

# Implications of **global climate change** for **estuarine & coastal** ecosystems (Gulf of Mexico in particular)

- The cumulative effects of global change, including climate change, increased population, & more intense industrialization & agribusiness, will likely continue & intensify the course of eutrophication in estuarine & coastal waters.
- As a result, the symptoms of eutrophication, such as noxious & harmful algal blooms, reduced water quality, loss of habitat & natural resources, & severity of hypoxia (oxygen depletion) & its extent in estuaries & coastal waters will increase.
- Global climate changes will likely result in higher water temperatures, stronger stratification, & increased inflows of freshwater & nutrients to coastal waters in many areas of the globe.
- Both past experience & model forecasts suggest that these changes will result in enhanced primary production, higher phytoplankton & macroalgal standing stocks, & more frequent or severe hypoxia.
- The negative consequences of increased nutrient loading & stratification may be partly, but only temporarily, compensated by stronger or more frequent tropical storm activity in low & mid-latitudes.
- In anticipation of the negative effects of global change, nutrient loadings to coastal waters need to be reduced now, so that further water quality degradation is prevented.

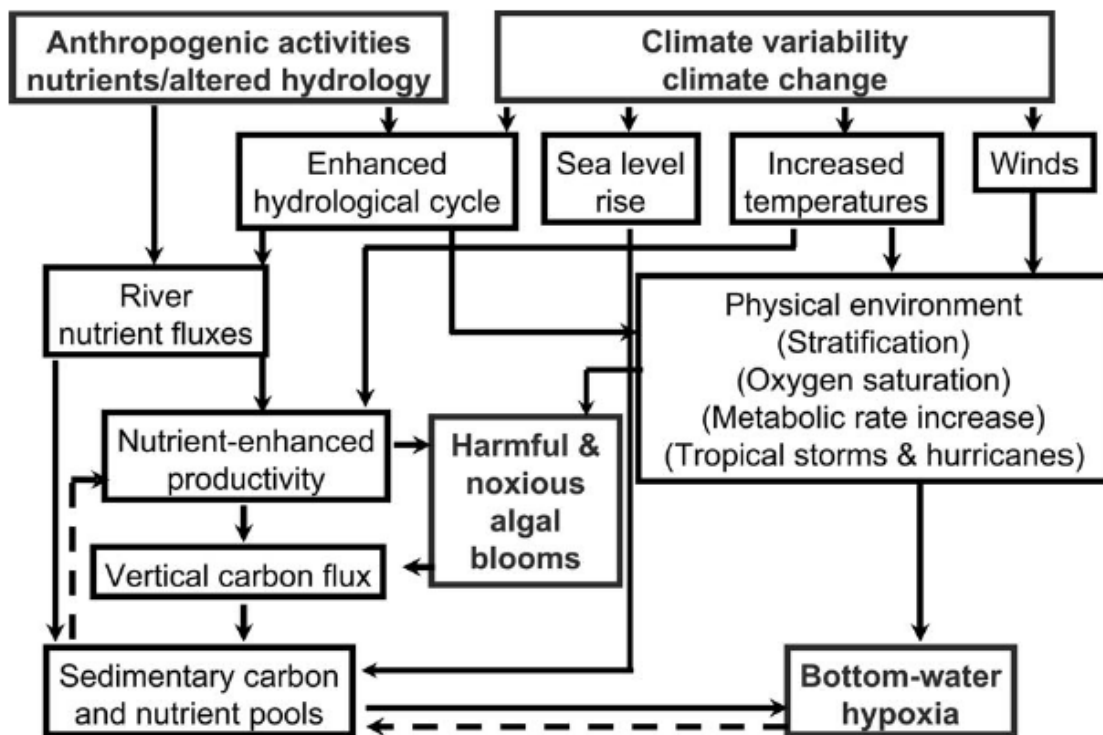


Figure 1. Potential physical and hydrological changes resulting from climate change and their interaction with current and future human activities. The dashed lines represent negative feedback to the system.

