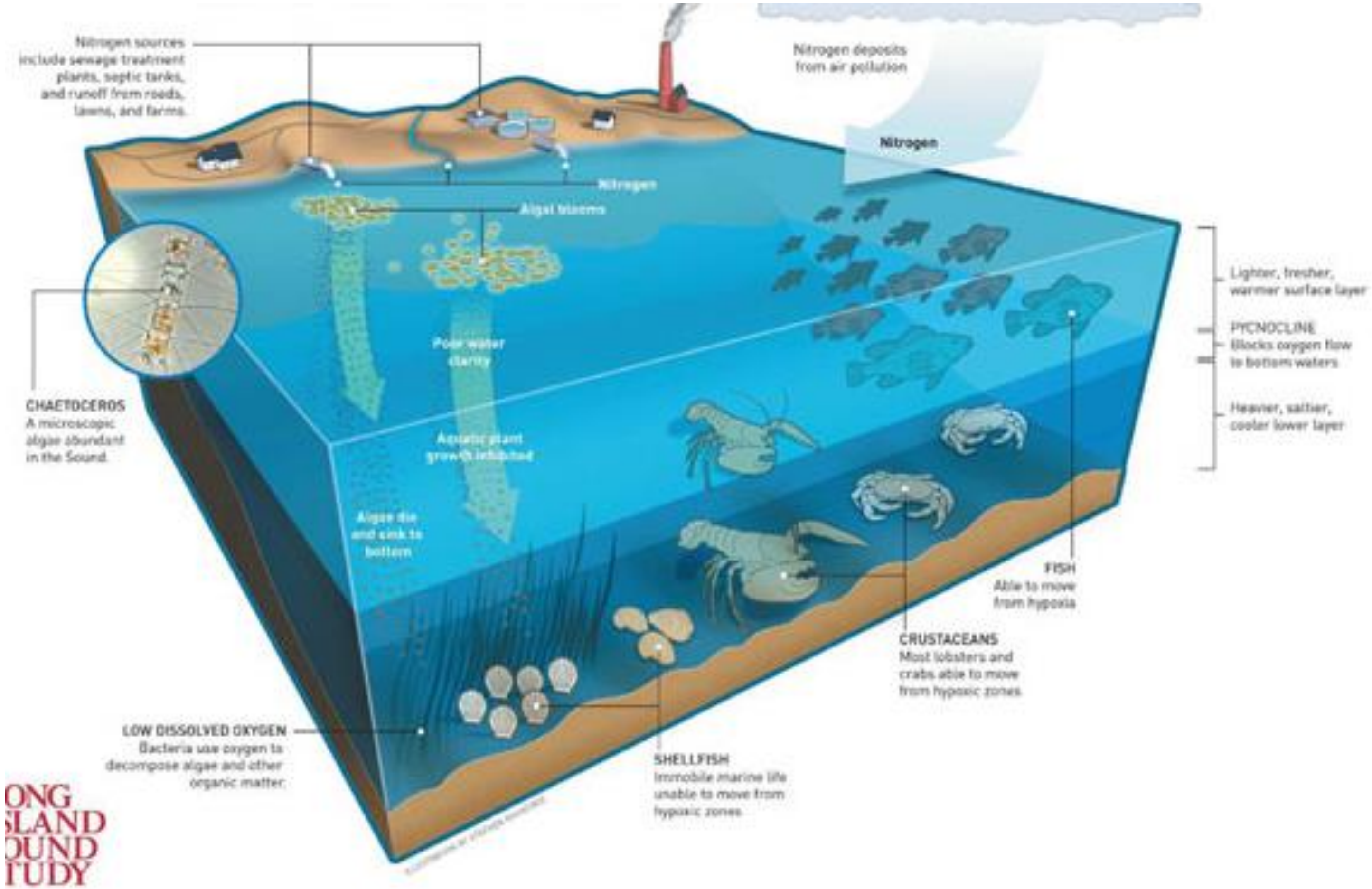
Ocean deoxygenation

- The loss of dissolved O_2 **(DO)** from the oceans occurred over the past 50 years.
- Including open-ocean deoxygenation and coastal deoxygenation
- **Drivers: global warming** and **anthropogenic nutrient enrichment in coastal waters**



Coastal deoxygenation

Global warming:

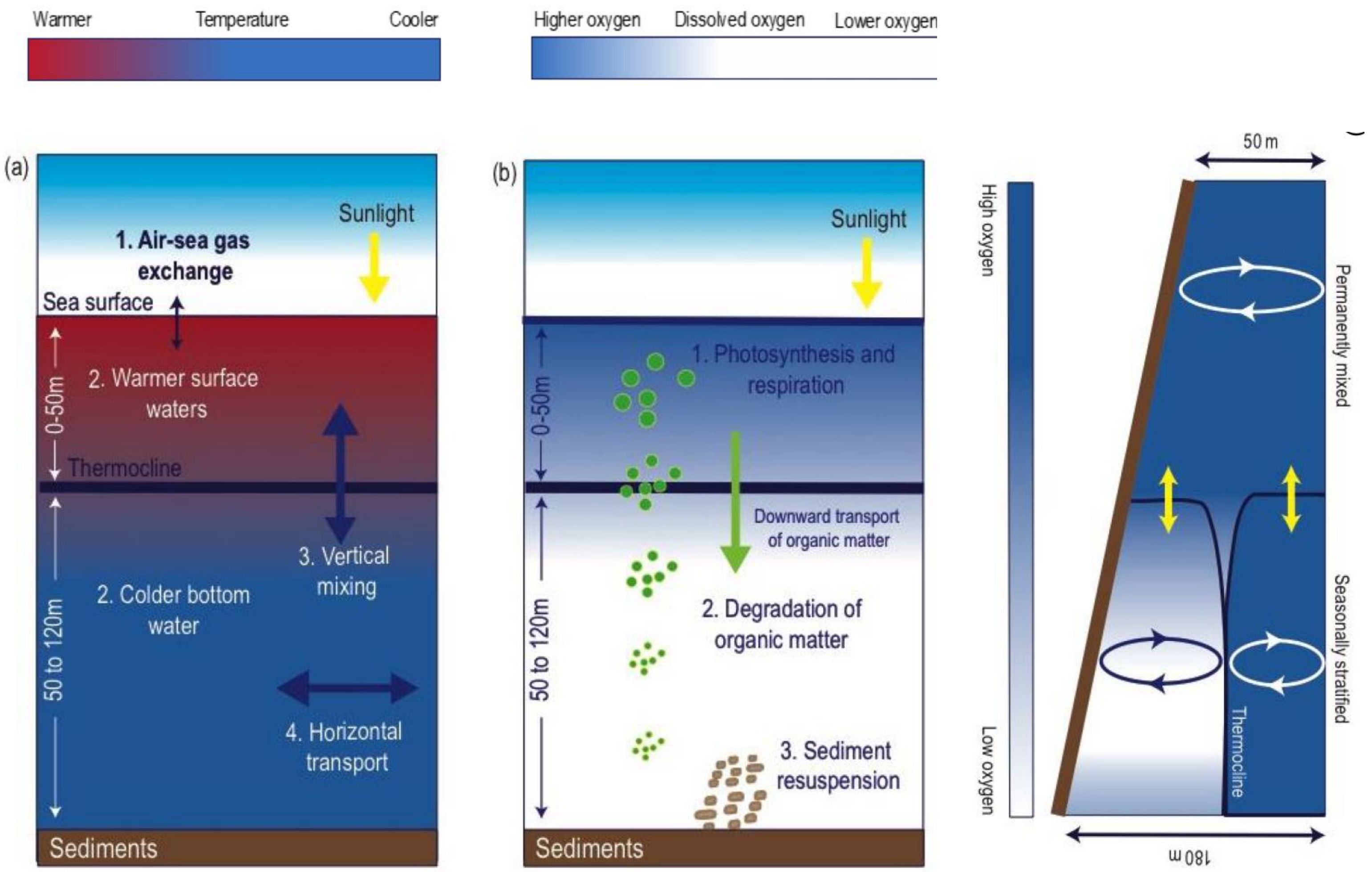
- Driven mainly by greenhouse gas emissions (e.g. **CO_2**、CH_4、N_2O)

Nutrient enrichment in coastal waters comes from:

- Fertilizers
- Human/live stock wastes

Smith et al., 2006

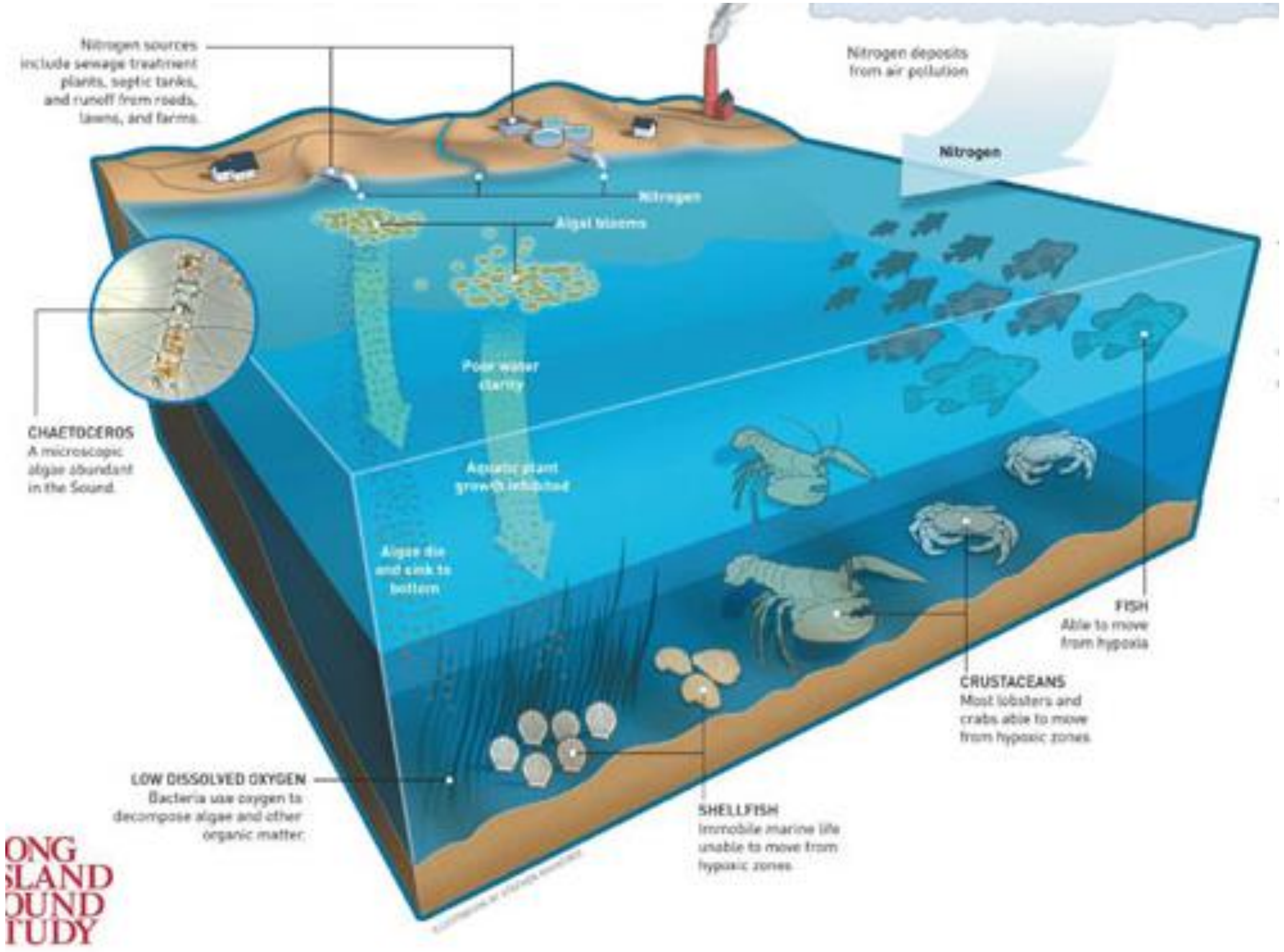
Ocean deoxygenation: process



- Stable thermocline develops in late spring due to temperature rising.
- Algae bloom happens in the surface layer due to rich nutrients and warm temperature.
- During the late stage of algae blooms, phytoplankton dies and sinks to the bottom, as well as other organic matters.
- Degradation of these organic matters deplete O_2 in the bottom, causing deoxygenation in different degrees.

Mahaffey et al., 2020

Ocean deoxygenation



Hypoxia:

A condition of low DO in seawater that becomes detrimental to aerobic organisms.

For examples:

- Alteration of behavioural and physiological responses
- Decreased growth rates
- Reduced fecundity
- Mortality and etc.

Hypoxia threshold: DO ≤ 2 mg/L (=63 μ mol /L)

- the DO concentration at which lethal or sub-lethal impacts to marine organisms occur.
- Importantly, there is no universal DO concentration at which seawater becomes hypoxic to its resident aerobic metazoans, since the sensitivity of marine organisms to low DO concentration is different due to different taxons, life stages, exposure time, temperature and etc.

Hypoxia： current situation and trend

- Nowadays, low-oxygen zones in both open ocean and coastal waters is expanding, which could continue within the next hundred years. Coastal hypoxia is expected to worsen, with the increased occurrence, frequency, intensity and duration of hypoxic events due to the global warming and human activities. (Diaz & Rosenberg, 2011).

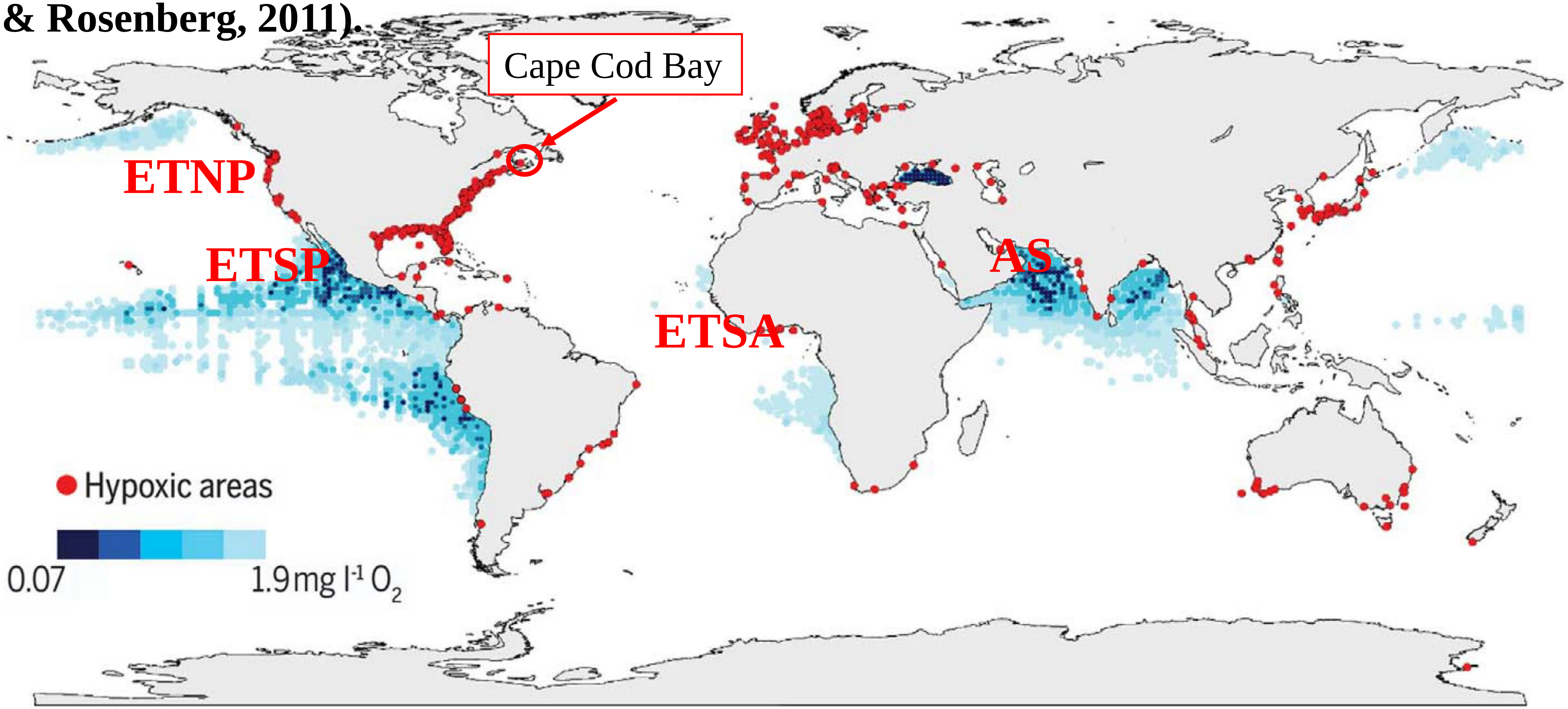


Fig. Low and declining oxygen levels in the open ocean and coastal waters affect processes ranging from biogeochemistry to food security (Breitburg, et al, 2018)

Severe hypoxic areas among the world

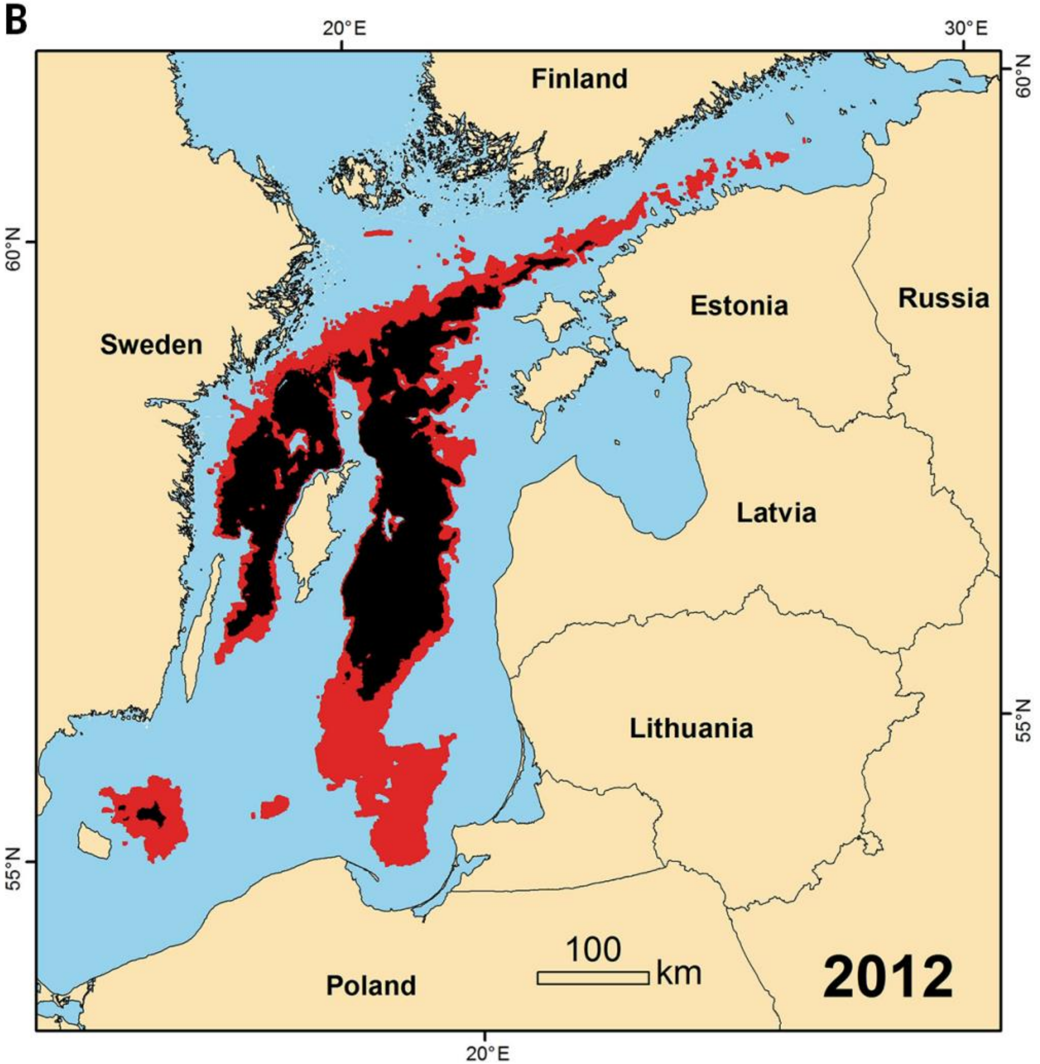
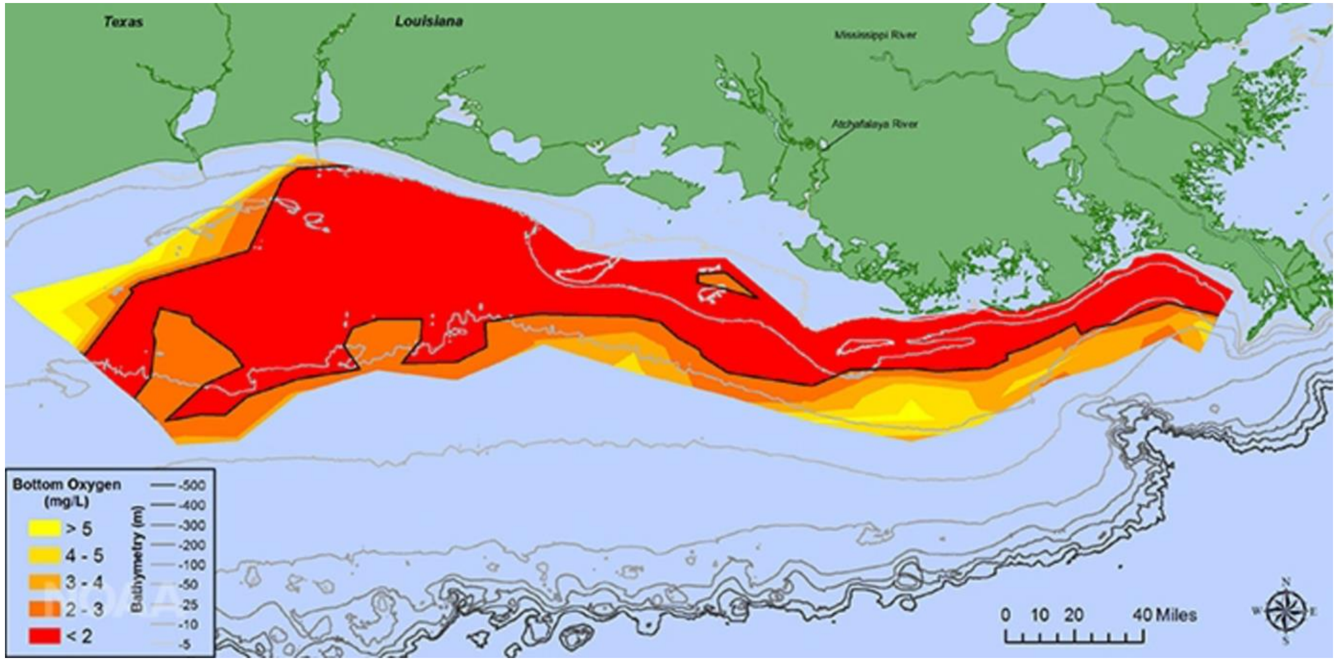


Fig. Oxygen levels at the bottom of the Baltic Sea during 2012 red, hypoxia, O_2 concentration (2 mg/L); black, anoxia

- In 2018, the semi-enclosed Baltic Sea was determined to contain the largest hypoxic area among the world ’ s coastal seas, with a size equal to the Republic of Ireland, about 70, 000 km^2.