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Result	Region	Likelihood	Factors contributing to likelihood assessment
<b>Ocean changes</b>			
Anthropogenic forcing has warmed the upper several hundred metres of the ocean during the latter half of the 20th century	Global (but with limited sampling in some regions)	Likely	Robust detection and attribution of anthropogenic fingerprint from three different models in ocean temperature changes, and in ocean heat content data, suggests high likelihood, but observational and modelling uncertainty remains. 20th-century simulations with MMD models simulate comparable ocean warming to observations only if anthropogenic forcing is included. Simulated and observed variability appear inconsistent, either due to sampling errors in the observations or under-simulated internal variability in the models. Limited geographical coverage in some ocean basins (Section 9.5.1.1; Figure 9.15).
Anthropogenic forcing contributed to sea level rise during the latter half 20th century	Global	Very likely	Natural factors alone do not satisfactorily explain either the observed thermal expansion of the ocean or the observed sea level rise. Models including anthropogenic and natural forcing simulate the observed thermal expansion since 1961 reasonably well. Anthropogenic forcing dominates the surface temperature change simulated by models, and has likely contributed to the observed warming of the upper ocean and widespread glacier retreat. It is very unlikely that the warming during the past half century is due only to known natural causes. It is therefore very likely that anthropogenic forcing contributed to sea level rise associated with ocean thermal expansion and glacier retreat. However, it remains difficult to estimate the anthropogenic contribution to sea level rise because suitable studies quantifying the anthropogenic contribution to sea level rise and glacier retreat are not available, and because the observed sea level rise budget is not closed (Table 9.2; Section 9.5.2).
<b>Circulation</b>			
Sea level pressure shows a detectable anthropogenic signature during the latter half of the 20th century	Global	Likely	Changes of similar nature are observed in both hemispheres and are qualitatively, but not quantitatively consistent with model simulations. Uncertainty in models and observations. Models underestimate the observed NH changes for reasons that are not understood, based on a small number of studies. Simulated response to 20th century forcings is consistent with observations in SH if effect of stratospheric ozone depletion is included (Section 9.5.3.4; Figure 9.16).
Anthropogenic forcing contributed to the increase in frequency of the most intense tropical cyclones since the 1970s	Tropical regions	More likely than not (>50%)	Recent observational evidence suggests an increase in frequency of intense storms. Increase in intensity is consistent with theoretical expectations. Large uncertainties due to models and observations. Modelling studies generally indicate a reduced frequency of tropical cyclones in response to enhanced greenhouse gas forcing, but an increase in the intensity of the most intense cyclones. Observational evidence, which is affected by substantial inhomogeneities in tropical cyclone data sets for which corrections have been attempted, suggests that increases in cyclone intensity since the 1970s are associated with SST and atmospheric water vapour increases (Section 3.8.3, Box 3.5 and Section 9.5.2.6).
<b>Precipitation, Drought, Runoff</b>			
Volcanic forcing influences total rainfall	Global land areas	More likely than not (>50%)	Model response detectable in observations for some models and result supported by theoretical understanding. However, uncertainties in models, forcings and observations. Limited observational sampling, particularly in the SH (Section 9.5.4.2; Figure 9.18).
Increases in heavy rainfall are consistent with anthropogenic forcing during latter half 20th century	Global land areas (limited sampling)	More likely than not (>50%)	Observed increases in heavy precipitation appear to be consistent with expectations of response to anthropogenic forcing. Models may not represent heavy rainfall well; observations suffer from sampling inadequacies (Section 9.5.4.2).

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## **Coupling between Climate variability & Coastal Eutrophication: Evidence & outlook for the northern Gulf of Mexico** (Justic et al. 2005)

### ○ Introduction

#### • Eutrophication

- Eutrophication is the manifestation of nutrient-enhanced aquatic primary productivity & is often indicated by the presence of noxious algal blooms & bottom-water hypoxia.
- The extent & severity of these phenomena have increased during the late 20th century, coincidentally with increased use of fertilizer in the watersheds & higher nitrogen & phosphorus concentrations in freshwaters.
- The temporal association between the increased use of nutrients in the watersheds & outbreaks of coastal eutrophication points to the anthropogenic nature of the phenomenon.

#### • Climate Variability & Coastal Eutrophication

- superimposed on this late 20th century eutrophication trend we find strong climatic signals that have impacted estuarine salinity, stratification, nutrient budgets, primary productivity & the magnitude of seasonal oxygen depletion.
- Quantifying the links between climate variability & coastal eutrophication is important given predictions that the earth's climate may become more variable over the next 100 y.
- Precipitation, evapo-transpiration & runoff are all expected to increase globally, & hydrologic extremes such as floods & droughts may become more common & more intense.
- Changes in global temperatures & the hydrologic cycle may influence estuarine & coastal eutrophication in two main ways (Fig. 1).
  - 1) First, the magnitude & seasonal patterns of freshwater & nutrient inputs would alter & influence nutrient controlled coastal productivity.
  - 2) Second, the characteristics of the physical environment may change, thereby affecting the susceptibility of coastal & estuarine ecosystems to eutrophication.

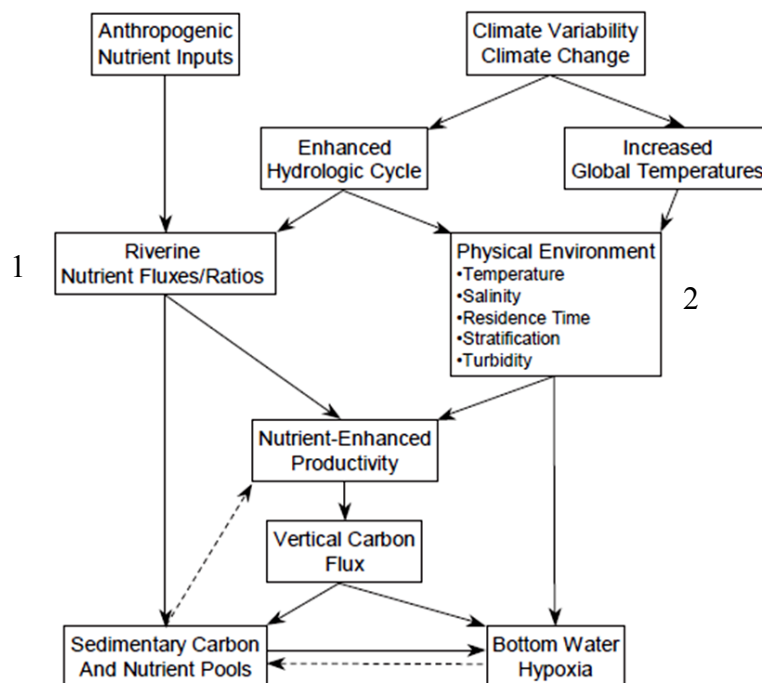


Fig. 1. Coupling between climate variability and coastal eutrophication. Broken arrows indicate feedback control.

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## ○ Evidence

### ● Mississippi River Discharge

- The Mississippi River discharge, in particular, appears to be influenced by the Atlantic Multi-decadal Oscillation (AMO), a 65–80 y climatic cycle with a 0.4 8C range in atmospheric temperature.
- The highest salinities occurred during the sixteenth & early seventeenth century & corresponded to large continent-wide droughts known from tree-ring records.
- These oscillations had profound affects on benthic & planktonic communities.
- A notable impact was a tendency towards greater oxygen depletion during wet periods & high river discharges.
- In the northern Gulf of Mexico (Fig. 2), climate driven variations in the Mississippi River fluxes of freshwater & nutrients strongly influence the areal extent & severity of hypoxia (<2 mg O<sub>2</sub> l<sup>-1</sup>)

### ● El Niño/Southern Oscillation (ENSO)

- Both the drought of 1988 & the flood of 1993 were caused by anomalous precipitation patterns associated in part with the El Niño/Southern Oscillation (ENSO).
- During 1988, a particularly strong, cold ENSO phase (La Niña) in the tropical Pacific triggered a series of anomalous circulation events that are believed to be responsible for the drought.
- In contrast, the 1993 flood was partly the outcome of an extended, warm ENSO phase (El Niño)

## ○ Changing Climate

- There is increasing acceptance that the buildup of greenhouse gases in the atmosphere is warming the earth
- The last decade of the 20<sup>th</sup> century was the warmest on record, & climatic records indicate that recent warming has no counterpart in the last 1000 years
- The global Earth's temperatures increased by almost 1 8C during the last 150 y, & general circulation models (GCMs) have projected further temperature increases of 1–6 8C over the next 100 y such a magnitude is expected to produce a general intensification of the hydrologic cycle that would be manifested in increased global precipitation, evapo-transpiration & runoff.
- General circulation models (GCMs) are not consistent in their predictions of the effects of climate change on precipitation & temperature, which are two important drivers of freshwater inflow to estuaries.
- Both models predict an increase in future extreme rainfall & runoff events, but they disagree in terms of both the magnitude & direction of changes in average annual runoff.
- The average annual runoff of the Mississippi River Basin, for example, was projected to decrease by 30% for the Canadian model, but increase by 40% for the Hadley model by the year 2099.

## ○ Climate Influences on Riverine Nutrient Fluxes

The degree to which climate change will influence the delivery of riverine nutrients to coastal waters will depend on the magnitude of inputs of anthropogenic nutrients to the landscape.

### ● Nitrogen fluxes

- For watersheds with little anthropogenic impact, nitrogen export is positively correlated with discharge.
- Assuming that the soil pool of nitrogen is in a steady state, nitrogen export from these watersheds should be related to nitrogen input resulting from nitrogen fixation & to atmospheric deposition of background levels of nitrogen.
- Incidentally, both nitrogen fixation & atmospheric deposition of nitrogen are positively correlated with precipitation & soil moisture .
- Riverine nitrogen fluxes should thus increase in response to increased precipitation & runoff.
- In watersheds with significant anthropogenic influence, riverine nitrogen flux appears to be strongly influenced by the magnitude of net anthropogenic inputs of nitrogen .