- In 2017, The large dead zone (23,309 km^2) ever recorded in the U.S. has appeared at the mouth of the Mississippi River, in Gulf of Mexico

Severe hypoxic area among the world

- **The area of summer hypoxia in the vicinity of the Changjiang estuary was 13,000 km² in 1999 (Li et al., 2002)**

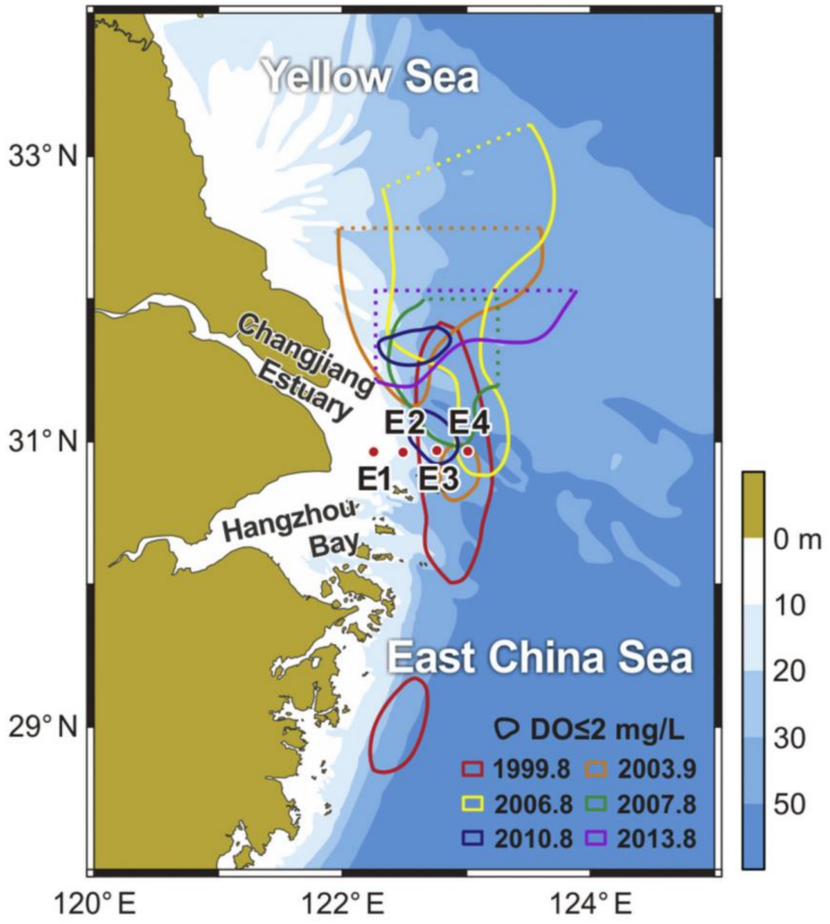


Fig. Changes of hypoxic zones (DO ≤ 2 mg/L) off the Changjiang Estuary. (Wu et al., 2020)

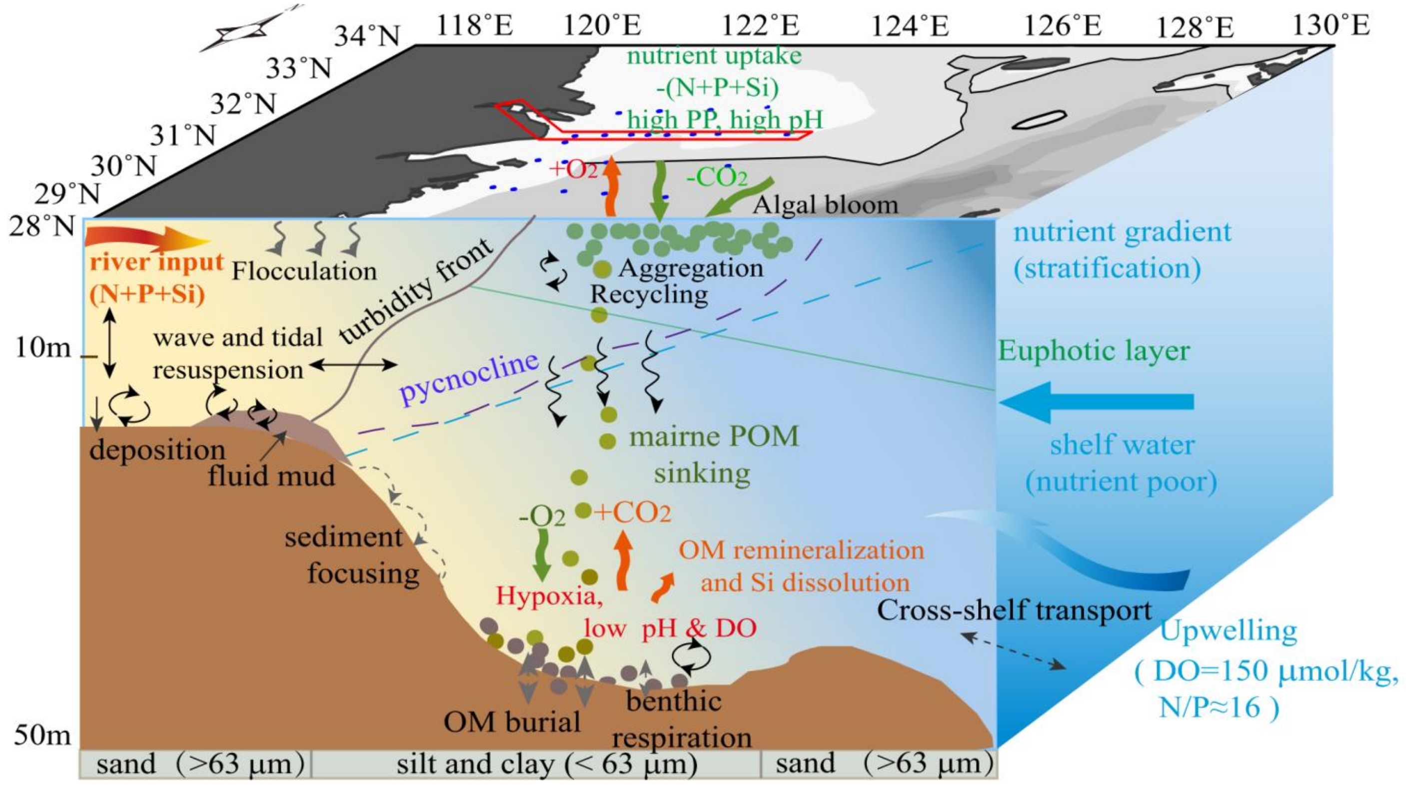
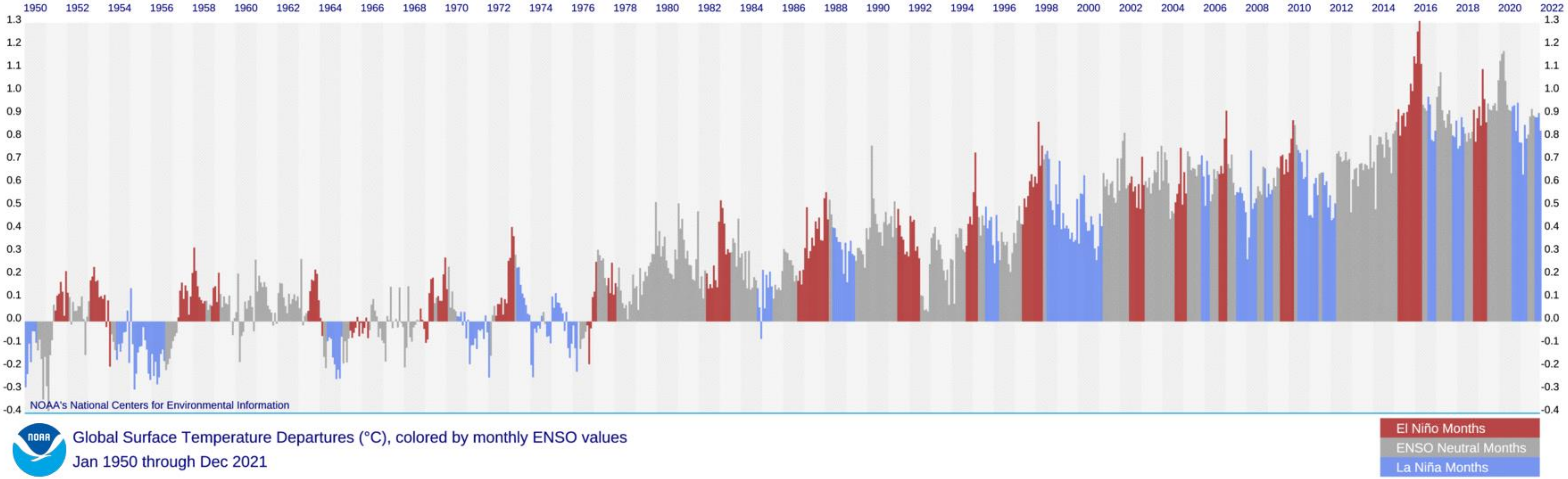


Fig. Conceptual model for the formation of summer hypoxia in bottom waters off the Changjiang Estuary. (Wang et al., 2017)

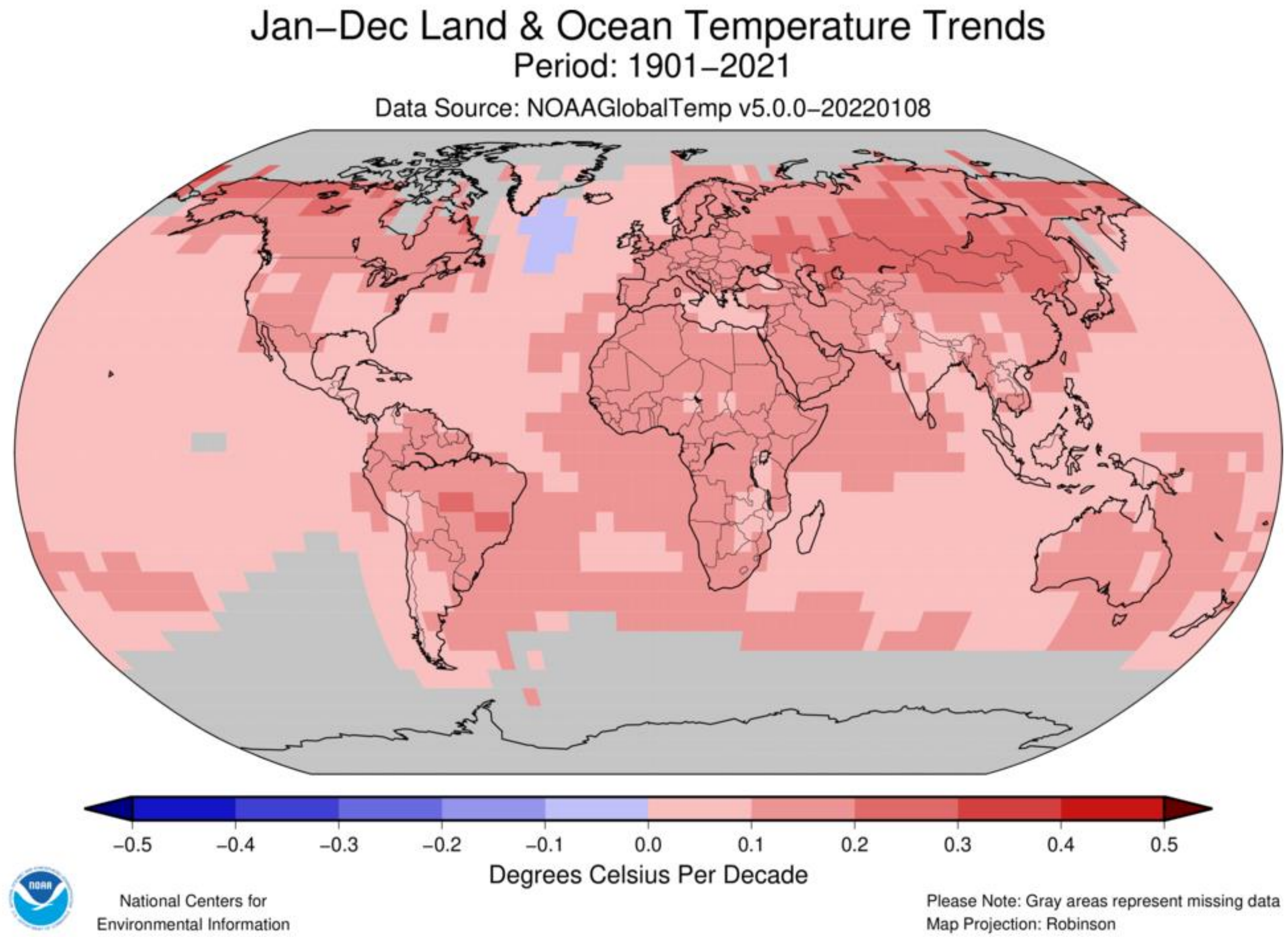
Climate change: global warming

Based on the data from NOAA



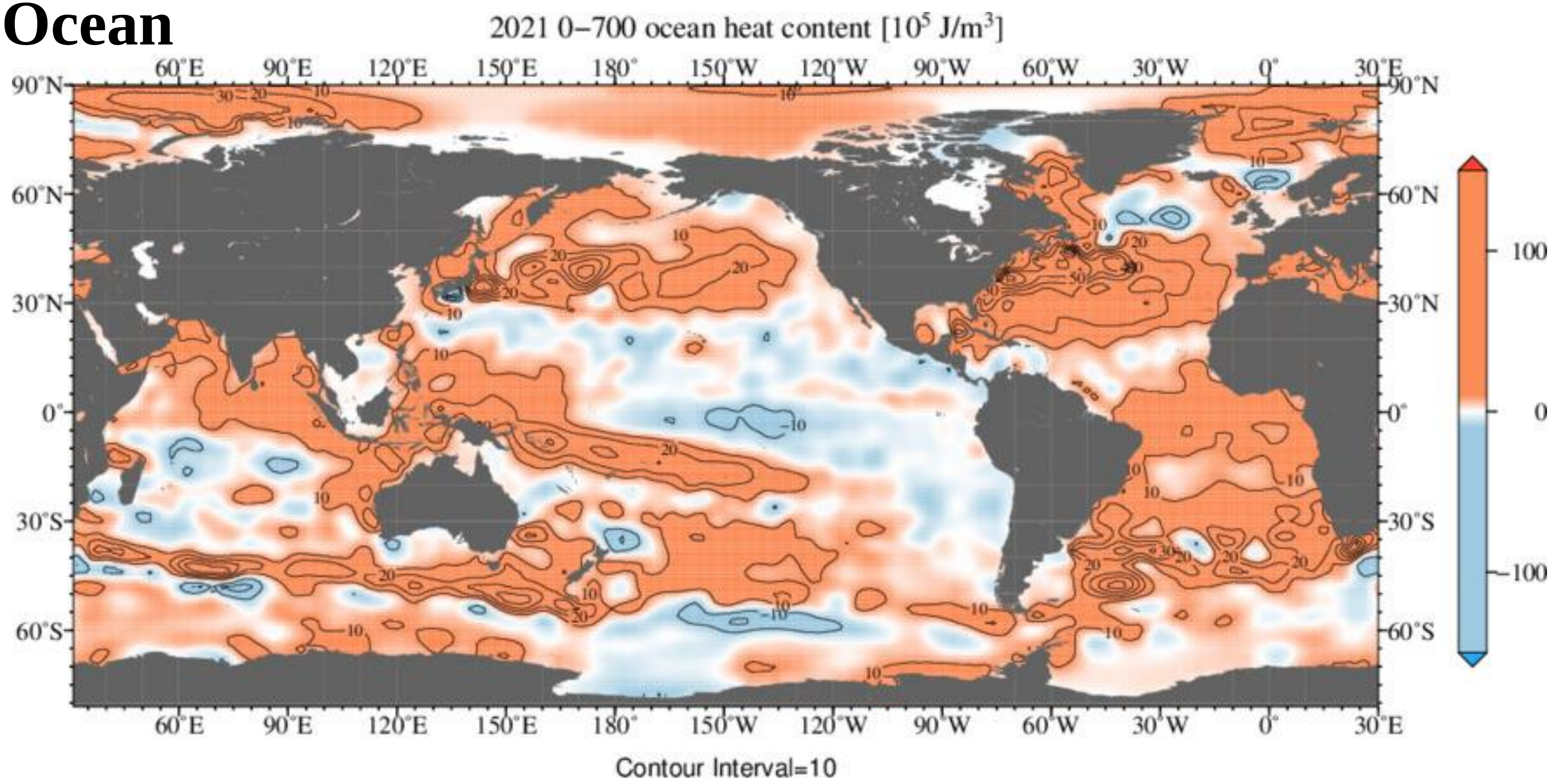
- Due to the massive use of fossil fuels, global warming driven by greenhouse gas emissions (e.g. **CO_2**、CH_4、N_2O) has been becoming increasingly severe.
- The average land and sea surface temperature has been increasing at a rate of 0.07 ^oC per decade since 1981 (NOAA, 2020).
- Temperature kept increasing since 1976, even in La Nina Months.

Climate change: global warming



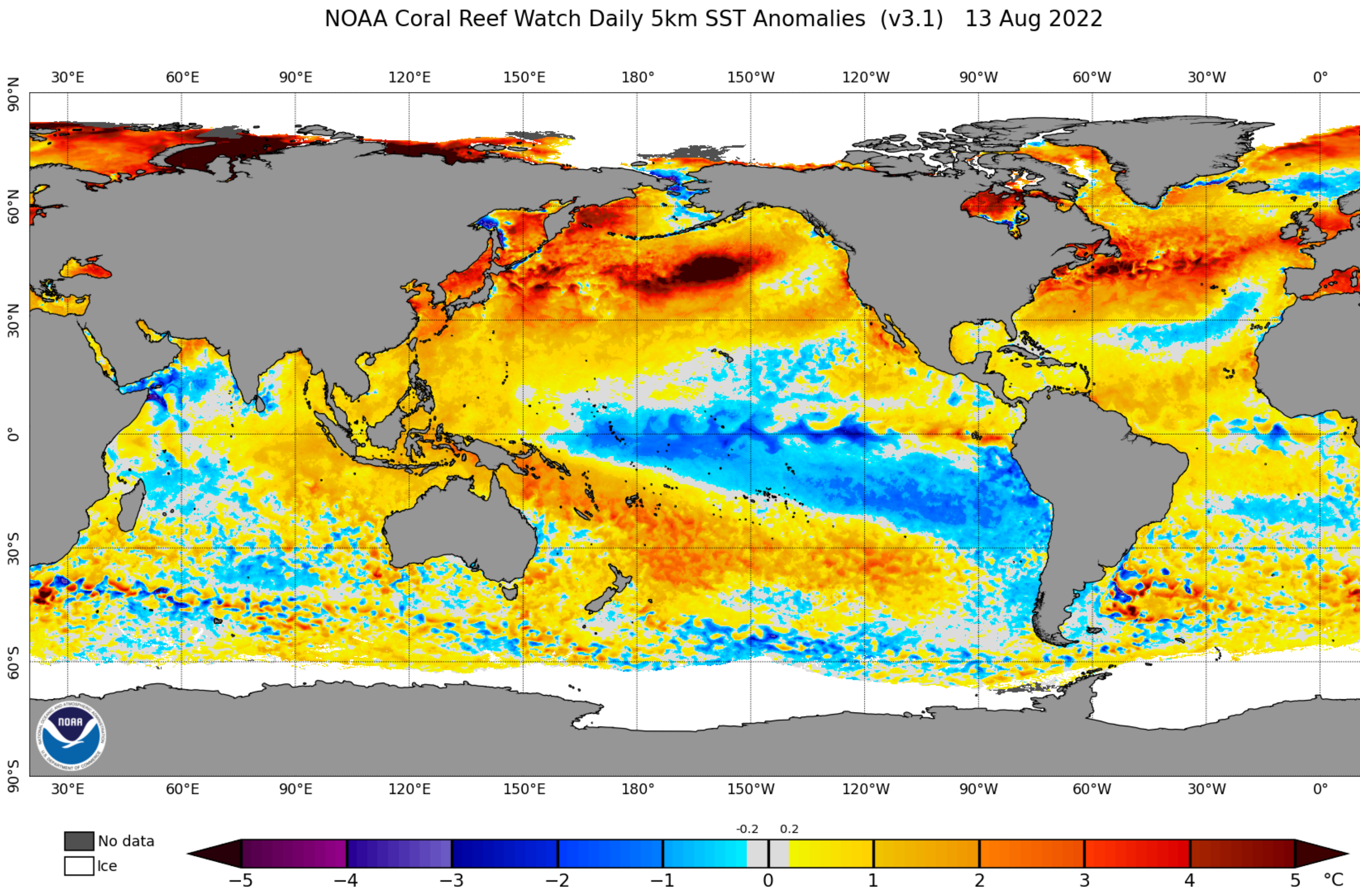
- By the end of the 21st century, assuming a business as usual model of greenhouse gas emissions, the global mean sea surface temperature increase will hit 5 ^{o}C (NOAA, 2020).