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- Such inputs, for example, account for ~70% of the variability in nitrogen export from the temperate regions of the North Atlantic Basin, indicating that future climate change is unlikely to strongly impact riverine nitrogen flux in such watersheds.
- During dry years nitrate accumulates in soils & underground waters.
- In wet years, nitrate is flushed into streams & enters the main river channels
- Furthermore, in the upper part of the watershed, a reduced water residence times in canals, lakes, & small streams reduces nitrogen loss by denitrification
- Wet years which follow dry years tend to produce the largest increases in nitrate flux
- Thus, unless anthropogenic inputs of nitrogen to watersheds are reduced, higher & more variable precipitation would enhance the magnitude of delivery of nitrogen to the coast.
- **Phosphorous & Silica Fluxes**
  - It is difficult to predict how climate variability will influence riverine fluxes of phosphorus & silica.
  - In watersheds with significant anthropogenic influence, riverine concentrations of phosphorus have generally varied with nitrogen concentrations
  - Silica concentrations, however, have remained constant, or decreased in some rivers.
  - The Mississippi River concentrations of dissolved inorganic nitrogen & total phosphorus increased three-fold & two-fold, respectively, during the second half of the 20<sup>th</sup> century, but the concentration of silica decreased by 50%.
  - One consequence of this has been a four-fold decrease in the riverine silica to nitrogen ratio
- **overall**
  - It is clear that the proportions of nutrients are likely to change in response to climate-driven changes in fluxes of freshwater & nutrients.
  - As a result of these differences in the behaviour of individual nutrients, the molar N:P ratio increases five-fold over a range of observed nitrogen flux values, while the molar Si:N ratio decreases two-fold
- **Ecosystem responses to altered freshwater inflow & nutrient fluxes**
  - Variability in freshwater inflow can influence many environmental factors of significance to coastal & estuarine ecosystems, including salinity, turbidity, residence times, stratification, nutrient concentrations, & nutrient ratios (Fig. 1).
  - Increased freshwater inflow can influence turbidity, water column stability & residence time, which all can modify the response of phytoplankton to nutrient enrichment & influence the process of eutrophication.
  - **Water Residence Times**
    - Water residence times can also affect the eutrophication process by influencing nutrient budgets.
    - There is a strong inverse relationship between estuarine residence times & nitrogen export to open coastal waters.
    - Thus, estuaries with short residence times (hours to days) are generally less susceptible to eutrophication than estuaries with long residence times (months to years).
    - Increased freshwater inflow may influence water column stability in a number of ways.
    - The Hudson River estuary, for example, becomes less stratified as freshwater inflow increases.
    - The opposite is the case in the northern Gulf of Mexico, where vertical density gradients are correlated with the Mississippi River discharge
    - Increased stratification could stimulate development of phytoplankton blooms by increasing the residence time of phytoplankton in the euphotic zone & slowing the sinking rates of phytoplankton.
    - Increased stratification is also likely to diminish vertical oxygen transport & promote the development of hypoxia in bottom waters



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- ***Pseudonitzschia* in the Gulf of Mexico**

- increased freshwater inflow may lead to increased phytoplankton production &/or biomass
- The evidence indicates that nutrient ratios influence the incidence of noxious & harmful flagellate blooms in the coastal waters worldwide.
- Evidence from the northern Gulf of Mexico indicates that abundance of lightly silicified diatom *Pseudonitzschia* has increased since the 1950s, coincidentally with increasing Mississippi River nitrate flux & decreasing Si:N ratios
- Some *Pseudonitzschia* species are known to produce toxins, so that there may be a direct link between Si limitation & toxic diatom blooms
- Evidence from the northern Gulf of Mexico indicates that diatom sinking contributes significantly to the vertical carbon flux that leads to hypoxia
- Most of the sinking diatoms are moderately to heavily silicified & their growth is stimulated by high Si:N ratios
- Consequently, changes in the riverine nutrient ratios can influence the vertical flux of carbon & the severity of hypoxia.

- **Outlook**

- Model scenarios were based on projected changes in the Mississippi River discharge, nitrate flux, & ambient water temperatures.
- Hence, depending on the assumptions about changes in freshwater inflow & temperature, major increases & decreases in the frequency of hypoxia are possible.
- The degree to which coastal eutrophication will be affected by future climate variability will vary from one system to another, depending on the characteristics of the physical environment & the current eutrophication status.
- The northern Gulf of Mexico & the Hudson River estuary are classic examples of river-dominated ecosystems that have become eutrophic in response to increased anthropogenic nutrient inputs.
- Yet, these two systems seem to show the opposite responses to climate-driven changes in freshwater inflow
- While increased freshwater inflow stimulates phytoplankton growth & increases eutrophication in the northern Gulf of Mexico, it decreases residence times in the Hudson so that phytoplankton growth is inhibited & the estuary becomes less eutrophic.

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## Forecasting Gulf's Hypoxia: The Next 50 Years?

(Justic et al. 2007)

### ○ **Introduction**

#### • **History** of Hypoxia

- Hypoxia typically occurs from **March** through **October** in waters **below the pycnocline**, & extends between **5 & 60 m depth offshore**
- Retrospective analyses & model simulations suggest that Gulf hypoxia has intensified during the last five decades, as a probable consequence of increased riverine nitrogen inputs & more balanced nutrient ratios in discharged freshwaters
- The concentration of nitrate, the predominant form of nitrogen in the Mississippi River, has increased 2.5-fold since the 1950s, coincidentally with the increased use of fertilizers in the watershed. Nitrogen is often considered to be the limiting nutrient for estuarine & coastal phytoplankton, & there is strong evidence that it controls the extent of primary production in the northern Gulf of Mexico

#### • **Formation** of Hypoxia

- Hypoxia develops from a suite of biological & physical factors, two of which are most important:
  - 1) **nutrient-enhanced surface primary productivity**, which manifests as high carbon flux to sediments
  - 2) **high stability of the water column**, which **controls vertical diffusive oxygen flux**
- Changes in the areal extent of hypoxia between flood years & drought years provide perhaps the best example of the synergistic nature of these influences.