Warmer Ocean



- The annual global ocean heat content (OHC) was record high in 2021, exceeding the previous record set in 2020.
- The seven highest OHC have all occurred in the last seven years (2015–2021).
- During 2021, the heating was distributed throughout the world's oceans, with record-high heat across the North Atlantic Ocean, the North Pacific Ocean, and Mediterranean Sea.

Climate change: global warming



Abnormally high temperature in the northern hemisphere occurred frequently in summer, 2022.

- The temperature has reached 40 ^{o}C or more in Europe, Asia, Americas in this summer, and it occurs frequently and last for a long time.
- Record-breaking high temperatures occurred frequently. For an example, 40.3 ^{o}C in Jul 19, 2022 in England.

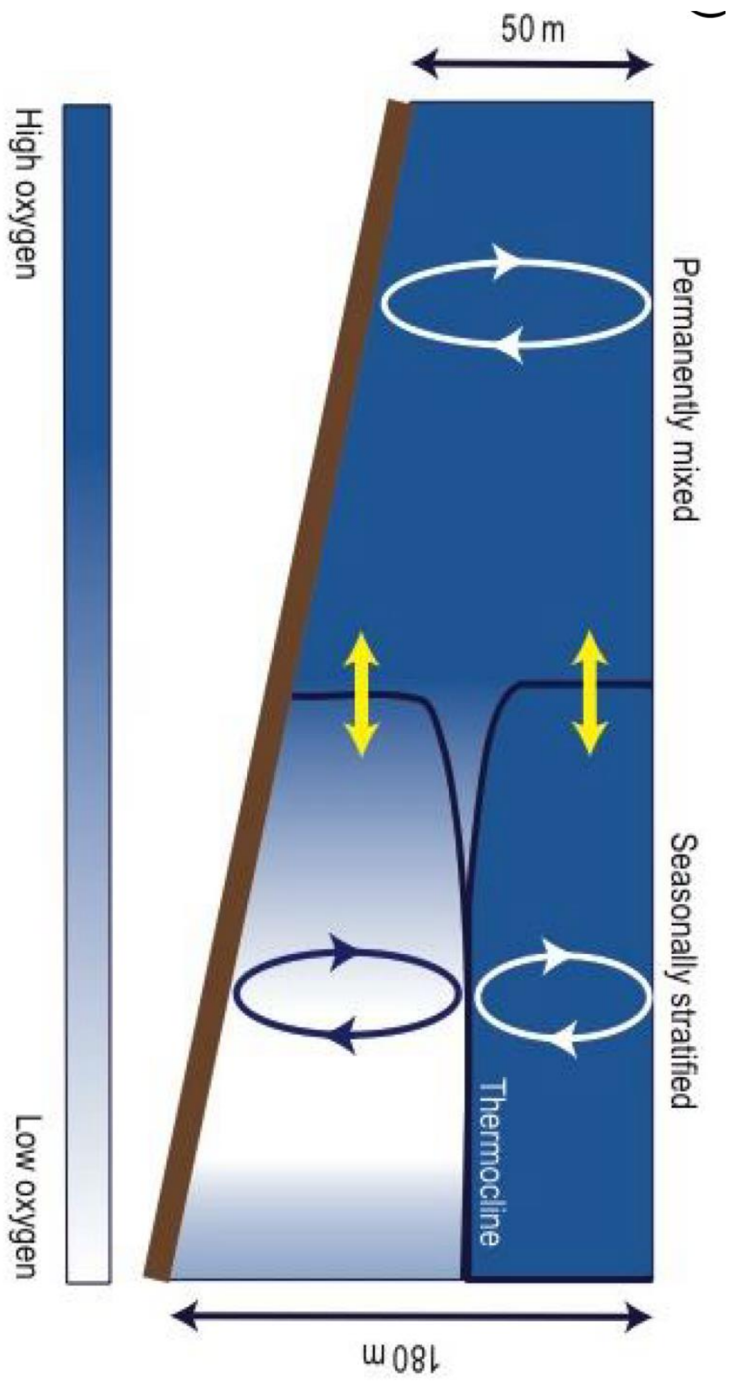
How dose global warming intensify hypoxia?

Directly

- Decrease oxygen solubility in water.
- Increase the rate of oxygen consumption via respiration.
- Reduce the introduction of oxygen from the atmosphere and surface waters into the ocean interior by enhancing stratification and weakening ocean overturning circulation.

Indirectly

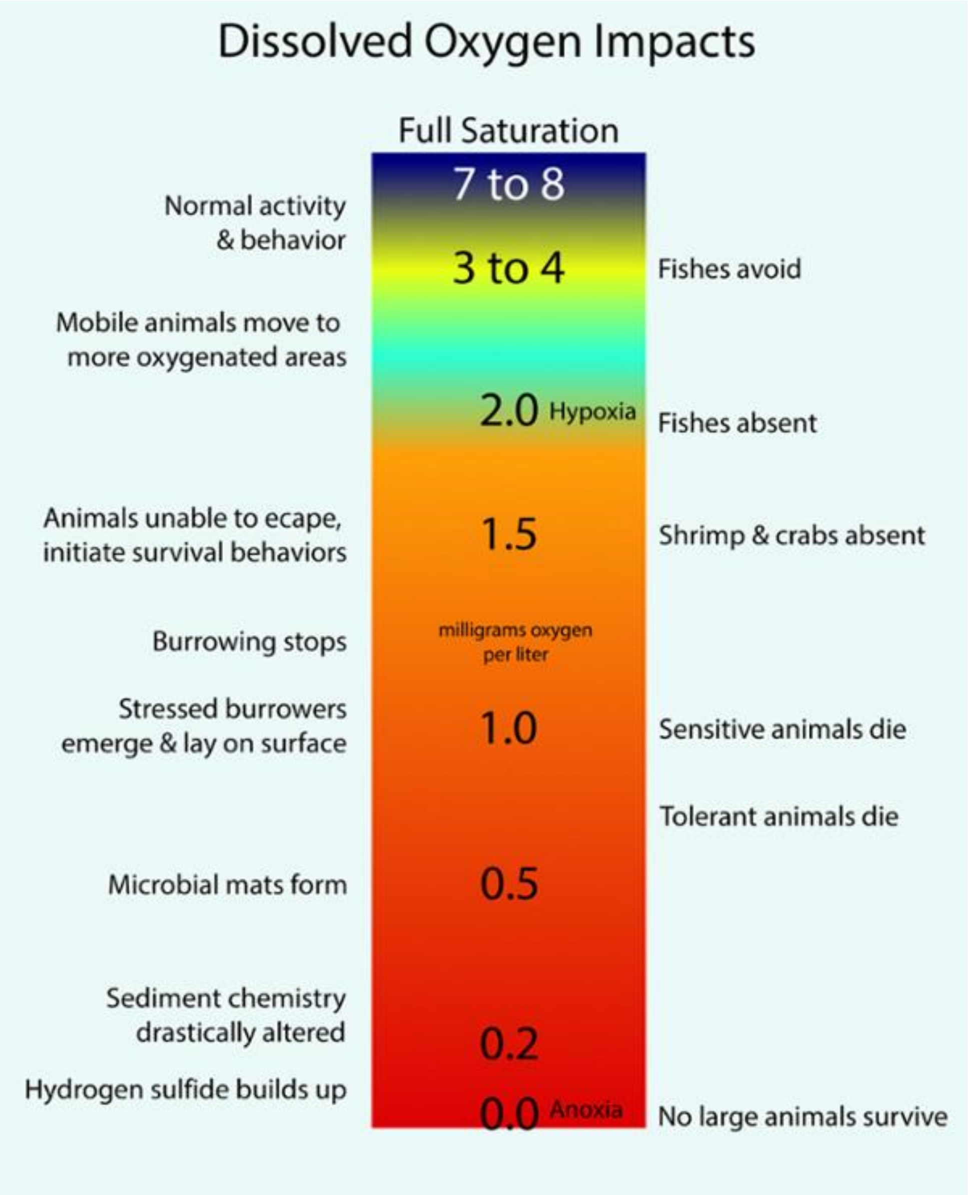
- Due to both global warming and increased nutrient loads, algae blooms, including Harmful algae blooms, display range expansion and increased frequency in coastal areas since the 1980s, intensifying hypoxia in coastal waters (Gobler, 2020).
- In the Baltic Sea, the North Sea and Chesapeake Bay, sea level rise may lead to stronger vertical stratification with consequent O_2 decline in the bottom water (Meire et al., 2013, 2017; Ni et al., 2019).



Hypoxia: ecological effects

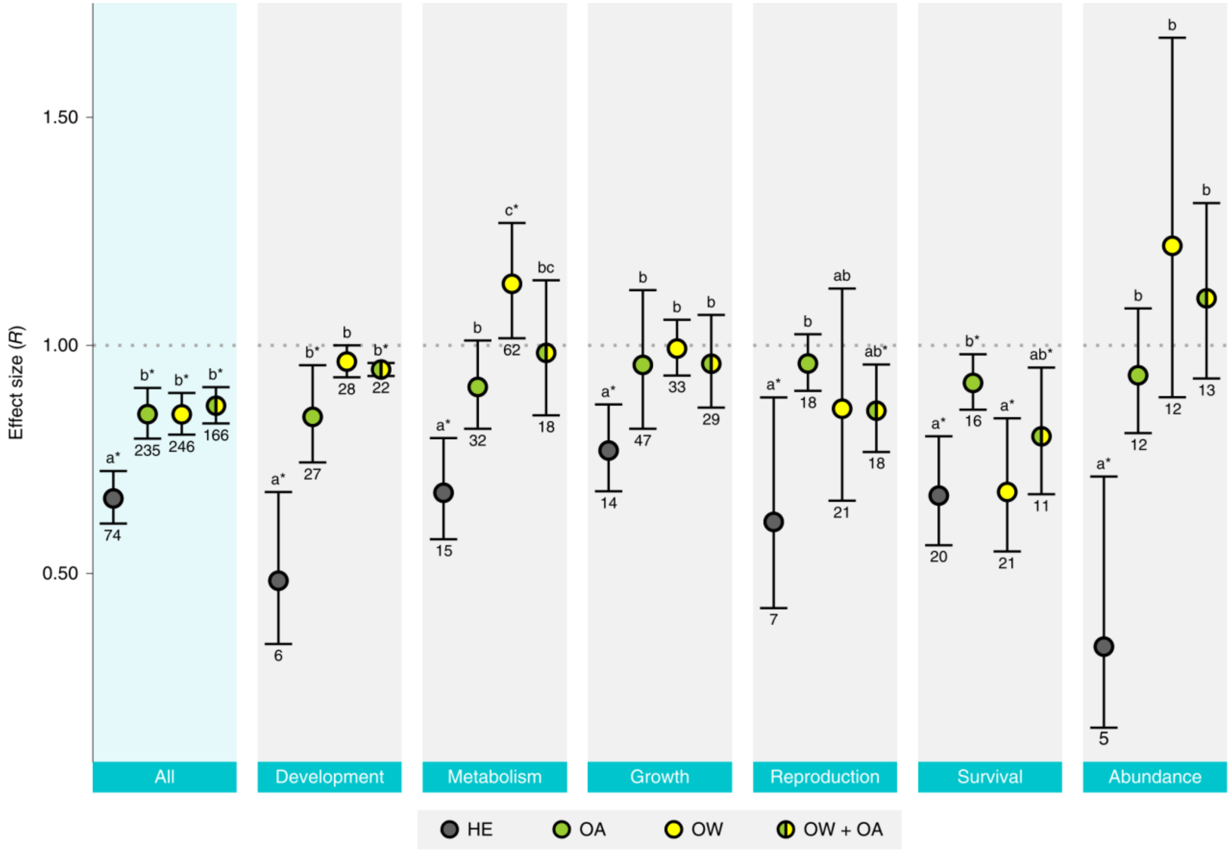
Oxygen is fundamental to life, which is essential for breathing or 'respiration' by all bacteria, protists, plants and animals that live in the sea. Hypoxia affects marine ecology negatively.

- **Hypoxia affects marine organisms in different degree**, e.g., alteration of behavioural and physiological responses, decreased growth rates, reduced fecundity, mortality and etc.
- Hypoxia changes migration and distribution of organisms.
- Hypoxia alters the community structure.
- Hypoxia constrains productivity, biodiversity, and biogeochemical cycles.
- Severe hypoxia contributed to dead zones. As oxygen depletion becomes more severe, persistent, and widespread, hypoxia sensitive organisms die one after another, even resulting in dead zones, negatively affecting food security and livelihoods.
- Effects of hypoxia on marine organisms enhanced by global warming.



Effects of hypoxia on marine organisms

In contrast to warming and acidification, hypoxic events elicited **consistent negative effects** relative to control biological performance—**survival** (–33%), **abundance** (–65%), **development** (–51%), **metabolism** (–33%), **growth** (–24%) and **reproduction** (–39%)—across the taxonomic groups (**mollusks, crustaceans and fish**).



HE: hypoxic events
OA: ocean acidification
OW: ocean warming

Fig. Average and detailed biological responses of combined marine biota to global change stressors (Sampaio, et al., 2021)

Effects of hypoxia on fish

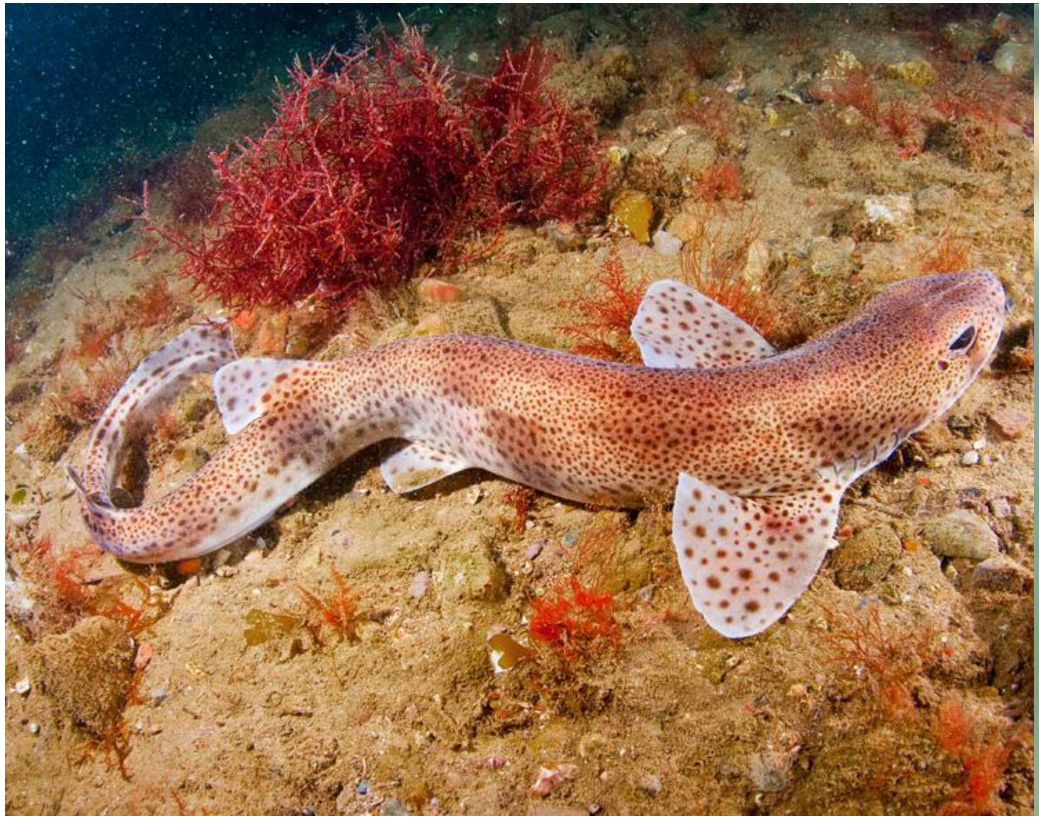
- **Mild hypoxia** can alter behavioural patterns, decrease feeding rates and cause changes in physiological processes (Vaquer-Sunyer & Duarte, 2008).

Atlantic salmon *Salmo salar*

- Within suitable temperature range, Atlantic salmon reduced consumption (by 13, 15, 63 and 73%, respectively) when confronted with hypoxia of varying degrees (down to 70, 60, 50 and 40% air saturation).
- Hypoxia also reduce the growth and survival of salmon significantly.
- Moderate hypoxia (40% air saturation) did not affect survival of salmon in 2 weeks.

Effects of hypoxia on fish

- Under low oxygen conditions (50% air saturation), the survival rate of small-spotted catsharks *Scyliorhinus canicula* embryos dropped to 61.9%—63.2% significantly (Musa et al., 2020).



Small-spotted catsharks *Scyliorhinus canicula*

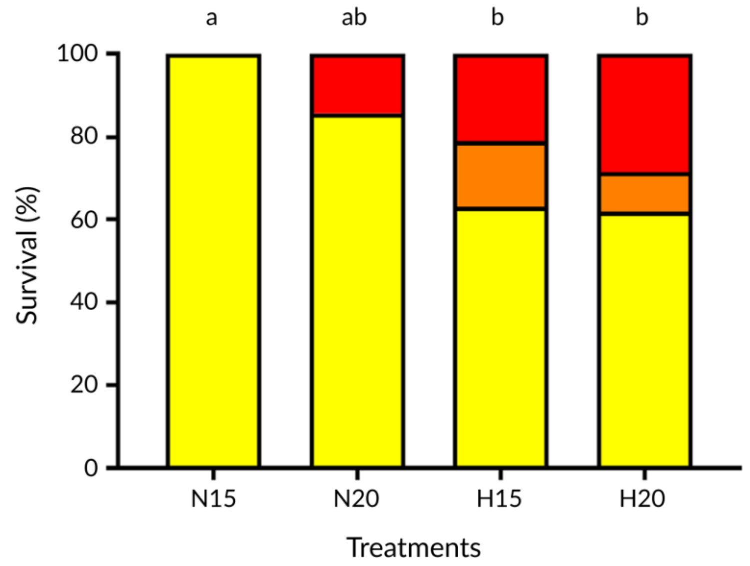
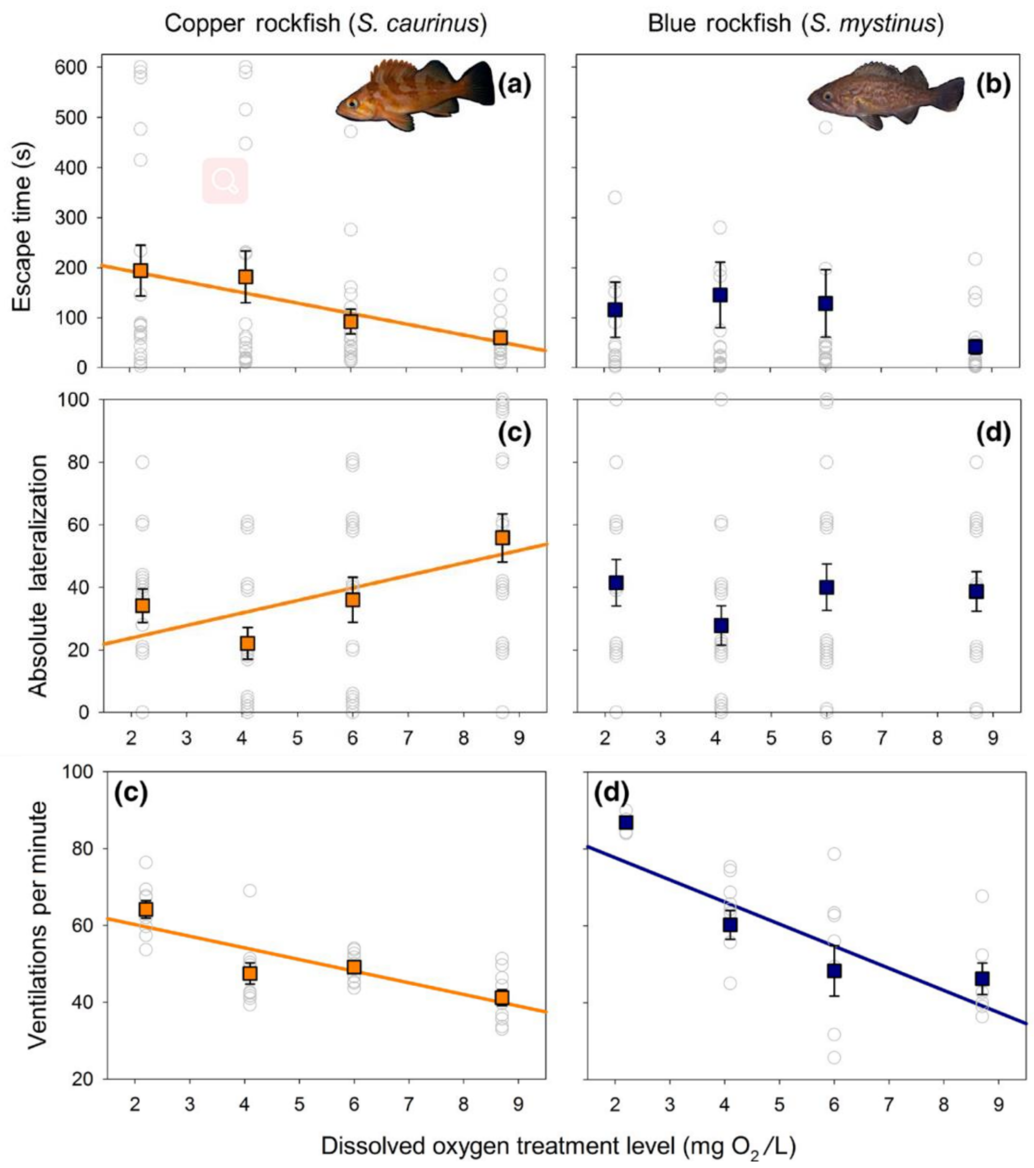


FIGURE 3 The percentage survival of *S. canicula* during embryogenesis under different climatic conditions. Dissimilar letters denote statistically significant differences between treatment groups. n = 19–21 per treatment group (log-rank (Mantel–Cox) test, $P < 0.05$). [red], died (early stages); [orange], died (later stages); [yellow], hatched

Effects of hypoxia on fish



Among different rockfish species:

- Copper rockfish *Sebastes caurinus* and blue rockfish *Sebastes mystinus* expressed sensitivity to hypoxia, and they increased ventilation rates to gain more oxygen.
- Copper rockfish was more sensitive to hypoxia than blue rockfish.
- Copper rockfish exhibited reduced absolute lateralization and increased escape time at the lowest DO levels, whereas blue rockfish did not vary with oxygen level.
- Thus blue rockfish have more chance to survive when hypoxia happens.

Absolute lateralization (LA)

$$L_A = \frac{|\#\text{right turns} - \#\text{left turns}|}{\#\text{right turns} + \#\text{left turns}} \times 100,$$

Mattiasen et al., 2020

Effects of hypoxia on marine organisms from different habitats

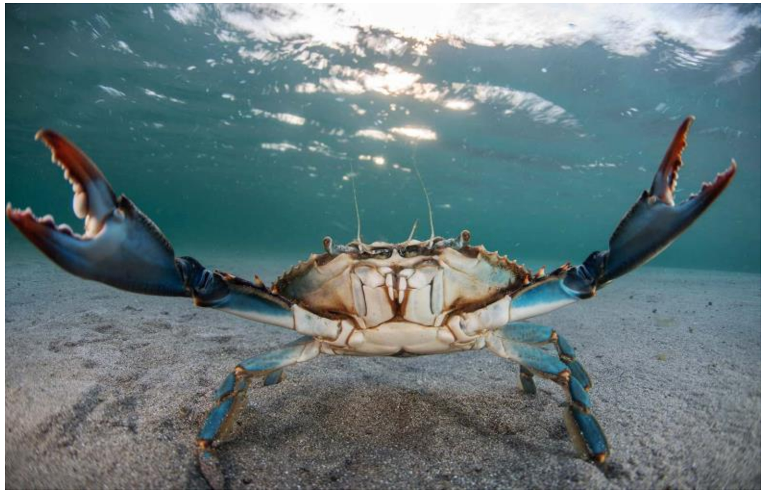
- Animals from low-oxygen habitats exhibit a range of physiological, morphological, and behavioral adaptations to hypoxia.
- Terebellid worms *Neoamphitrite* sp. with large branches and high hemoglobin levels can survive in the extremely low oxygen levels found at 400 m depth in the Costa Rica Canyon. (Breitburg et al ., 2018)
- Off Oregon and central California, some rockfishes inhabited the oxygen minimum zone at depths of 600–1,000 m and were adapted to low-oxygen conditions (Jacobson & Vetter, 1996).
- In contrast, rockfish species that inhabit coastal zones, may not be adapted to low-oxygen conditions (Jacobson & Vetter, 1996).

Terebellid worms *Neoamphitrite* sp.

Sebastolobus alascanus

Sebastolobus altivelis
(mainly 800-1000 m depth)

Effects of hypoxia on crustacean at different stages



Blue crab *Callinectes sapidus*

Stone crab Menippe mercenaria

the king crab
Paralithodes camtschaticus

Squat lobster
Pleuroncodes monodon

- Generally, smaller juveniles of crustacean were more sensitive to hypoxia than larger conspecifics.
- And neither life stage was able to survive short periods of severe hypoxia.

Gravinese, 2020

Effects of hypoxia on abalone

- The combination of hypoxia and thermal stress reduced the survival two abalones, but the hybrid *Haliotis discus hannai* ♀ × *Haliotis fulgens* ♂ (DF) had higher survival capacity than *H. discus*. (Shen et al., 2020)

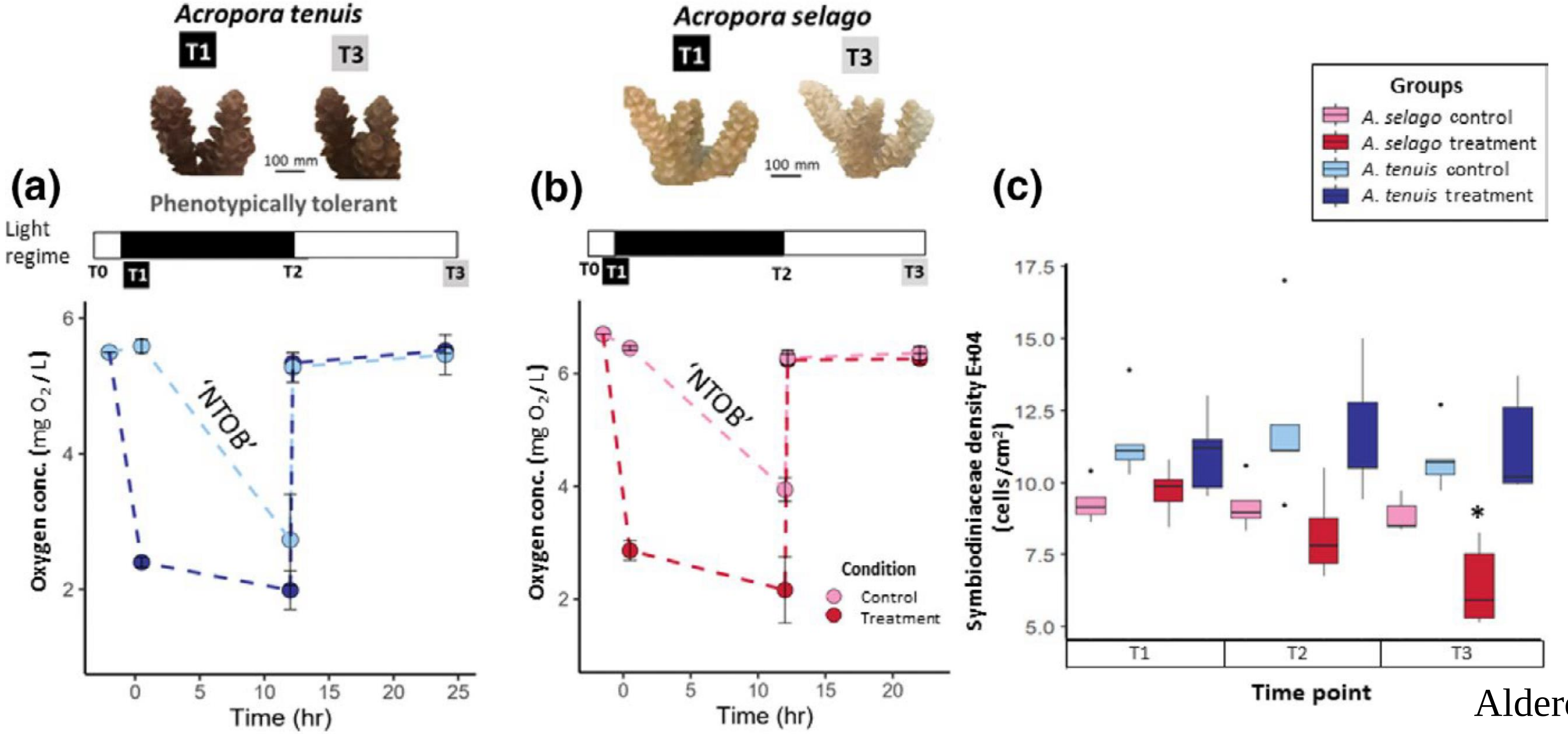
Haliotis discus hannai

hybrid *Haliotis discus hannai* ♀ × *Haliotis fulgens* ♂ (DF)

Effects of hypoxia on corals

- Response of common reef-building corals from the Great Barrier Reef to hypoxia:

1) *Acropora tenuis*, environmentally resilient, exhibited bleaching resistance
2) *Acropora selago*, environmentally susceptible, conversely exhibited a bleaching phenotype response to hypoxia



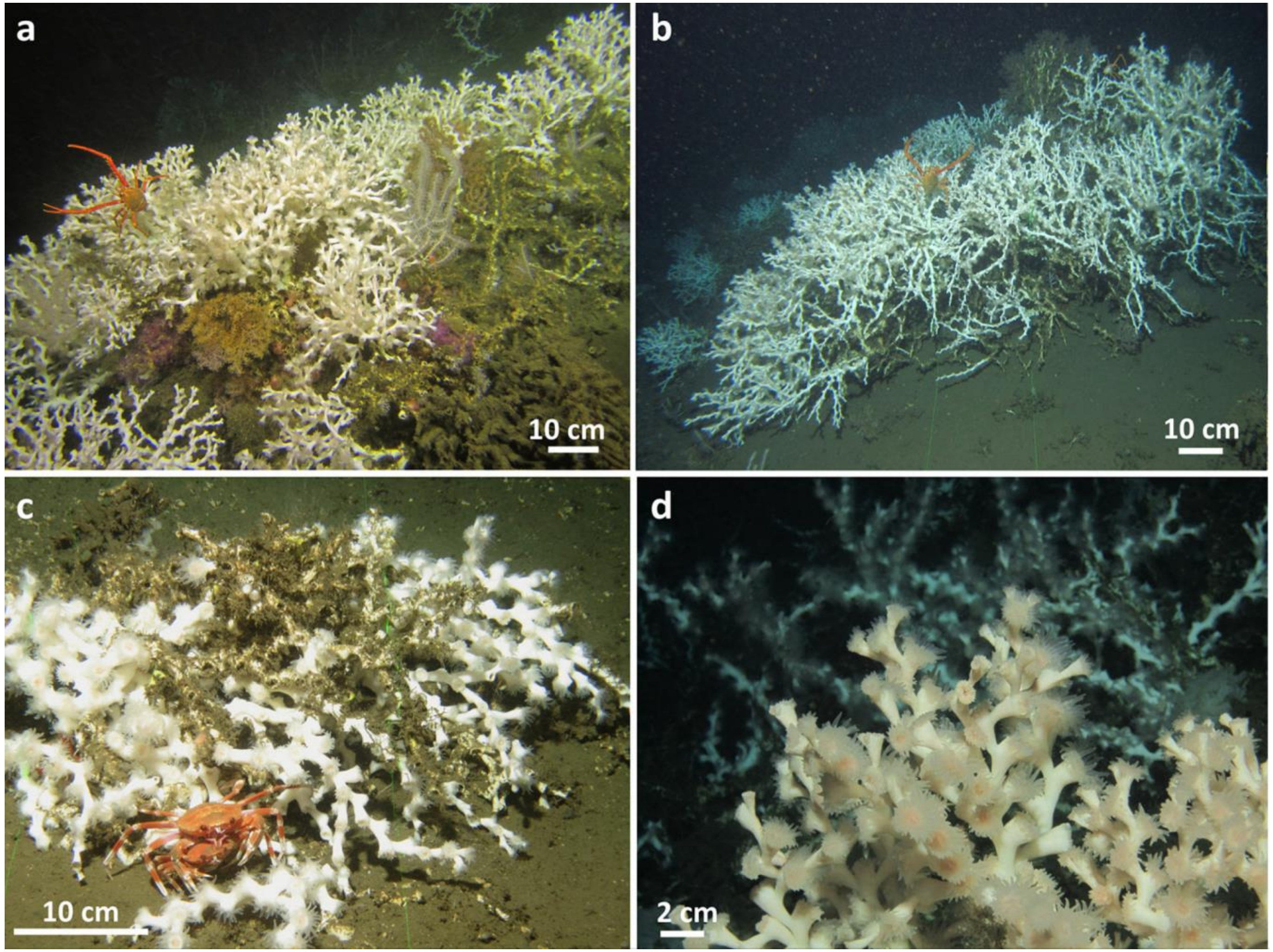
Alderdice et al, 2021

Effects of hypoxia on corals

- Mass coral bleaching and mortality have recently occurred where reefs have experienced chronic low oxygen events. (Altieri et al., 2017)

A low-oxygen event caused extensive mortality of corals and associated organisms in Bocas del Toro, Panama.

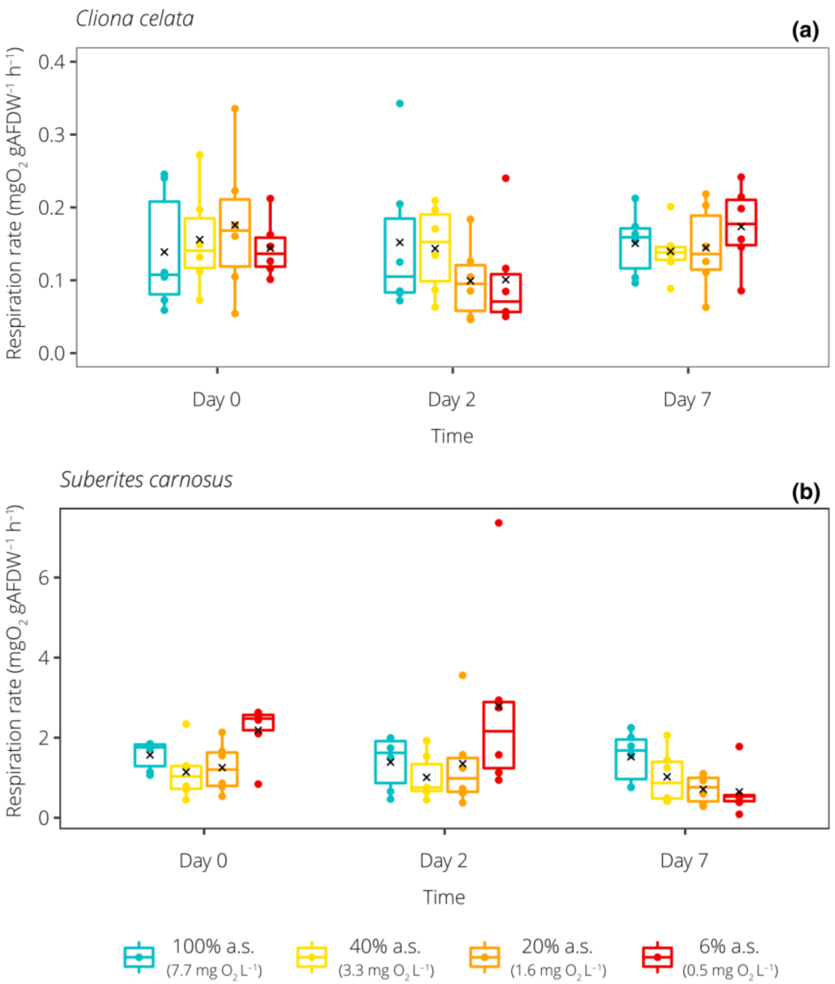
Effects of hypoxia on corals



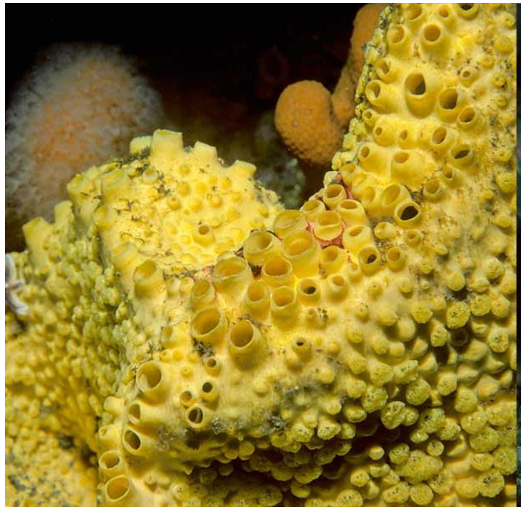
Lophelia pertusa

- Thriving cold-water corals *Lophelia pertusa* observed in the oxygen minimum zone off Angola (350-500 m depth), where the temperatures were 6.8–14.2 ^{o}C and DO was 0.6–1.5 mL/L (Hebbeln et al., 2020).

Effects of hypoxia on Sponges



- Compared to other sessile organisms, sponges are more tolerant of hypoxia.
- The respiration rates of Sponges ***Cliona celata*** **and** ***Suberites carnosus*** were not affected under hypoxia, even when the DO concentration decreased to 0.4 mg O_2/L, showing that sponges can uptake oxygen at very low concentrations in the surrounding environment (Micaroni et al., 2021).
- ***Halichondria panicea*** can feed and respire with oxygen levels down to 4% of air saturation (Mills et al., 2014) .


Cliona celata


Suberites carnosus


Halichondria panicea

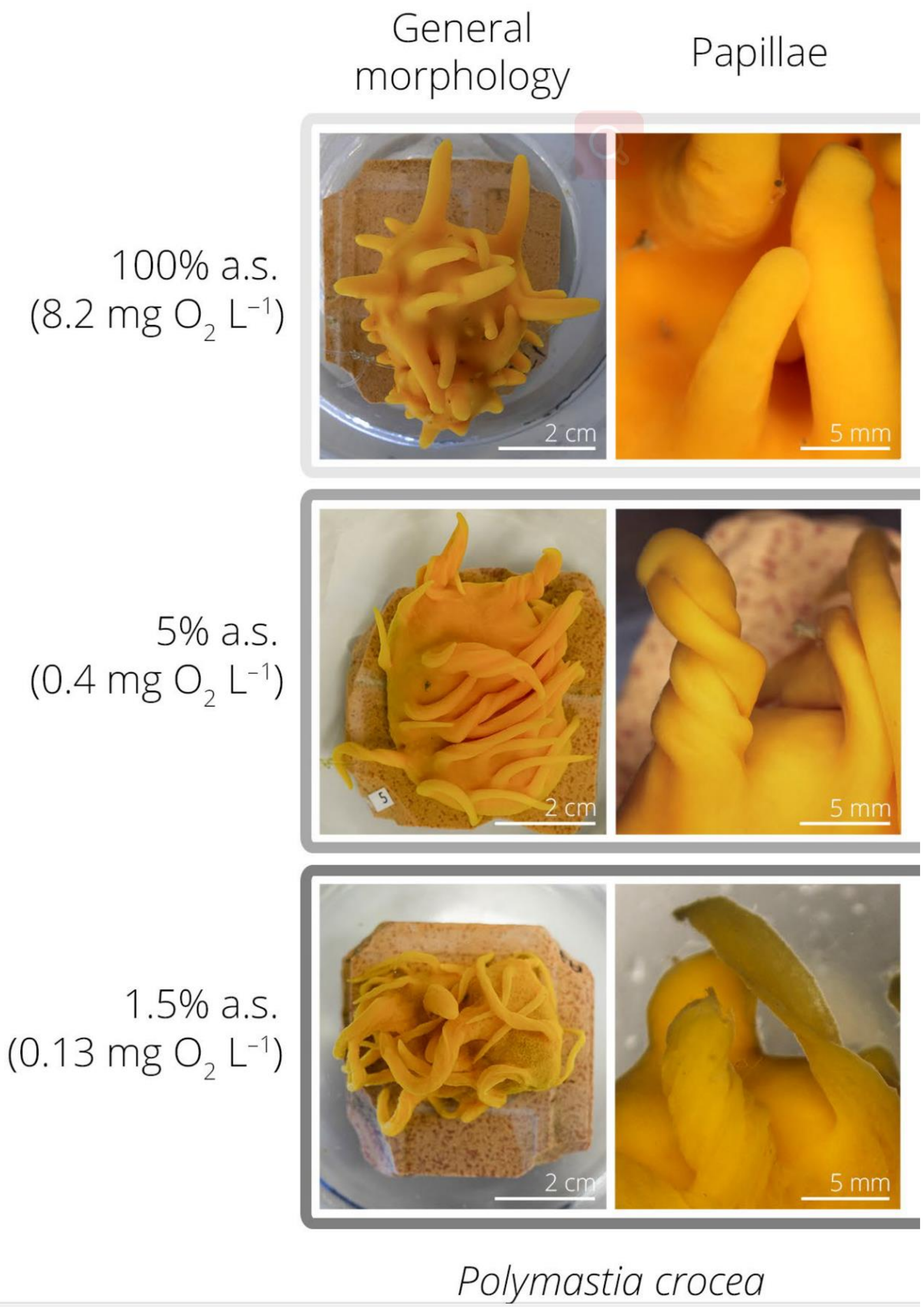
Effects of hypoxia on Sponges

- All the sponges survived in the experimental conditions (3.3, 1.6, 0.5, 0.4 and 0.13 mg O_2/L, over 7-12 days), except *Polymastia crocea*.
- *Polymastia crocea*, which showed significant mortality at the lowest oxygen concentration (0.13 mg O_2/L, lethal median time: 286 h).
- Sub-lethal oxygen thresholds for most sponges are in the range of 6–20% a.s. (0.48–1.56 mg O_2/L), whilst lethal thresholds are lower than 5% a.s. (0.4 mg O_2/L).