#### • **Climate Change** & Hypoxia

- There are several lines of evidence suggesting that climatic factors profoundly influence the decadal & inter-annual variability of hypoxia in the northern Gulf of Mexico.
- The average Mississippi River discharge increased 30% since the 1950s, which contributed to the overall increase in nitrate flux.
- Development of hypoxia in the northern Gulf of Mexico is highly sensitive to inter-annual variability in the Mississippi River discharge, as evidenced by changes in the aerial extent & severity of hypoxia between flood & drought years

### ○ **Building a Consensus through Modeling**

- Hindcasts of the areal extent of hypoxia in the Gulf of Mexico suggest that large hypoxic regions were not likely to have been present prior to the mid 1970s & that the size of those regions grew steadily until the mid 1980s

### ○ **Improving Hypoxia Models**

- The existing Gulf's hypoxia models support the view that large-scale reductions in the nitrogen flux of the Mississippi River would eventually lead to a decrease in areal extent & severity of hypoxia.
- Because most current forecasting models have inadequate spatial resolution, they are not able to predict how the location & the volume of hypoxic waters will change in response to nutrient reduction.
- Upwelling wind stress can cause freshwater to pool over the Texas-Louisiana shelf
- Buoyant plumes are difficult to simulate because of both strong advection & active mixing throughout the plume
- Estimating the relative forcings of biology & physics as controls of hypoxia in relatively stagnant bottom waters remains one of the biggest challenges in hypoxia modeling.

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## ○ **Simple Versus Complex Models**

### • **Simple Models**

#### **Pro's**

- An advantage of simple models is that their data requirements for inputs & calibration-validation are much less extensive than for complex models.
- Simple models can often be applied & tested using data from much **longer periods** of record than complex models
- The ability to test simple models for long periods of record confers them with a degree of **robustness** that strengthens their ability to **forecast future conditions**, subject to the above caveats.

#### **Con's**

- simple models provide information on only a limited number of parameters
- Simple hypoxia models can indeed be valuable as forecasting tools, but they do so at the expense of providing understanding of the complex cause-effect mechanisms governing the development of hypoxia.

### • **Complex Models**

#### **Pro's**

- Complex models can provide understanding of cause-effect mechanisms that are impossible to derive solely from observational data

#### **Con's**

- A disadvantage of complex models is their extensive data requirements for inputs, calibration, & validation.
- It is much more difficult to apply complex models for long periods of record & confirm their robustness over the full dynamic ranges of their external forcing functions
- Complex models can also be valuable as forecasting tools, but it is much more difficult & expensive to develop, calibrate, & validate such models & demonstrate their robustness over the full range of conditions for which they were designed

## ○ **The Next 50 Years?**

- A scientific consensus now exists that the buildup of greenhouse gases in the atmosphere is warming the earth.
- General circulation models have projected further temperature increases of 1–6°C over the next 100 yr
- An increase in global temperatures of such a magnitude is expected to produce a general **intensification of the hydrologic cycle** that would be manifested in increased global precipitation, evapotranspiration & runoff
- Hydrologic extremes such as floods & droughts would likely become more common & more intense
- A modeling study that examined the effects of global warming on the annual discharge of the 33 largest rivers of the world suggested that the average annual discharge of the Mississippi River would increase 20% if the concentration of atmospheric CO<sub>2</sub> doubled.
- Unless anthropogenic nitrogen inputs to watersheds are reduced, higher & more variable precipitation, projected by many climate models would enhance nitrate delivery to the Gulf.

## ○ **Conclusions**

Because most current forecasting models have inadequate spatial resolution, they are not able to predict how the location & volume of hypoxic waters will change in response to nutrient reduction



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## Global change & Eutrophication of Coastal Waters (Rabalais et al. 2009)

### ○ Introduction

#### • Global Change

- The world's climate has changed, & human activities will continue to contribute to the acceleration of emission of greenhouse gases & rising temperatures.
- The effects of global climate change (GCC) are already detectable in the decline in snow cover, glaciers & polar ice, which have led to a poleward shift in plant & animal distributions, & caused changes in algal & fish communities & foodwebs
- The regional outcomes of the various GCC scenarios will likely manifest in many different & synergistic effects on various components of ecosystems.
- The drivers causing coastal eutrophication are set within a larger framework of multiple human-induced stressors, including overfishing, chemical contaminants, coastal habitat degradation, & invasive species.

#### • Eutrophication

- Eutrophication, defined as the increased rate of primary production & accumulation of organic matter, usually results from the excessive addition of nutrients, & results in undesirable changes in ecosystems.
- Eutrophication is a global phenomenon, with significant effects on foodwebs, water quality, & aquatic chemistry.