Polymastia crocea

Cliona celata

Suberites carnosus



Effects of hypoxia on marine organisms of different taxons

Sponges and sea anemones are most tolerant to hypoxia among these marine organisms.

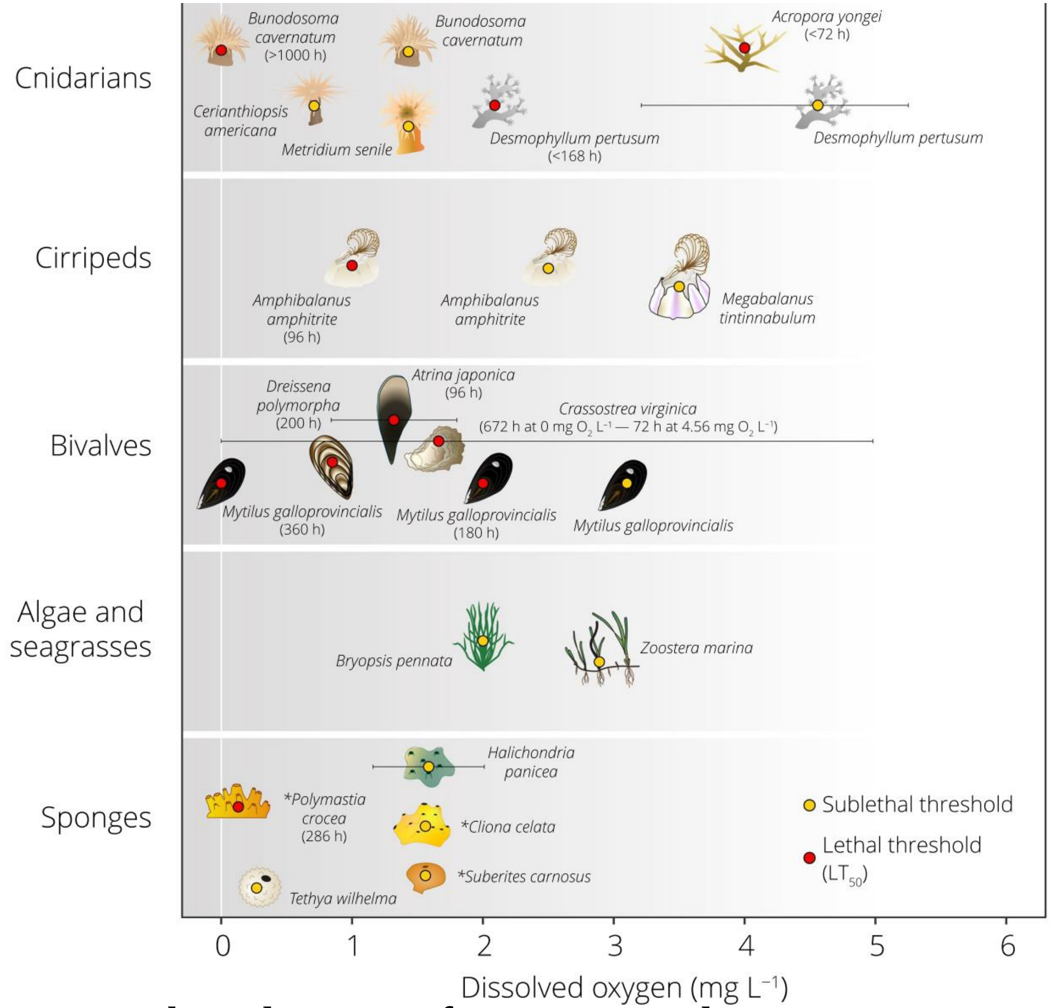


Fig. The tolerance of marine sessile organisms to hypoxia. (Micaroni et al., 2022)

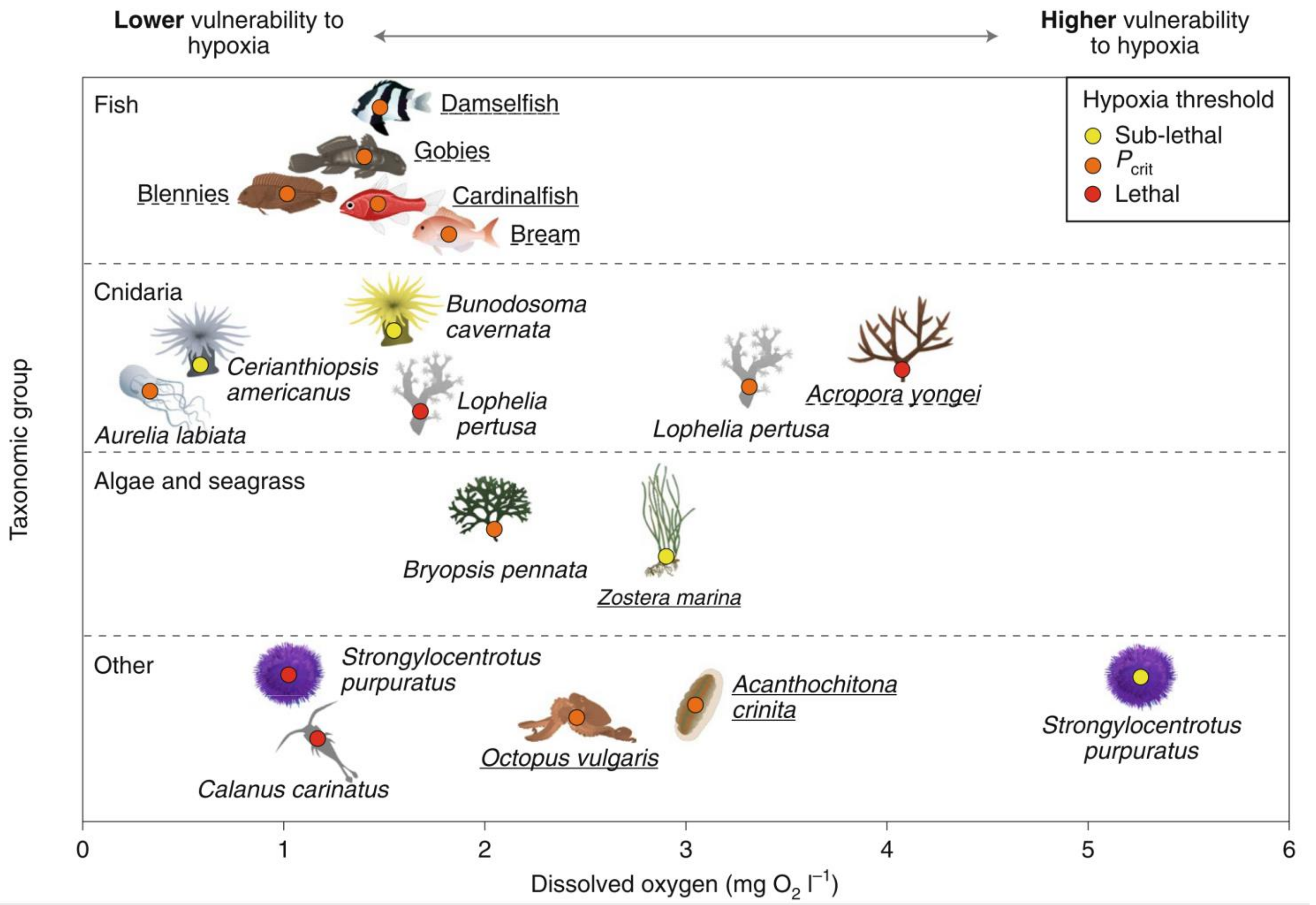


Fig. Hypoxia thresholds of several taxonomic groups (Hughes et al., 2020).

Hypoxia: ecological effects

Oxygen is fundamental to life, which is essential for breathing or 'respiration' by all bacteria, protists, plants and animals that live in the sea. Hypoxia affects marine ecology negatively.

- **Effects of hypoxia on marine organisms in different degree**, e.g., alteration of behavioural and physiological responses, decreased growth rates, reduced fecundity, mortality and etc.
- **Hypoxia changes migration and distribution of organisms.**
- Hypoxia alters the community structure.
- Hypoxia constrains productivity, biodiversity, and biogeochemical cycles.
- Severe hypoxia contributed to dead zones. As oxygen depletion becomes more severe, persistent, and widespread, hypoxia sensitive organisms die one after another, even resulting in dead zones, negatively affecting food security and livelihoods.
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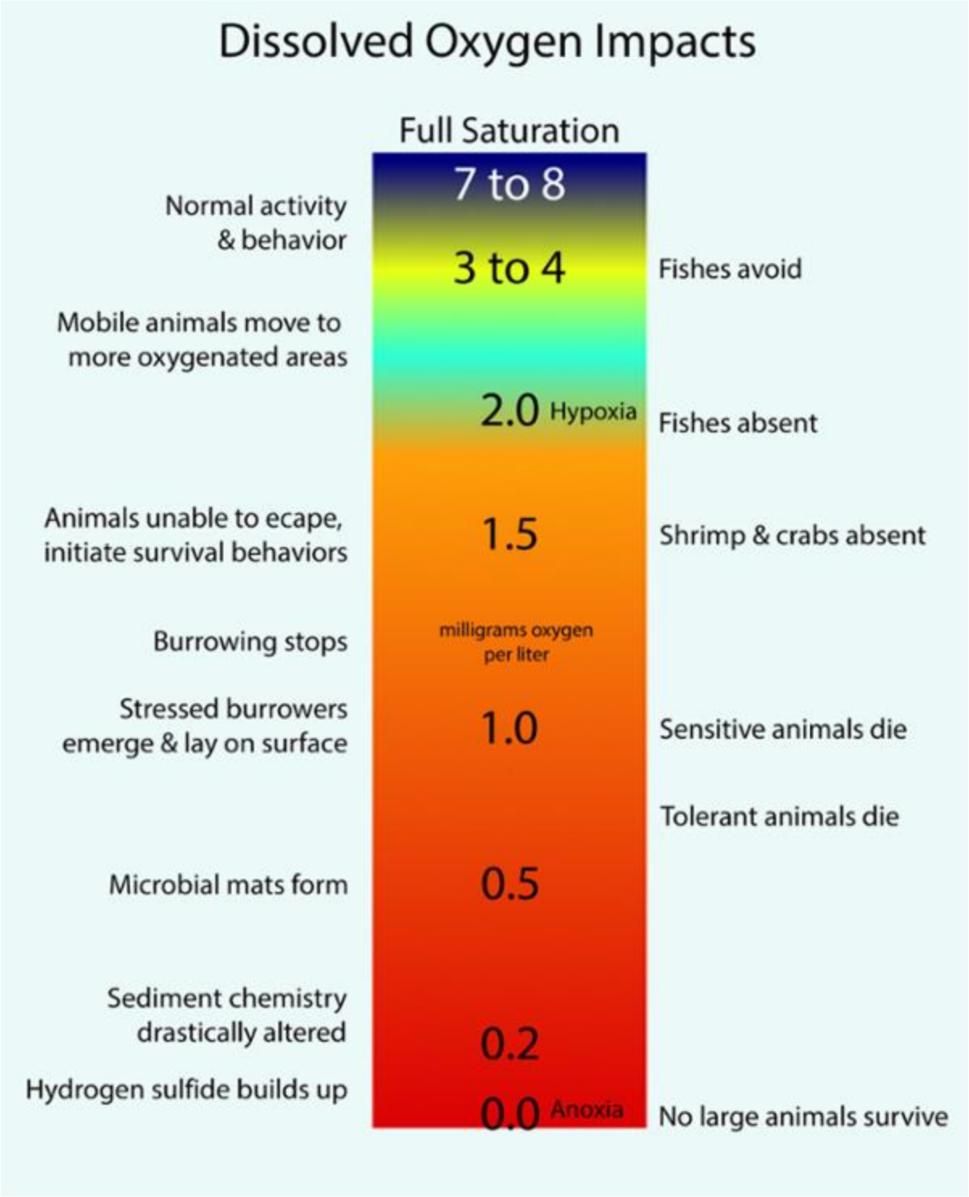


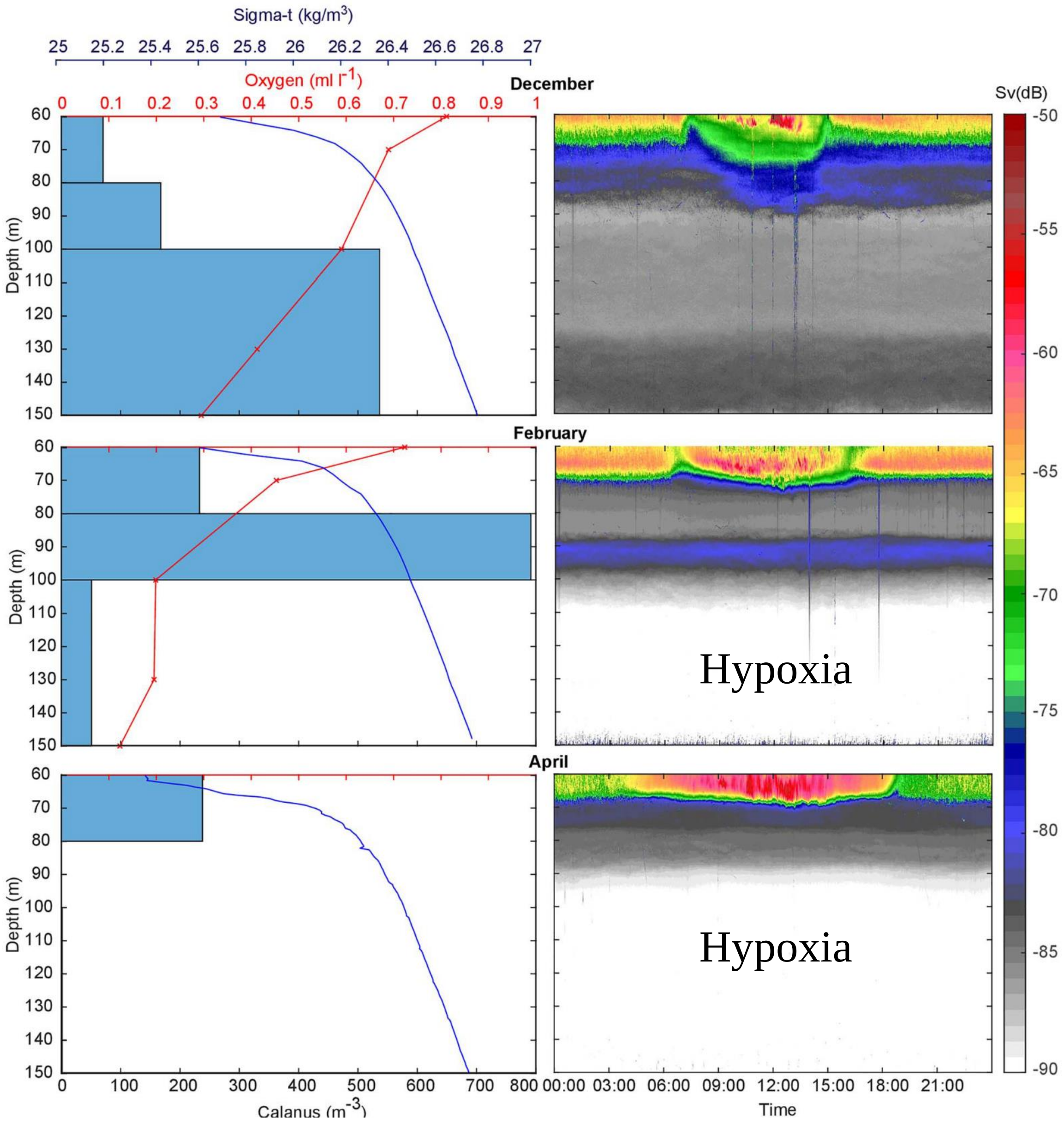
Hypoxia changes migration and distribution of organisms

Habitat compression:

- The presence and expansion of low-water column oxygen reduces diel migration depths, compressing vertical habitat of fishery species and their prey, e.g., *Calanus* sp..

Habitat expension:

- Some hypoxia-tolerant fish and invertebrate species expand their ranges in OMZs where their predators and competitors are excluded.
- Migration into and out of hypoxic waters can allow some animals to utilize oxygen depleted habitats for predator avoidance or to feed on hypoxia-tolerant prey, and then to return to normoxic waters.



Kaartvedt et al., 2021

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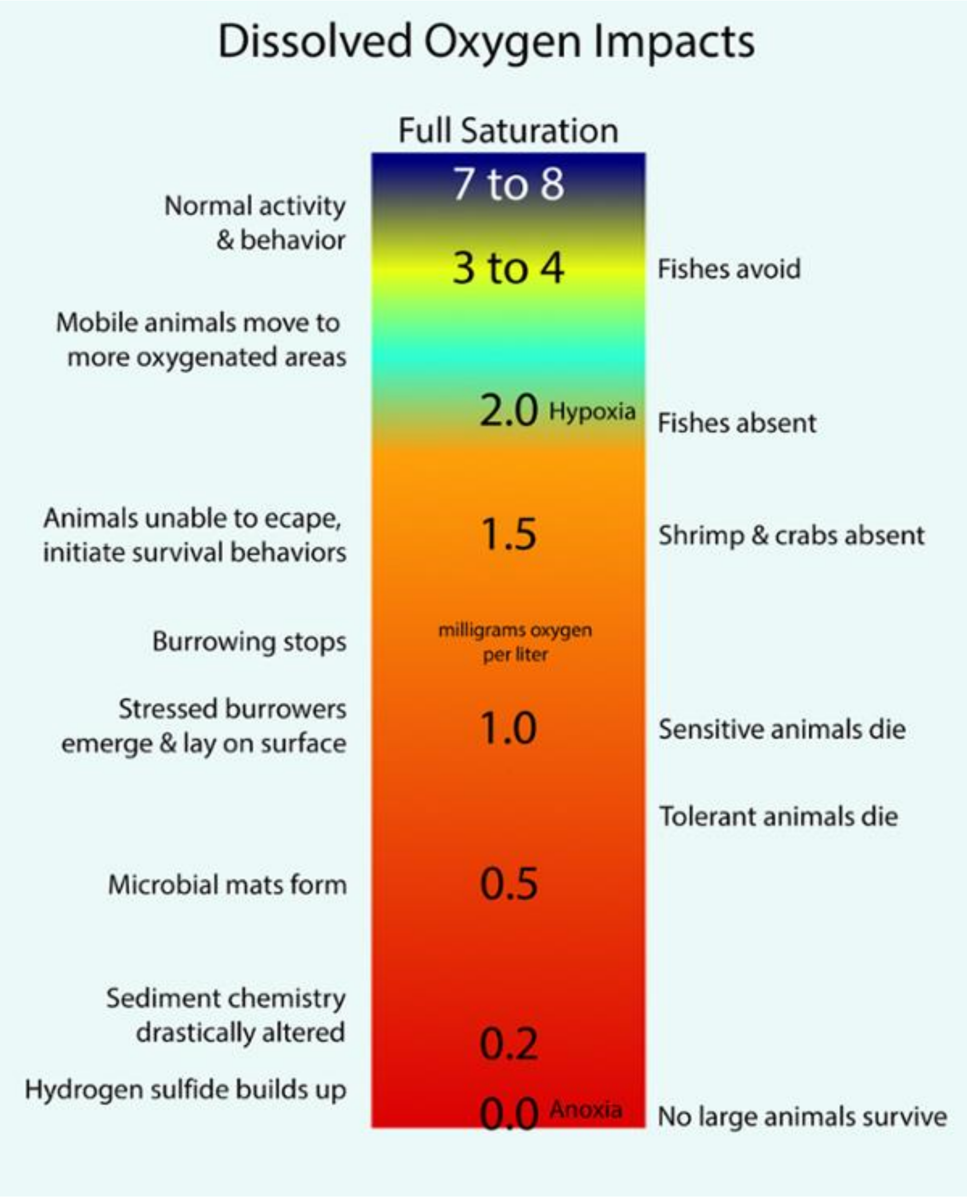
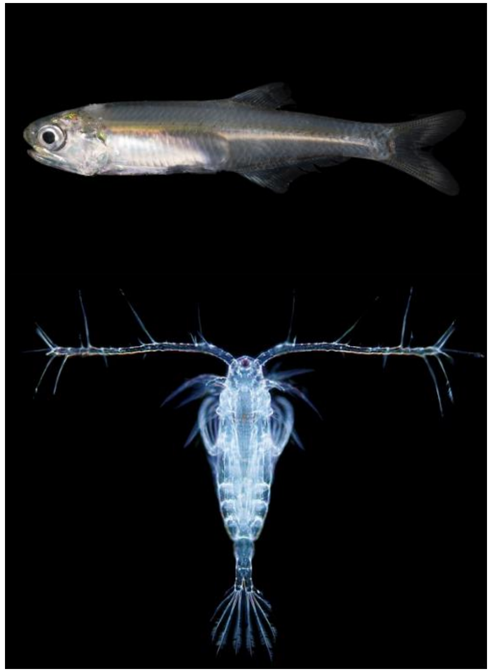


Hypoxia alters the community structure

- Hypoxia happened and lasted about three months every year in Chesapeake Bay, the largest estuary in the United States (Diaz, 2008).
- Hypoxia caused the death or escape of hypoxia sensitive copepods (e.g. *Acartia tonsa*) and bay anchovies *Anchoa mitchilli*, resulting in more bay nettles *Chyrsaora chesapeakei* and comb jellyfish *Mnemiopsis leidyi*.
- Hypoxia changed the community structure, with the dominant groups changed from copepods and planktivorous fish to gelatinous zooplankton.