### ○ GCC & Coastal Systems

- If the average global temperature rises by 0.4°C over the next three decades & by 1.8 – 4.0°C over the next century there will be major changes in ecosystem structure & function, trophic interactions, & habitat ranges & migration patterns of many species.
- Most GCC scenarios project predominantly negative consequences for biodiversity & ecosystem goods & services (**Figure 1**).
- The major drivers of these changes are increased temperature, sea level rise, enhanced hydrological cycles, & shifts in wind patterns, which might alter coastal currents.

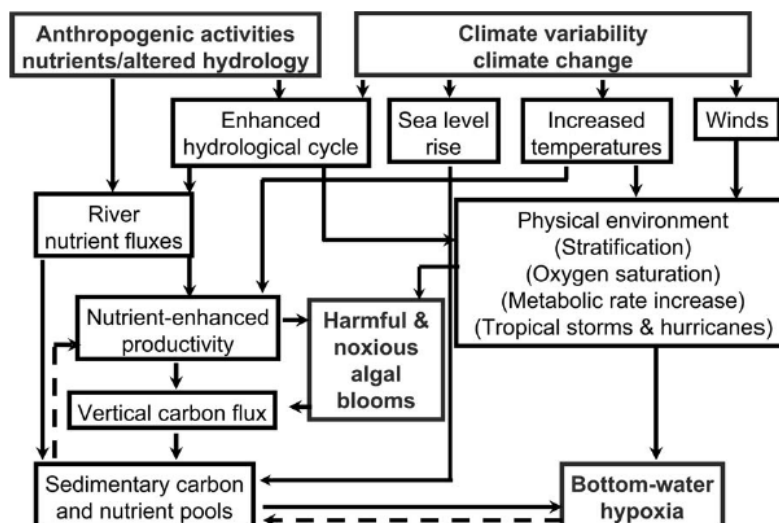


Figure 1. Potential physical and hydrological changes resulting from climate change and their interaction with current and future human activities. The dashed lines represent negative feedback to the system.

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## • Temperature & Salinity

- Increasing temperatures on their own have the potential to **strengthen pycnoclines** (density differences dictated by a combination of temperature & salinity) in estuarine & coastal waters, but lower surface salinity (e.g. from increased freshwater run-off) would be more of a factor in stratifying the water column (**Figure 2**).
- Stronger pycnoclines may result in **less diffusion of oxygen** from the upper part of the water column to the lower part of the water column, resulting in less dissolved oxygen in bottom waters.
- Decreasing oxygen concentrations in the lower part of the water column will negatively affect biological communities (**Figure 3**) & secondary production, & disrupt biogeochemical cycles

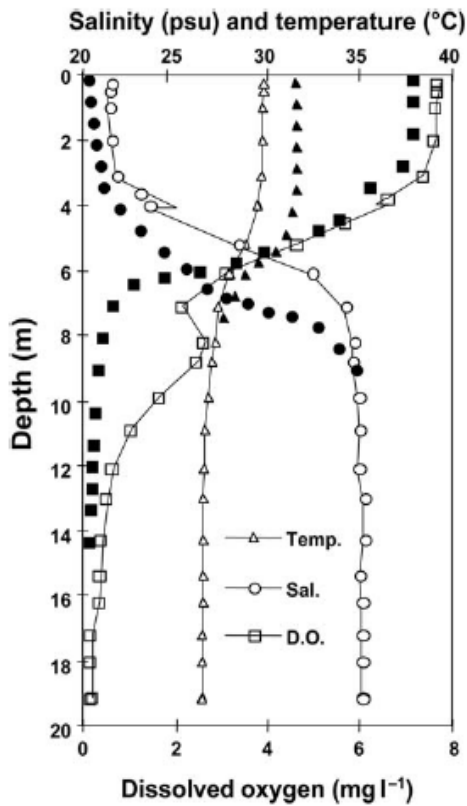


Figure 2. Typical thermocline, halocline, and oxycline for a station in 20 m, ~100 km west of the Mississippi River delta in midsummer (see Figure 5). The open symbols are recorded data, and the filled symbols are predicted changes with increased surface water temperature and increased freshwater discharge. For dissolved oxygen (D.O.), the predicted response is for lower oxygen in the upper water column because of decreased saturation and lower oxygen higher in the water column and lower values below the thermo- and halocline.