Anchoa mitchilli

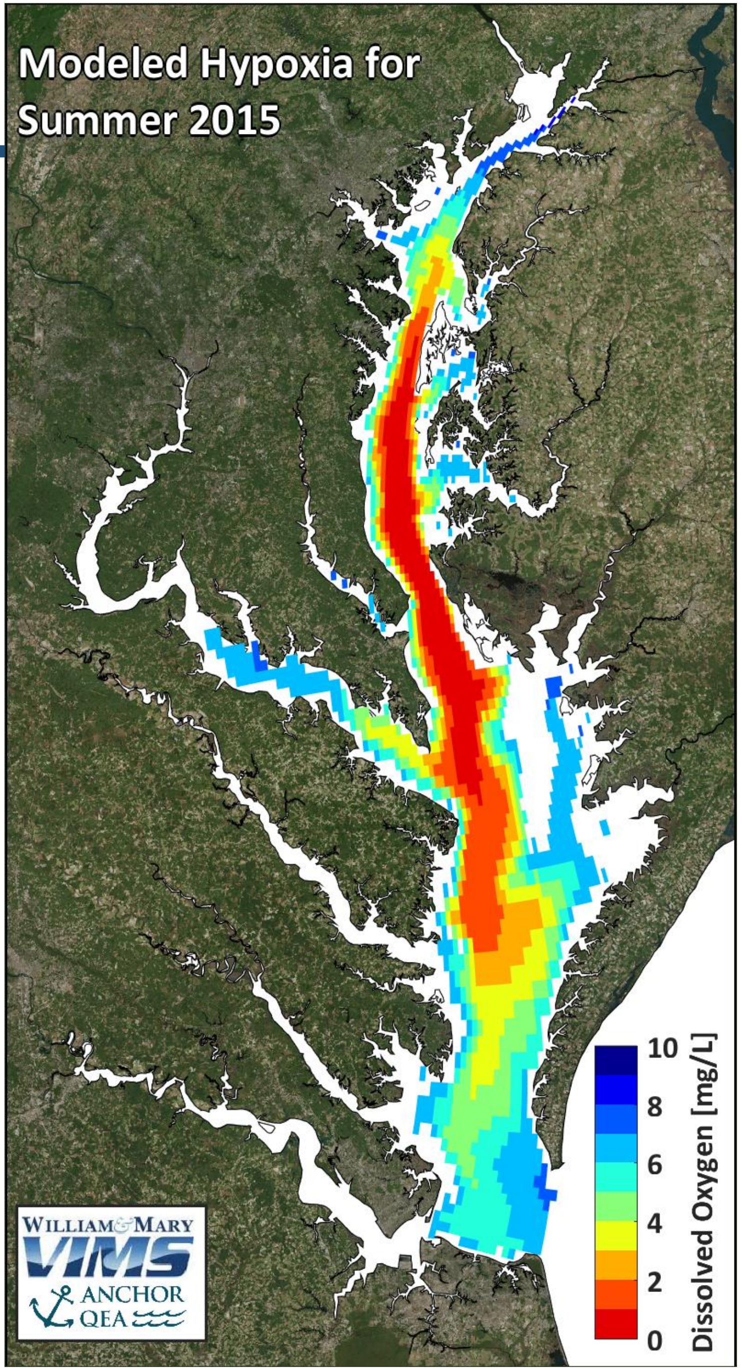


Acartia tonsa

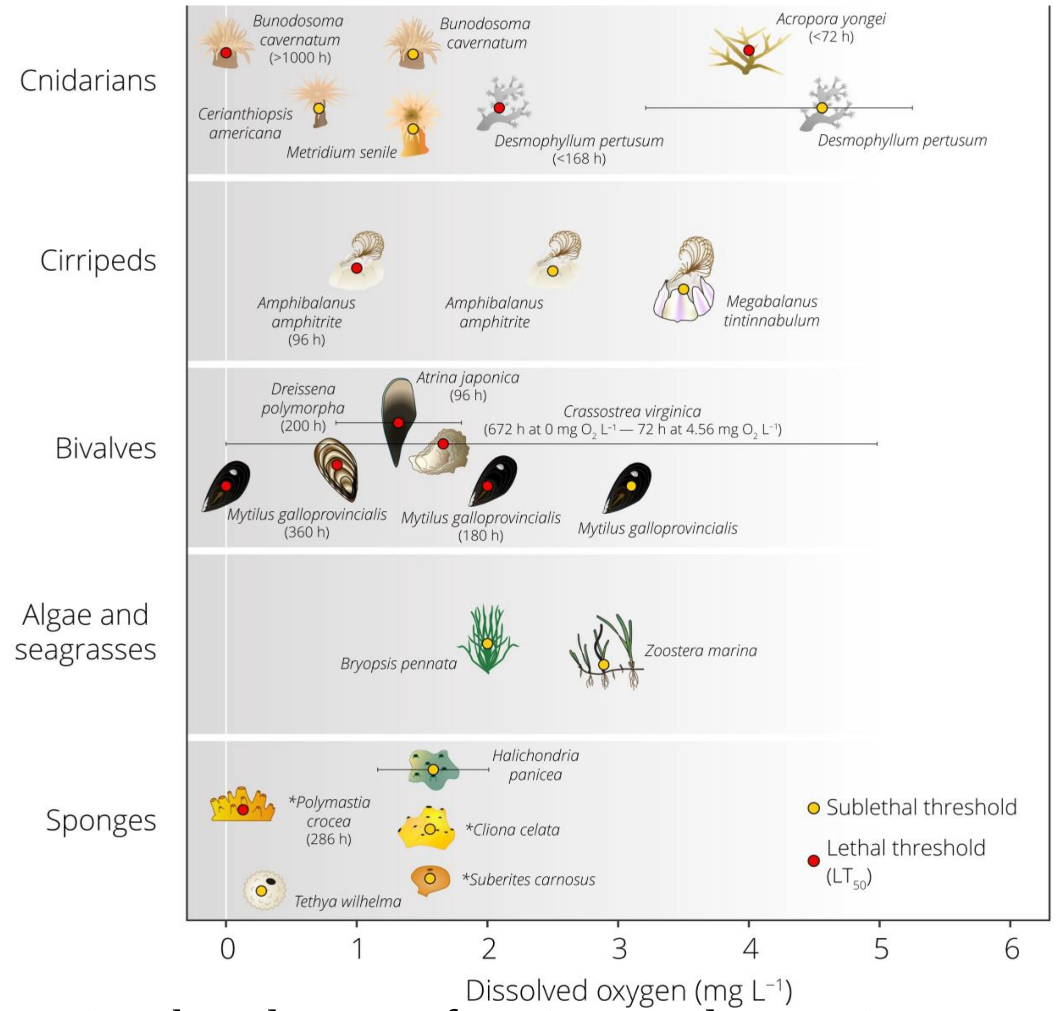
Mnemiopsis leidyi

Chyrsaora chesapeakei

Slater, 2020



Hypoxia alters the community structure



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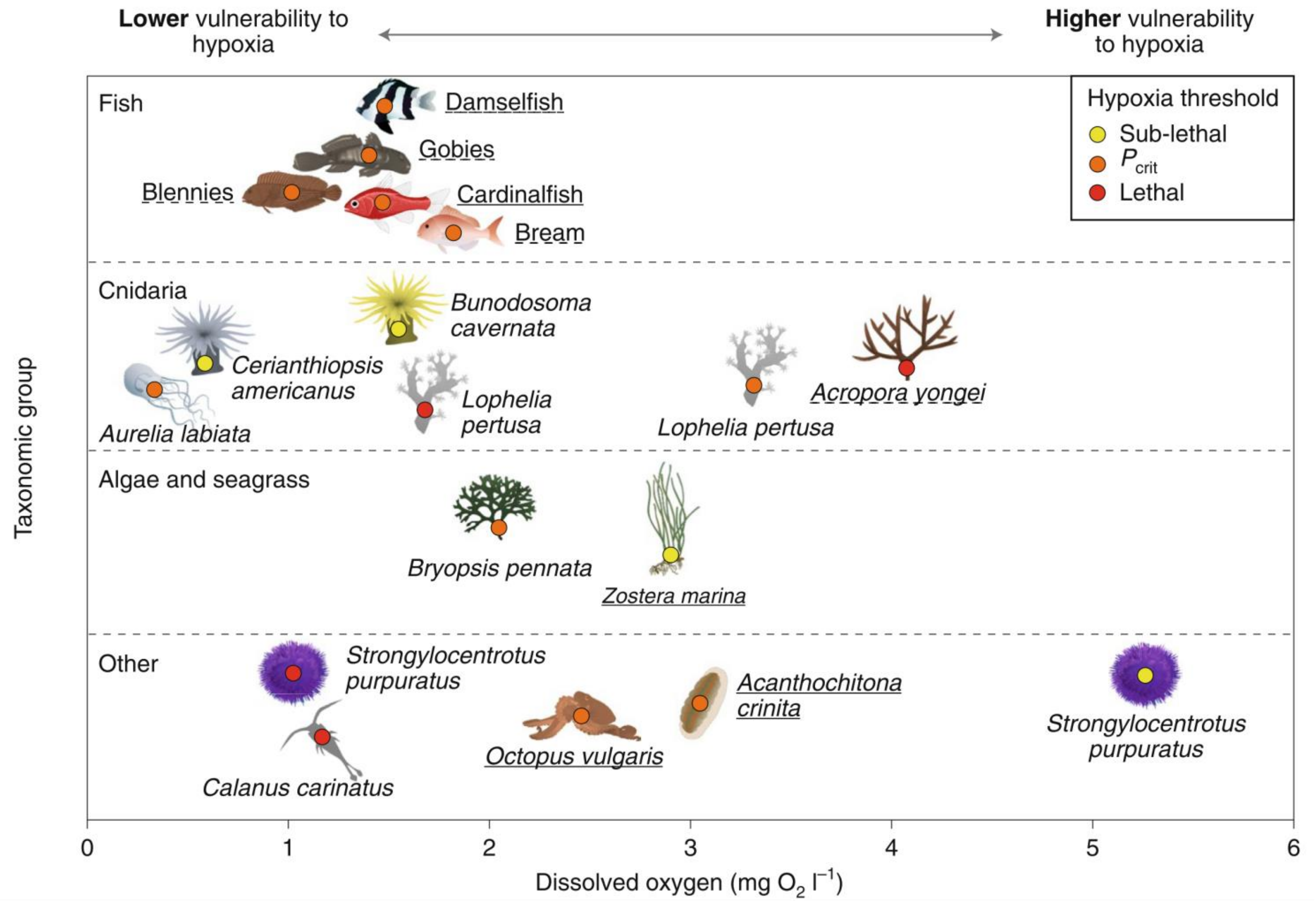

Fig. Hypoxia thresholds of several taxonomic groups (Hughes et al., 2020).

Hypoxia: ecological effects

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- **Effects of hypoxia on marine organisms in different degree**, e.g., alteration of behavioural and physiological responses, decreased growth rates, reduced fecundity, mortality and etc.
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- Hypoxia alters the community structure.
- Hypoxia constrains productivity, biodiversity, and biogeochemical cycles.
- **Severe hypoxia contributed to dead zones.** As oxygen depletion becomes more severe, persistent, and widespread, hypoxia sensitive organisms die one after another, even resulting in dead zones, negatively affecting food security and livelihoods.
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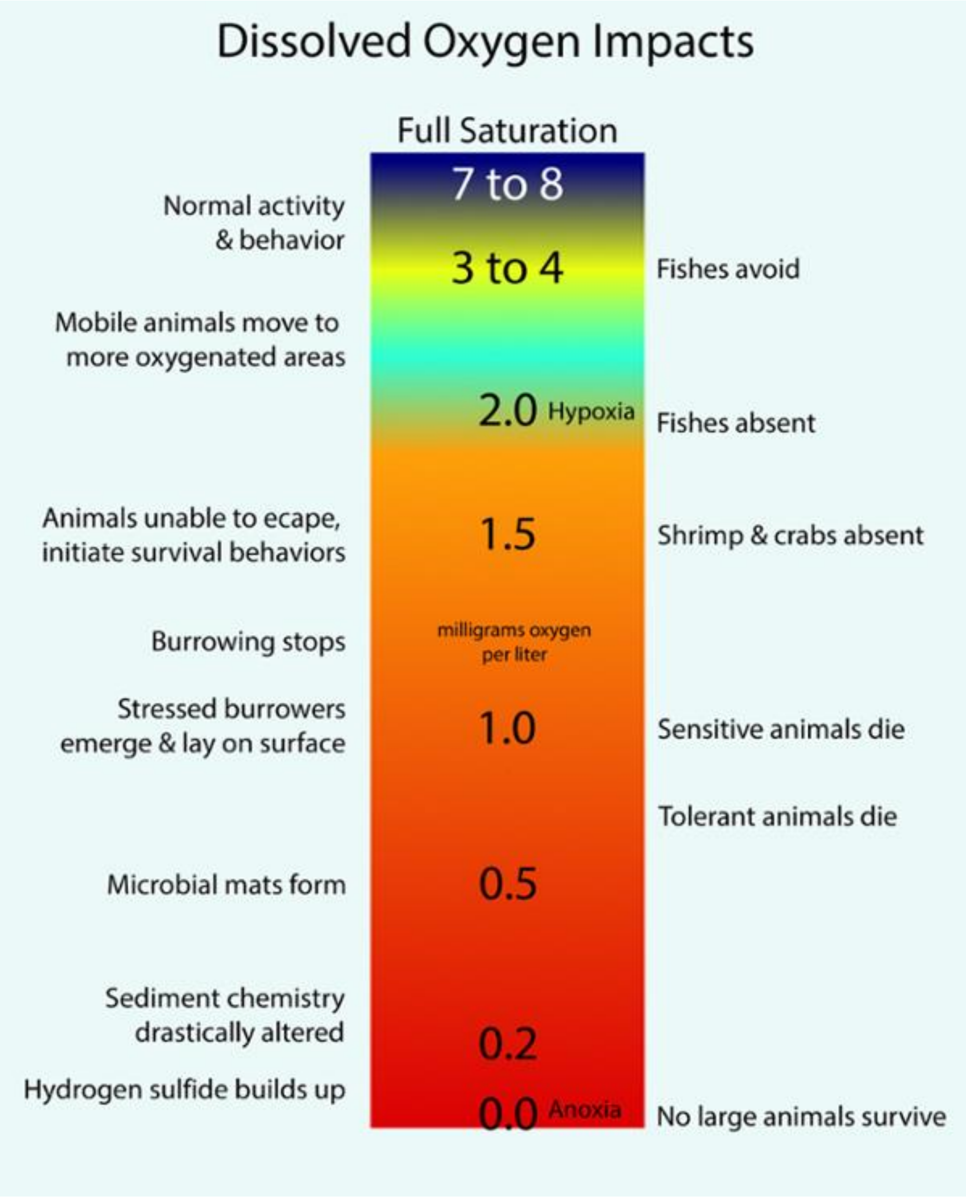
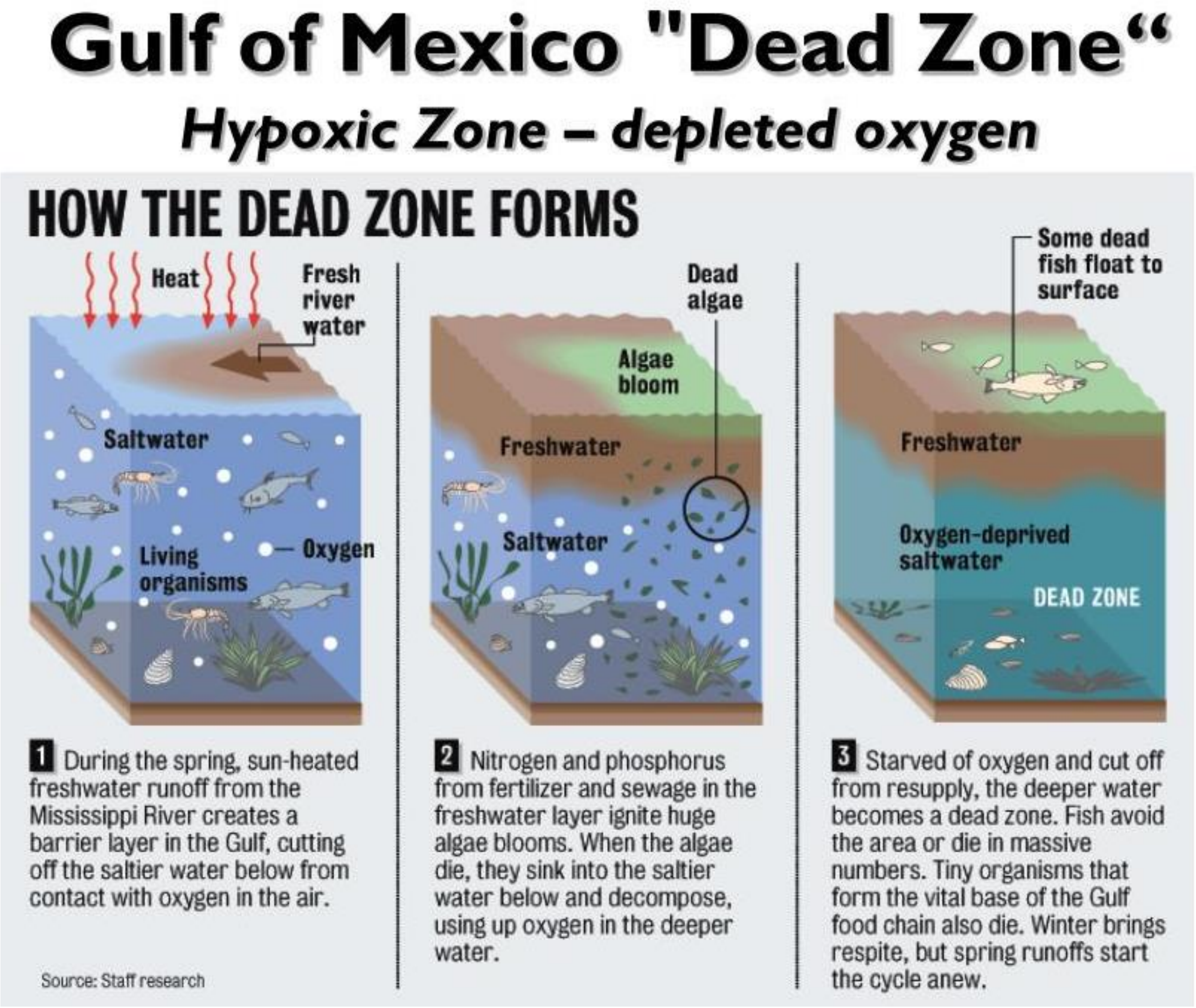


Severe hypoxia contributed to dead zones

- As oxygen depletion becomes more severe, persistent, and widespread, hypoxia sensitive organisms die one after another, even resulting in dead zones, negatively affecting food security and livelihoods.
- Famous dead zone in Gulf of Mexico.
- A prolonged hypoxia event occurred off the Oregon coast in 2006 from July to October, with low-oxygen waters extending through 80% of the water column and covering an area of 3,000 km^2 . A complete absence of fish from rocky reefs that traditionally harbor high abundances and diversity. (Chan et al., 2008).



Severe hypoxia contributed to dead zones

Two Million Dead Fish Appear in Chesapeake Bay due to hypoxia.