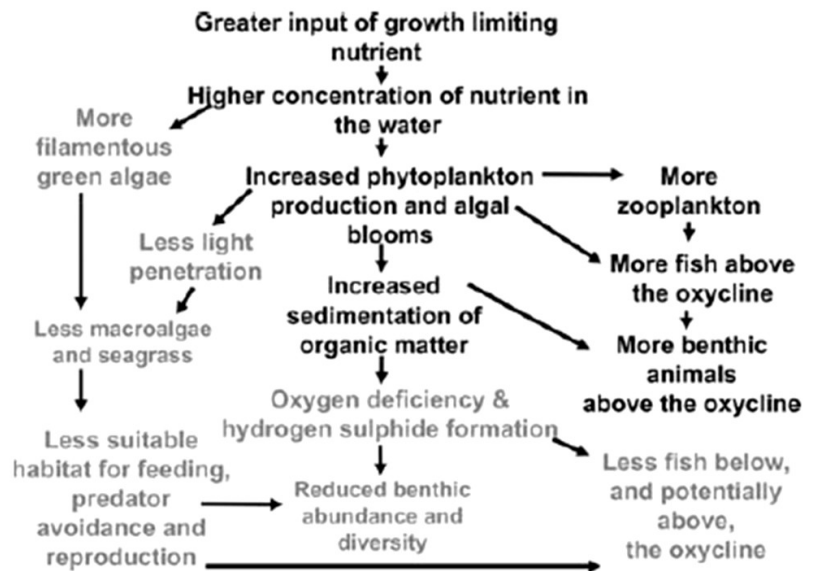


Figure 3. Schematic representation of the cascading effects of increasing nutrients in a coastal ecosystem. The harmful effects of nutrient overenrichment are presented in grey letters.

## • Regional Wind Patterns

- Increased temperatures may also affect regional wind patterns, resulting in changes in circulation & mixing.
- If wind patterns or intensity change, coastal currents & their effects on coastal waters might change to either aggravate a low oxygen condition or, conversely, to alleviate it.

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- **Tropical Storms & Hurricanes**

- If the frequency of tropical storms & hurricanes increases as a result of increased water temperatures in the lower to mid-latitudes as predicted by certain GCC models, the vulnerability of coastal habitats will increase greatly.
- Warmer Atlantic Ocean sea surface temperatures could increase the frequency & severity of tropical storms
- The effects of hurricanes & tropical storms on stratification, & how much they temporarily alleviate hypoxia in the coastal waters of the northern Gulf of Mexico, depend on several factors, which include barometric pressure, windspeed, storm trajectory, & the forward speed & circumference of the wind & wave field.
- The timing of storms is also critical.
- If hurricanes occur early in the “hypoxia season”, there will only be transient dissipation of hypoxia.
- If they occur later in summer, re-stratification may be slowed by an increasing frequency of autumn/winter storms (mixing & thermal turnover).
- Hurricanes have also caused the development of extensive hypoxia in North Carolina coastal waters & in some Florida systems.

- **Biological Processes**

- The rates of biological processes, including photosynthesis & respiration, are expected to increase with higher water temperatures, but only up to a point.
- For instance, primary production may proceed at a higher rate, but will eventually become limited by light (self-shading) or lack of nutrients.
- In addition, aerobic organisms will be brought closer to their thermal limits.
- These 2 factors, when combined, may result in a decrease in the physiological capacity of aerobic organisms

- **Enhanced Hydrological Cycle**

- Increased precipitation will result in more water, sediments, & nutrients reaching the coastal zone, where they are likely to enhance eutrophication through nutrient-enhanced production, increased stratification, or both
- Reduced precipitation will lower the amount of nutrients & water reaching the coastal zone &, perhaps, result in oligotrophication & reduced fisheries productivity.

- **Sea Level Rise**

- GCC models predict that coastal zones will be exposed to an accelerated sea level rise & increased erosion
- Most climate models predict that the eustatic sea level rise in the 21<sup>st</sup> century will be between 20-60 cm
- Human actions in the coastal zone have already affected the rate of relative sea level rise by levee & channel construction & withdrawal of water, oil & gas
- Coastal wetlands, including saltmarshes & mangroves, are projected to be negatively affected by sea level rise, especially where they are constrained on their landward side by geomorphology, that is to say, a gradient of increasing elevation or sediment composition, or from the increasing human-induced pressures on coastal areas for space, resources, or pollutant loading, including higher nutrient fluxes.
- The world’s coastal-zone population could grow from 1.2 billion people (in 1990) to between 1.8 & 5.2 billion people by the 2080s, adding to the negative effects of climate change.
- Coastal wetlands are important ecosystems because of their natural removal of reactive nitrogen & many other pollutants.
- Decreases in wetland area will result in disruptions in the overall effectiveness of ecosystem services, particularly the removal of excess nutrients that could cause eutrophication.
- In addition, any degradation of marsh ecosystems associated with the subsequent release of organic matter & nutrients could for a limited time contribute to local instances of eutrophication (**Figure 3**).

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## ○ **Eutrophication & its Symptoms**

### ● **Causes of Eutrophication**

- The causes of eutrophication should not be confused with the process itself.
- Eutrophication may result from changes in the physical characteristics of a system (e.g. hydrology), biological interactions (e.g. reduced grazing), or an increased organic & inorganic nutrient loading.
- Although the series of causes may include direct natural or anthropogenic carbon enrichment, eutrophication in the coastal ocean in the 20th & 21st centuries has more often been related to the excessive loading of nutrients, which stimulates phytoplankton growth.
- Humans are producing more & more reactive nitrogen & phosphorus, resulting in fluxes of nitrogen & phosphorus to coastal waters that far exceed their natural production rate. Eutrophication is likely to be aggravated where river discharge & fertilizer use increase (**Figure 1**)