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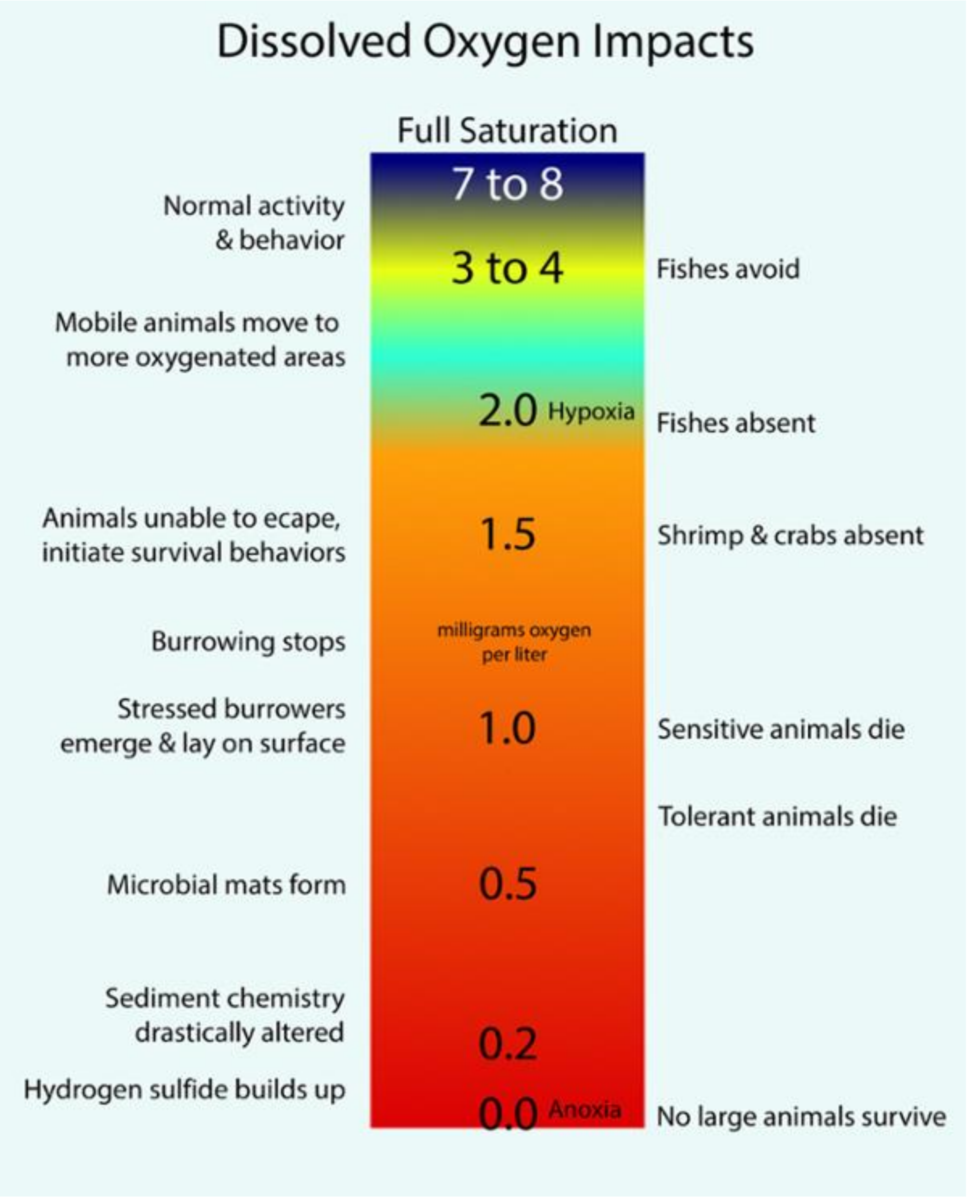
- Hypoxia constrains productivity, biodiversity, and biogeochemical cycles.
- Severe hypoxia contributed to dead zones. As oxygen depletion becomes more severe, persistent, and widespread, hypoxia sensitive organisms die one after another, even resulting in dead zones, negatively affecting food security and livelihoods.
- **Effects of hypoxia on marine organisms would be enhanced by global warming.**



Effects of hypoxia on marine organisms enhanced by global warming

- Ocean hypoxia is often combined with ocean warming and acidification, resulting in multiple stressors on marine organism.
- Acute high temperature exposure impairs hypoxia tolerance in an intertidal fish, e.g., the triplefin fish Bellapiscis medius.
- Mortality of reef-building corals and associated decreasing reef biodiversity in the Caribbean, have been attributed to increased water temperature and lower DO. (Altieri et al., 2017; Johnson et al., 2018).

The triplefin fish *Bellapiscis medius*

Hypoxia: Current Situation and Trend

- **Expansion of low-oxygen zones in both open ocean and coastal waters, which could continue within the next thousand years. Coastal hypoxia is expected to worsen, with the increased occurrence, frequency, intensity and duration of hypoxic events due to global warming and human activities. (Diaz & Rosenberg, 2011).**

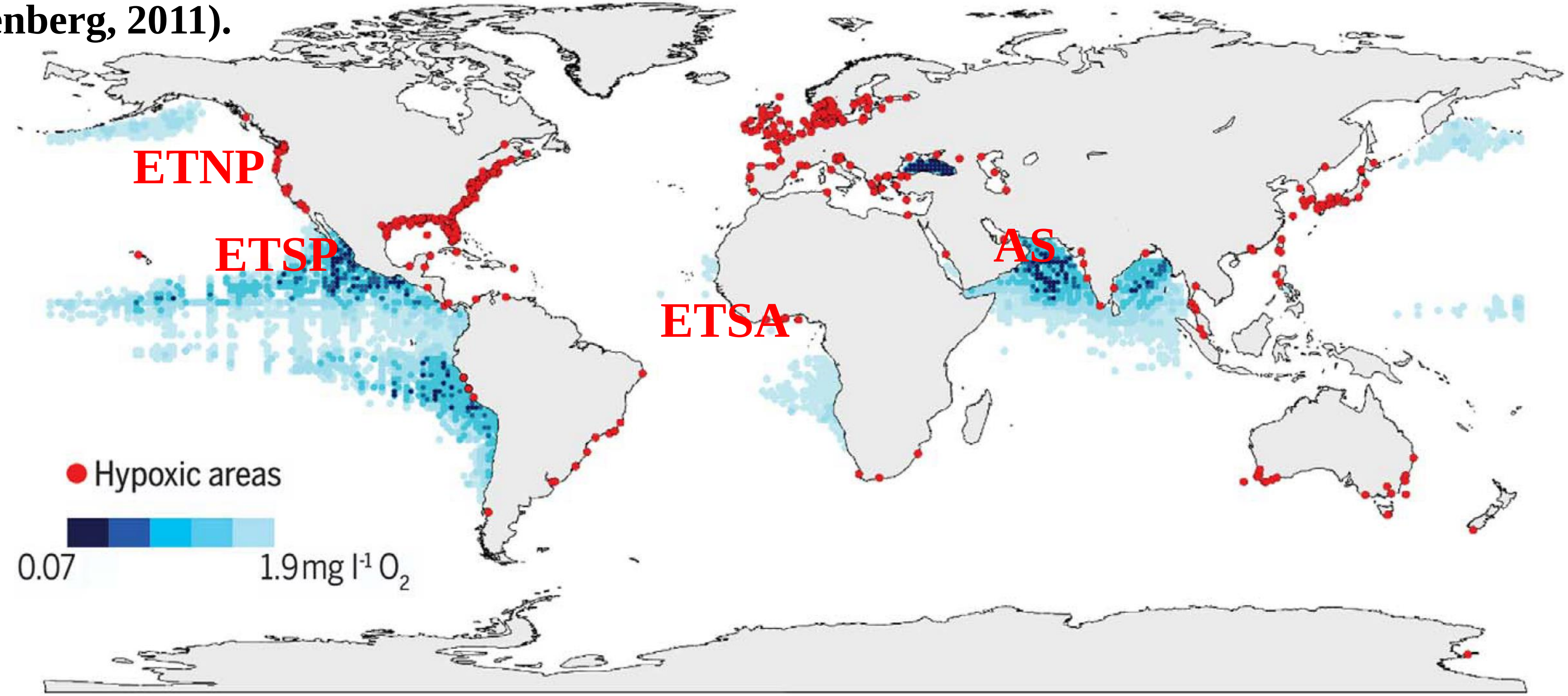
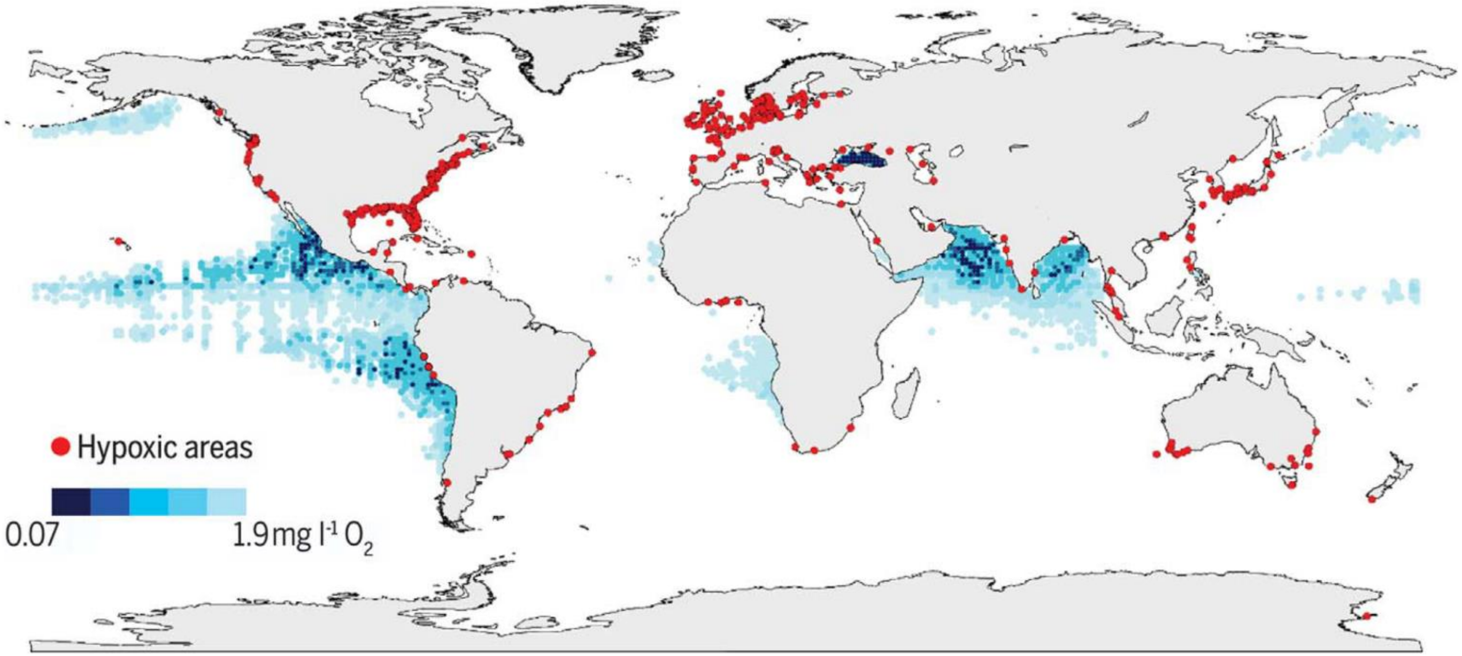


Fig. Low and declining oxygen levels in the open ocean and coastal waters affect processes ranging from biogeochemistry to food security (Breitburg, et al, 2018)

The map of Biodiversity hotpots

The hypoxic zones
vs
biodiversity hotpots



- **The hypoxic zones coincide with most biodiversity hotpots**
- From late spring to autumn, hypoxia often happens in shallow coastal habitats, such as seagrass beds, coral reefs, and oyster reefs, which serve as critical nursery habitats for the many commercially and ecologically important juvenile crustaceans and fish.
- Productivity in coastal waters is high and provides abundant food to human, as well as oxygen.

Efforts to reduce hypoxia

- **Live a green lifestyle.**
- **Decrease the greenhouse gas (e.g. CO_2) emissions to slow down the global warming.**
- **Reduce anthropogenic nutrients inputting into the coastal waters.**

Case 1: Nitrogen management favors improved oxygen conditions in Long Island Sound

- **Background:** Long Island Sound, a large urbanized estuary, on the U.S. East Coast near New York City. The estuary has experienced summer hypoxia since the 19th century following the onset of intensive agriculture, hypoxia grew worse in the 1970s and hypoxic areas expanded in the 1980s.
- **Nitrogen management make effects:**
- The Total Maximum Daily Load aimed at reducing nitrogen loads from wastewater treatment plants throughout the watershed, since the late 1980s.
- Total nitrogen concentrations have decreased (0.06 mg/L per decade), while Bottom dissolved oxygen has increased (0.48 m/L per decade). The hypoxic area has reduced since 1994.

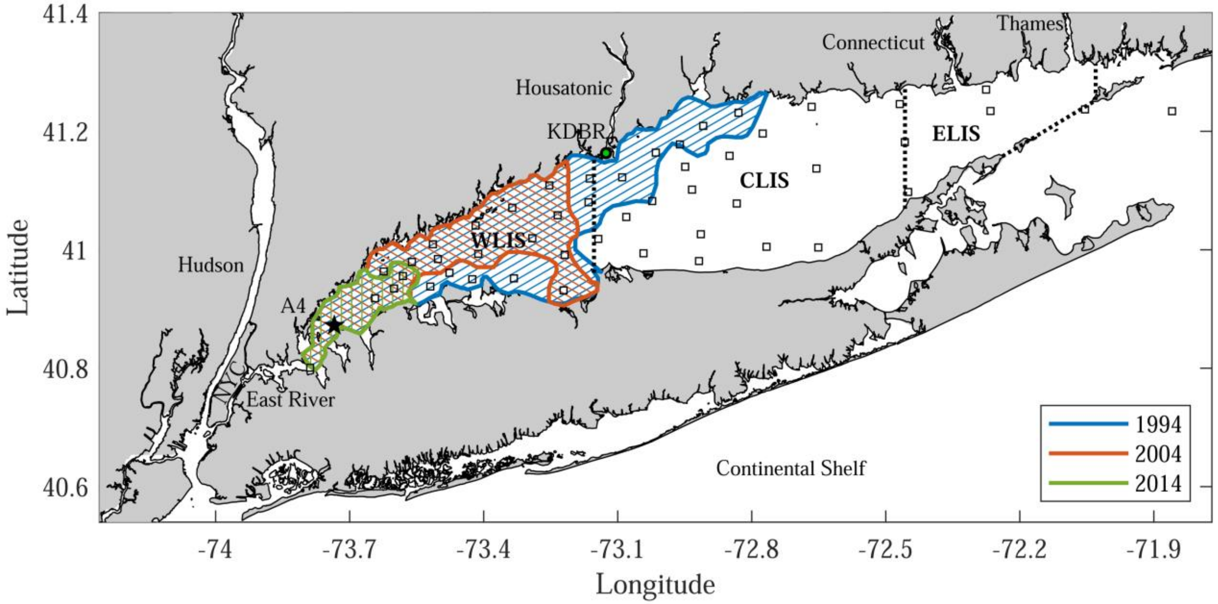


Fig. Long Island Sound location map with hypoxic areas in August

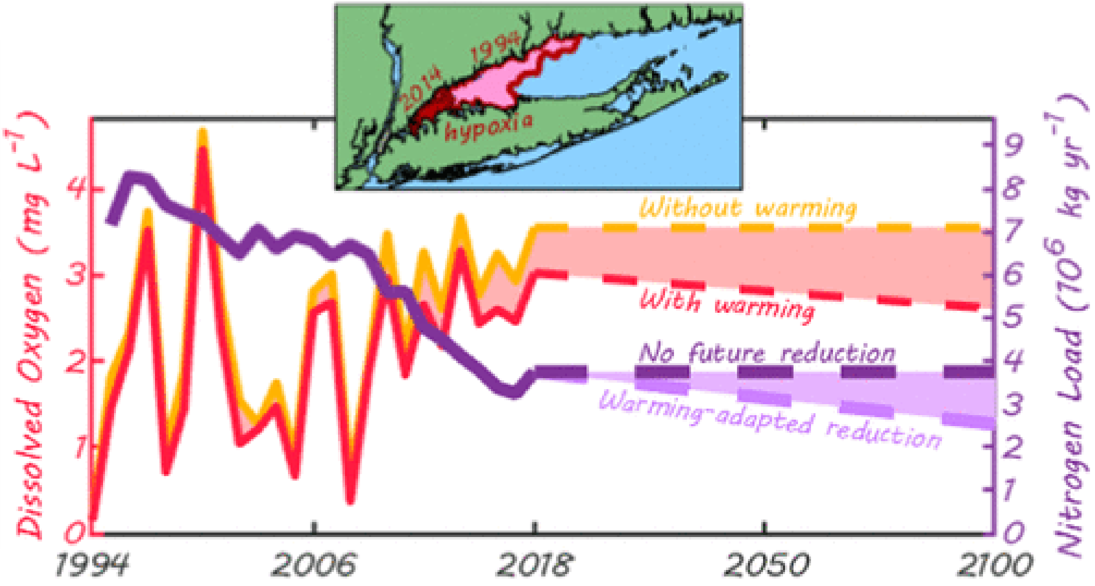
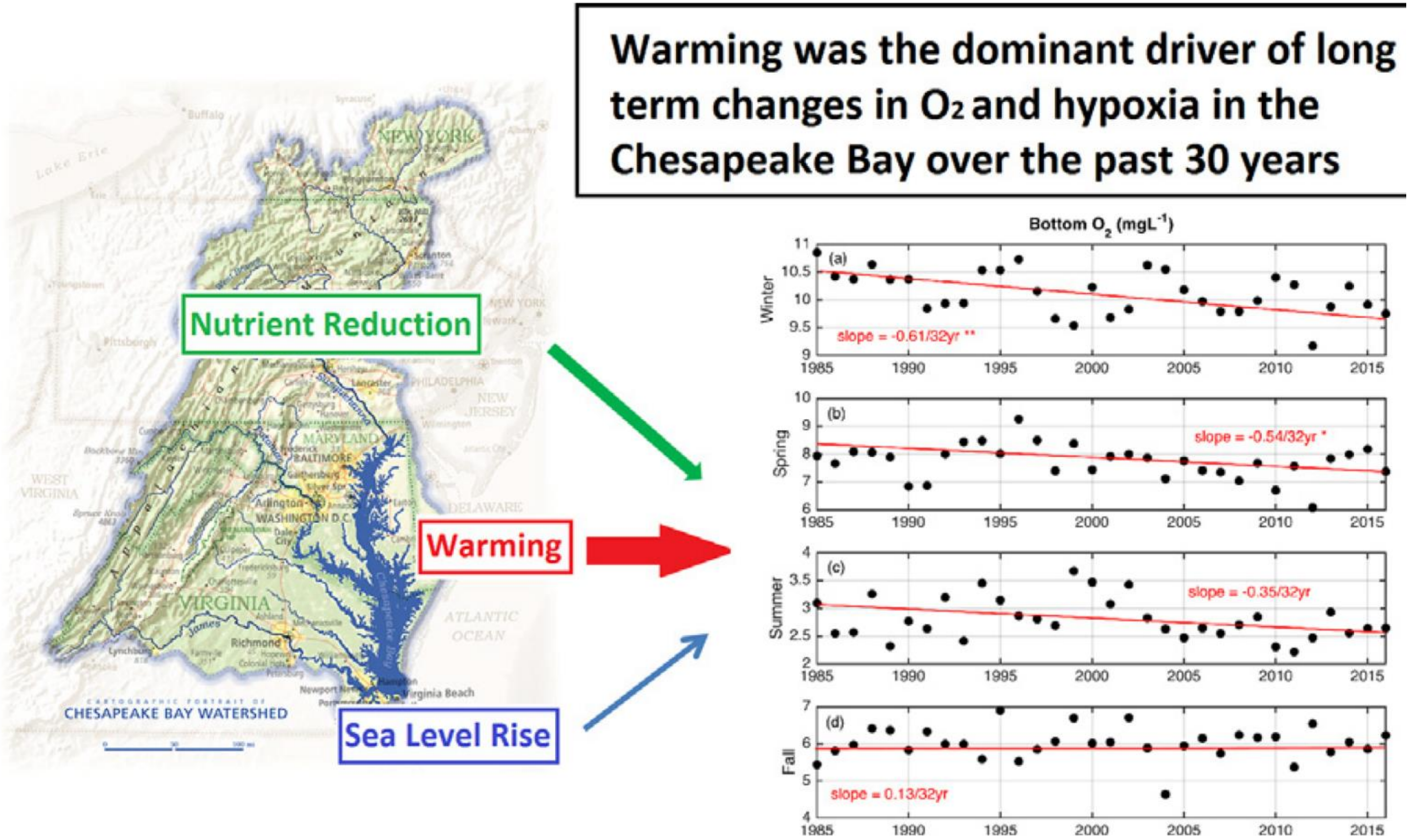


Fig. The responses of DO to managed nitrogen load reductions and climate change.