### ● **Process of Eutrophication**

- When nutrient-limiting phytoplankton growth is added to an aquatic system, the response of the phytoplankton community is to increase its rate of production & biomass accumulation up to a point (**Figure 3**).
- The **beneficial aspects** of increased primary production are illustrated in **black** letters in **Figure 3**, including the increase in fished species & their prey organisms.
- Negative effects can occur if the increase in nutrients is above the capacity of the system to absorb the increased phytoplankton production.
- Algal blooms may result in increased sedimentation of organic matter on the seabed & subsequent oxygen depletion when they decompose, especially below the pycnocline
- Once the oxygen concentration decreases to a critical level, mobile species flee the area, while sessile organisms initiate survival behaviours, or begin to die as dissolved oxygen continues to decline

### ● **Climate Change & Eutrophication**

- Climate change & increased anthropogenic nutrient loading will make coastal ecosystems more susceptible to the development of hypoxia through enhanced stratification, decreased oxygen solubility, increased metabolism & remineralization rates, & increased production of organic matter.
- All these factors related to global change may progressively result in an onset of hypoxia earlier in the season & possibly an extended duration of hypoxia, as predicted for Chesapeake Bay
- The prevalence of hypoxia in estuarine & coastal areas is increasing, which is consistent with the idea that hypoxia is largely driven by increased nutrient loading to coastal waters
- The changes in various indices of eutrophication-related hypoxia in the United States demonstrate an increased percentage of estuarine & coastal ecosystems from the 1980s into the 2000s (Table 1).
- There has been almost a doubling in reports of systems with hypoxia over this 20-year period.
- It seems quite clear that more & more coastal systems, especially in areas of increased industrialization & mechanized farming, where physical conditions are appropriate & where nutrient loads are predicted to increase, are likely to become eutrophic (with accompanying hypoxia) in the future, even in the absence of GCC.

## ○ **Case history: Mississippi River watershed & Gulf of Mexico**

- The coupled Mississippi River watershed & coastal Gulf of Mexico ecosystem is a well-known example of continental-scale landscape change, with increased nutrient loads to the gulf resulting from human activity in the watershed (particularly from agricultural practices) & an eutrophic coastal ecosystem manifested by increased primary production & development of extensive & severe seasonal hypoxia
- The hypoxic zone in the Gulf of Mexico is the second largest human caused hypoxic area in global coastal waters

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- Changes in the watershed, & subsequent flux of nutrients to the gulf, enhance the high phytoplankton productivity that results in noxious & harmful algal blooms & high organic loading to the seabed.
- The high freshwater discharge supports salinity stratification throughout the year, which is strengthened by warmer surface waters from spring to autumn.
  
- **Changes in the Mississippi River Watershed**
  - The nitrate load of the Mississippi River (the product of nitrate concentration  $\times$  discharge) increased  $\sim$ 300% from the 1950s to the mid-1990s
  - The most significant driver in the change of nitrate load is the increase in concentration of nitrate in the river, not the freshwater discharge
  - An increase in precipitation (10–30% per century) should result in increased erosion & loss of phosphorus & increased flux of dissolved inorganic nitrogen, particularly nitrates, through the soils & artificially drained agriculture areas.
  - An increase in the base flow of water, because of enhanced seasonal snowmelt, is predicted to result in a 1–2-week earlier peak stream flow.
  - The spring peak delivery of nutrients & freshwater to the northern Gulf of Mexico begins a seasonal cycle of increased primary production & flux of organic matter to bottom waters, which subsequently results in low oxygen concentrations
  - The combination of increased nutrient loads (from human activities) & increased freshwater discharge (from GCC) will aggravate the already high loads of nutrients from the Mississippi River to the northern Gulf of Mexico & strengthen stratification (all other factors remaining the same).
  - Higher temperatures in other parts of the watershed are predicted to decrease precipitation & magnify drought conditions.
  
- **Changes in the coastal Gulf of Mexico**
  - The projected average temperature increase in the ocean over the next century is 1.5–2.0°C, which will most likely strengthen the pycnocline in the coastal waters of the Gulf of Mexico (**Figure 2**).
  - A stronger pycnocline will lower the flux of dissolved oxygen from the upper water column to the lower water column.
  
- **Summary**
  - Coastal water quality is currently on the decline.
  - The projected increased nutrient loading is predicted to increase the incidence & severity of eutrophication & hypoxic water formation.
  - The likelihood of strengthened stratification alone, from increased surface water temperature as the global climate warms, is sufficient to worsen hypoxia where it currently exists & will facilitate its formation in other coastal areas.
  - The interplay of increased nutrients & stratification may be offset by the potential for more frequent &/or severe tropical storm systems.
  - The future activity of tropical storms under increased global temperatures, however, is unclear, remains the subject of debate, & only temporarily alleviates hypoxia.
  - The overall forecast is for more eutrophication & for hypoxia to worsen, with increased occurrence, frequency, intensity, & duration.
  - The need remains for water & resource managers to reduce nutrient loads to reduce global eutrophication & its associated negative effects & to prevent further degradation.