(Whitney & Vlahos, 2021)

Case 2: Nitrogen management mitigated hypoxia in Chesapeake Bay

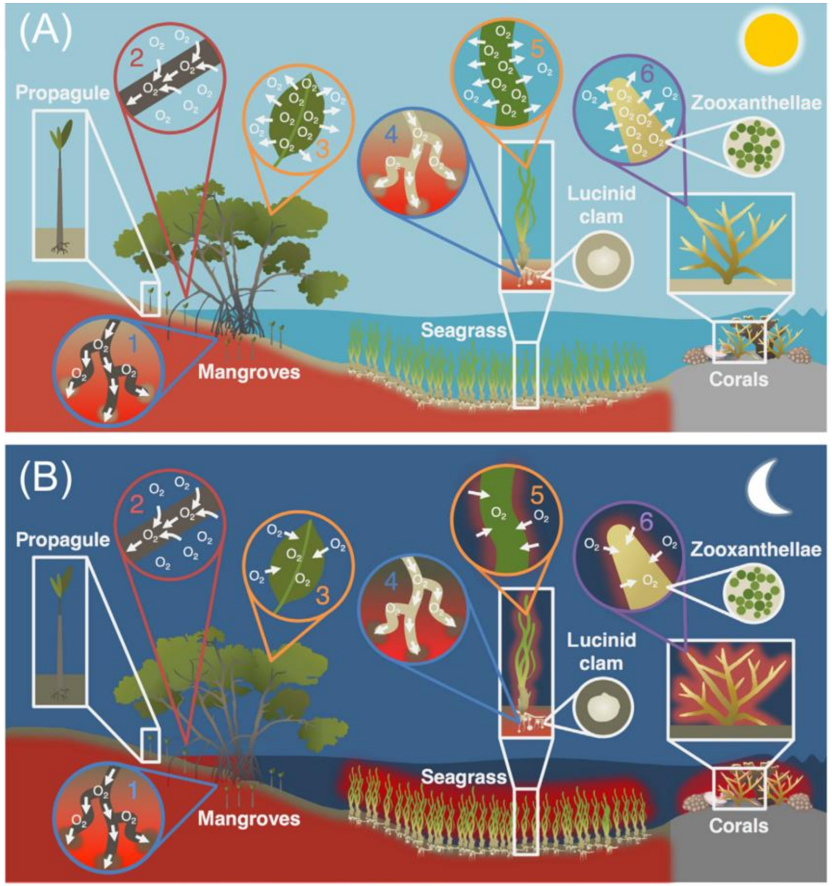
- Chesapeake Bay has suffered from seasonal hypoxia since the 1950s.
- Warming was the dominant factor to cause the long-term declining trend of O_2 in Chesapeake Bay over the past three decades.
- **Nutrient reduction caused moderate increases in O_2** and the effect of sea level rise was small.
- **Climate change erased the benefit of nutrient management to mitigate hypoxia.**



Ni et al., 2020

Efforts to reduce hypoxia

- **Protect marine environment and ecosystem, for examples, coral reefs, seagrass beds, mangrove and etc.**



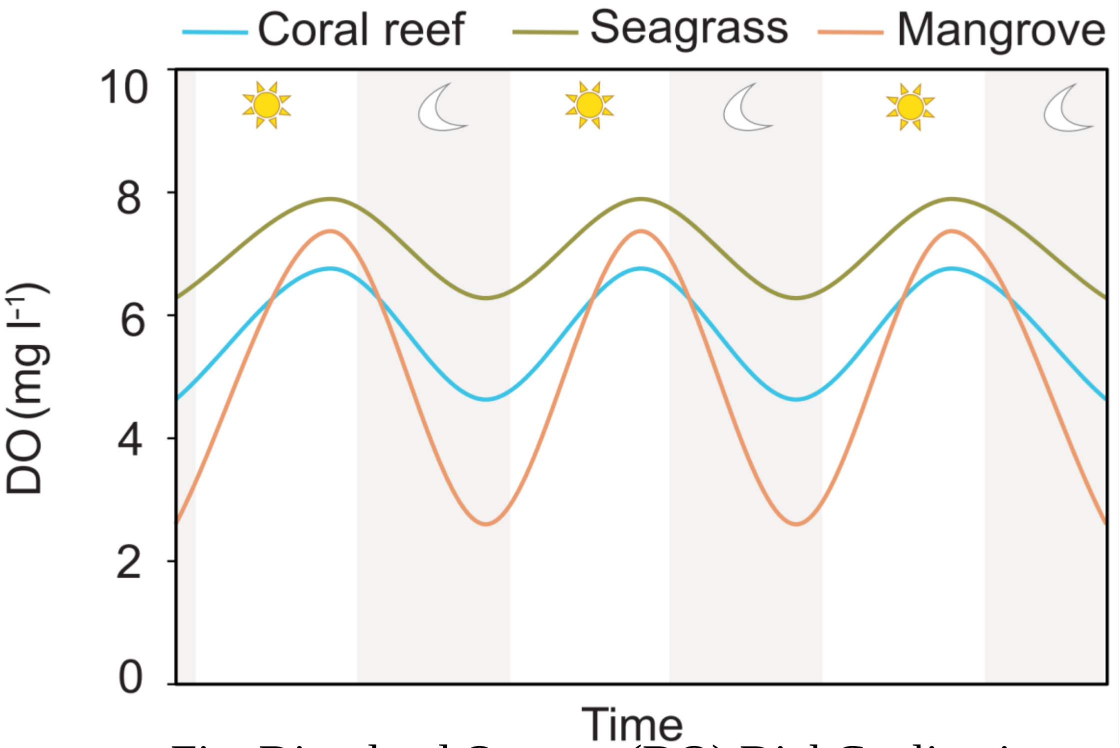


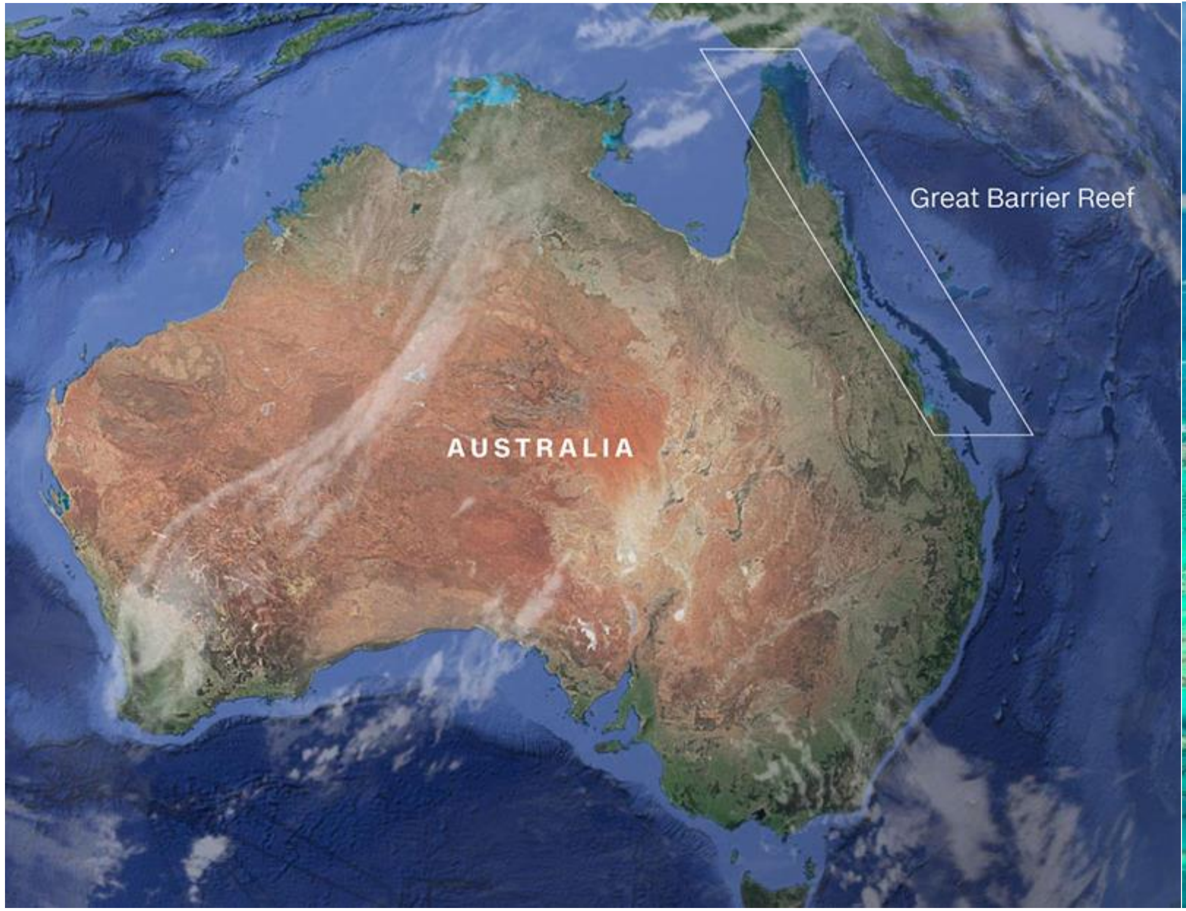
Fig. Dissolved Oxygen (DO) Diel Cycling in Tropical Coastal Habitats

Fig. Interactions of Mangroves, Seagrasses, and Corals with Oxygen Across the Coastal Tropical Seascape.

Altieri et al., 2021

Efforts to reduce hypoxia

- **Create marine protected areas and no-catch zone**

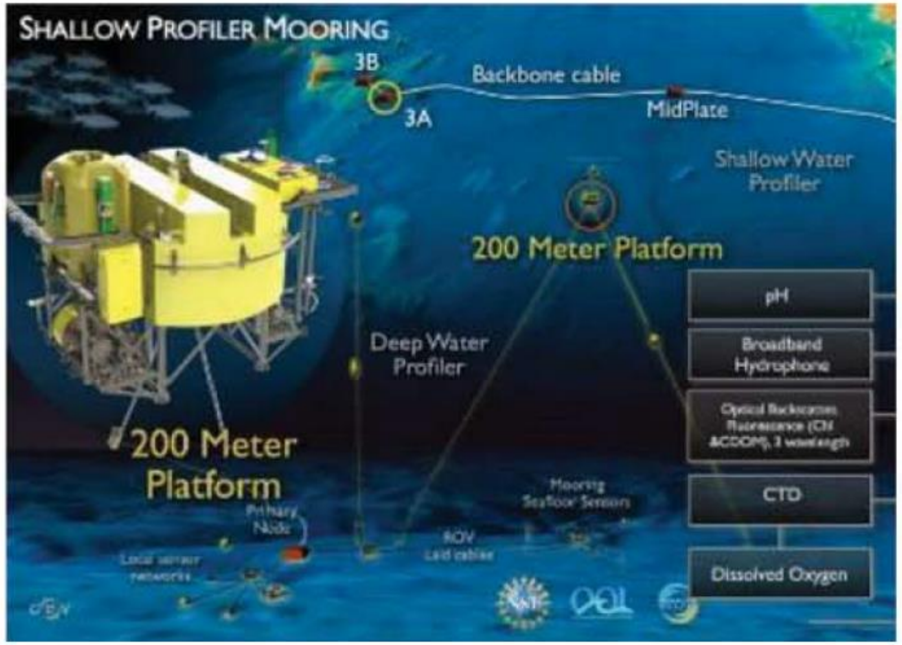


Great Barrier Reef Marine Park

Florida Keys National Marine Sanctuary

Efforts to reduce hypoxia

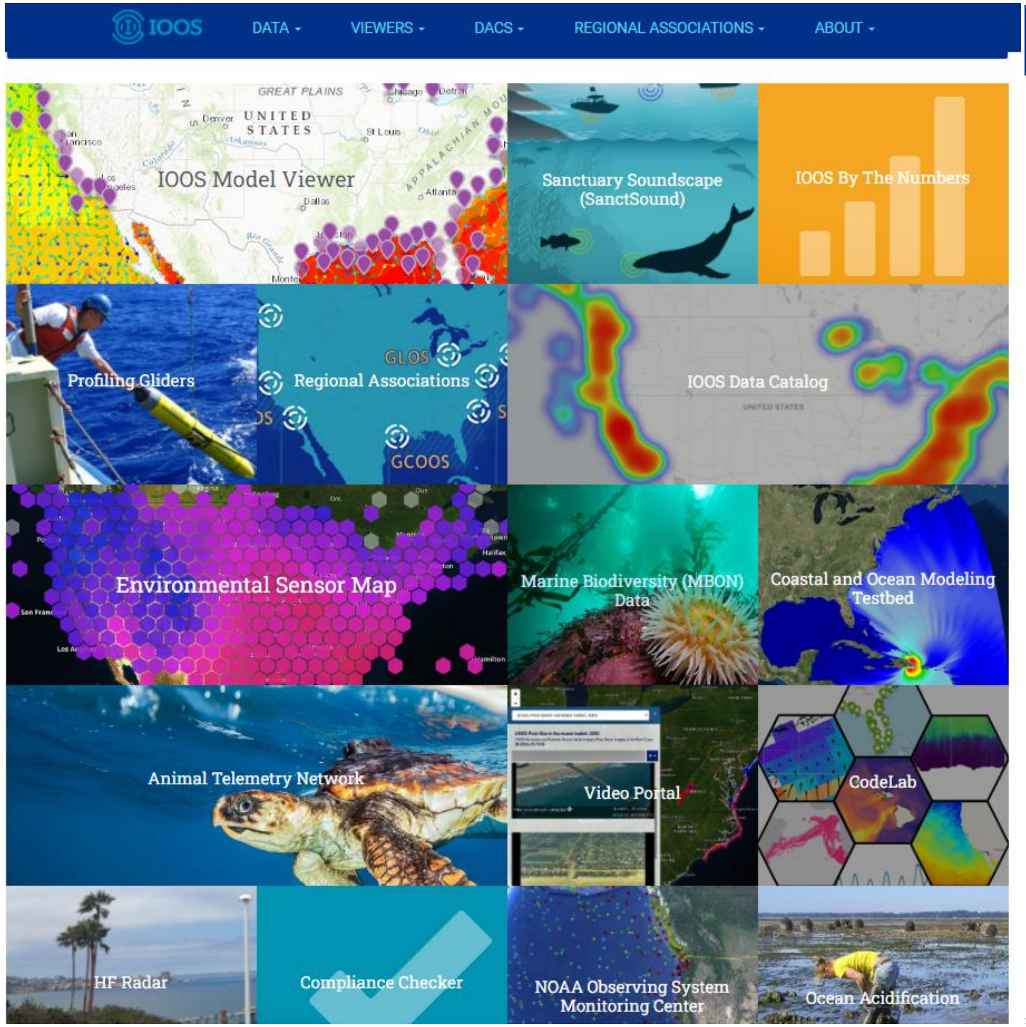
- **Implement and maintain monitoring and analysis programs**
- **Monitoring, data analysis, and dissemination of results are critical to detect problems and determine the effectiveness of management and restoration efforts**

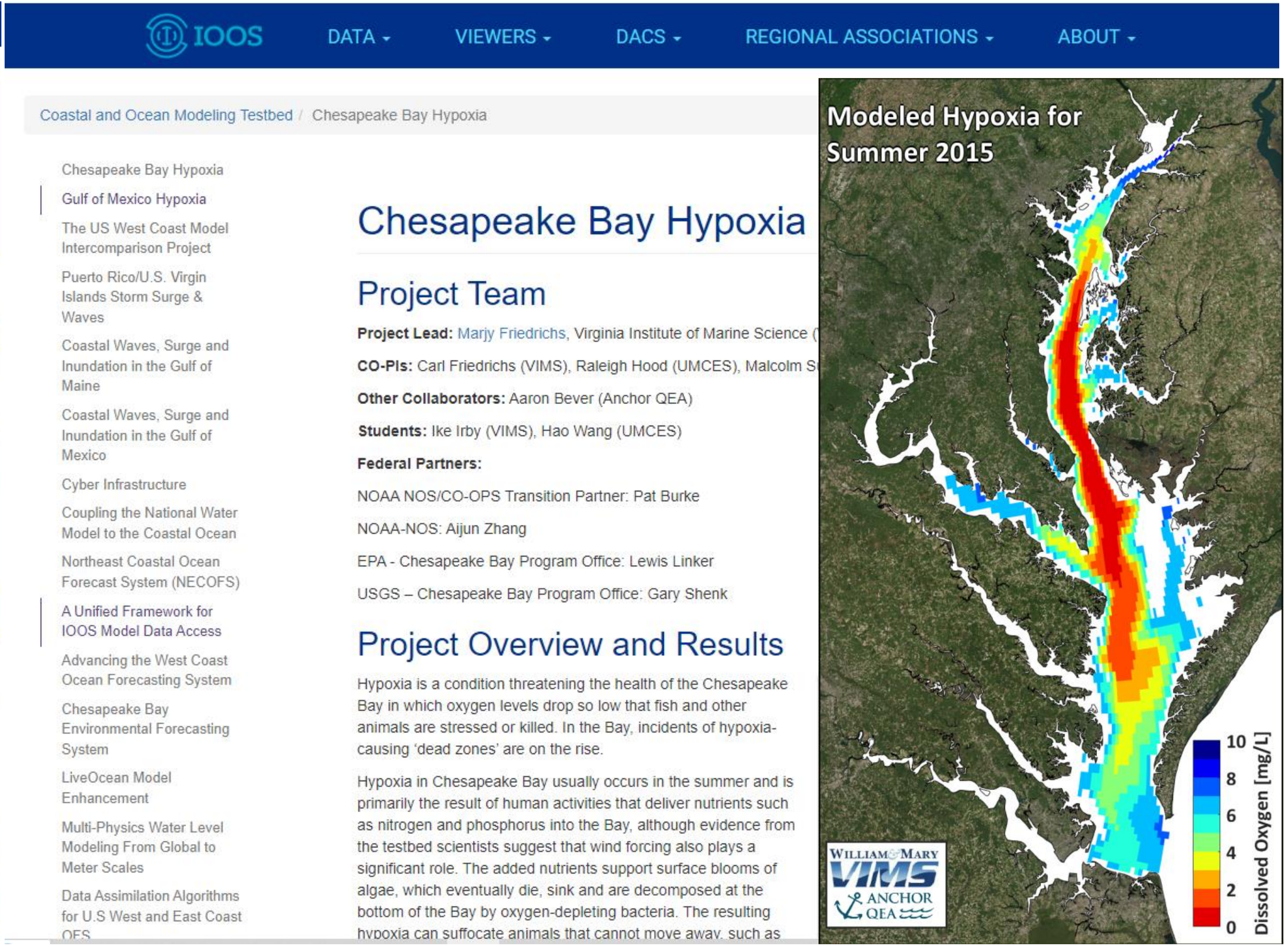


Efforts to reduce hypoxia

Ocean Observing projects

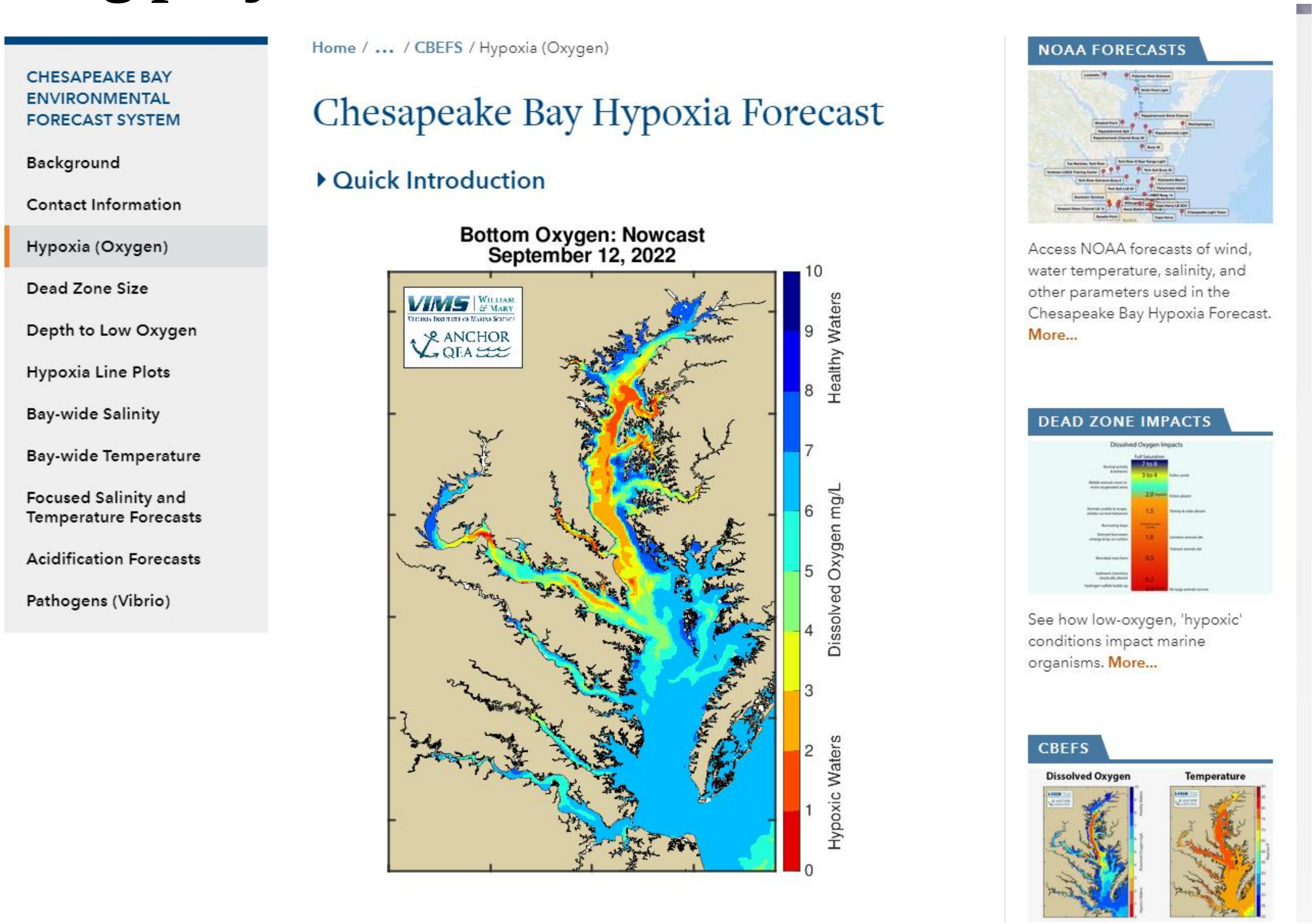
IOOS | Integrated Ocean Observing System





Efforts to reduce hypoxia

Ocean Observing projects



Efforts to reduce hypoxia

Ocean Observing projects

Yellow Sea & East Sea Buoy Observation Station

Thanks for your attention.