
CLEAN WATER ACT

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Synonyms

Federal Water Pollution Control Act Amendments

Definition

The US Congress enacted the Clean Water Act in 1972 (P.L. 92-500, the 1972 Amendments to the Federal Water Pollution Control Act), which is the principal law dealing with polluting activity in streams, rivers, lakes, and estuaries of the USA (Copeland, 2006). The Clean Water Act established a water quality standards approach for regulating water quality, with the US Environmental Protection Agency responsible for developing national water quality criteria. A waterbody found to be in violation of a water quality standard was to be listed as “impaired” with consideration of the establishment of a total maximum daily load (TMDL) of the pollutant in violation of the standard (Lee et al., 2005).

Description

The Federal Water Pollution Control Act was originally enacted in 1948 and later amended in 1972 as the Clean Water Act (P.L. 92-500). Subsequent amendments were made in 1977 (P.L. 95-217), 1981 (P.L. 97-117), and 1987 (P.L. 100-4). As noted by Copeland (2006), the Clean Water Act consists of two main parts: “regulatory provisions that impose progressively more stringent requirements on industries and cities in order to meet the statutory goal of zero discharge of pollutants, and provisions that authorize federal financial assistance for municipal wastewater treatment construction.”

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Cross-references

Anoxia, Hypoxia, and Dead Zones
Eutrophication
Halogenated Hydrocarbons
Nonpoint Source Pollution
Oil Pollution
Polycyclic Aromatic Hydrocarbons
Trace Metals in Estuaries
Water Quality

CLIMATE CHANGE

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Synonyms

Climate variability

Definitions

Climate change (including climate variability) refers to regional or global changes in mean climate state or in patterns of climate variability over decades to millions of years often identified using statistical methods and sometimes referred to as changes in long-term weather conditions (IPCC, 2012). Climate is influenced by changes in continent-ocean configurations due to plate tectonic processes, variations in Earth’s orbit, axial tilt and precession, atmospheric greenhouse gas (GHG) concentrations, solar variability, volcanism, internal variability resulting from interactions between the atmosphere, oceans and ice (glaciers, small ice caps, ice sheets, and sea ice), and anthropogenic activities such as greenhouse gas emissions and land use and their effects on carbon cycling.

Introduction

Earth’s climate has varied over all timescales due to changes in global energy balance and radiative forcing caused by changes in solar radiation reaching Earth’s atmosphere, volcanism, Earth’s orbital configuration (precession, tilt, eccentricity), atmospheric greenhouse gas concentrations, and ocean basin-continent distributions. Regional and global climate changes can be amplified or dampened by complex feedback mechanisms involving sea-ice albedo, methane release from permafrost and marine sediments, land surface vegetation cover, ice sheet dynamics, and atmosphere-ocean-land exchange of carbon dioxide. In addition to natural climate changes, there is substantial evidence from instrumental records, climate modeling, and paleoclimate reconstructions that humans have influenced global and regional climate.

Estuaries, inlets, bays, fjords, tidal marshes, and other coastal systems are directly or indirectly affected by climate change. Instrumental records from stream gauges, water quality measurements, and, more recently, satellites provide trends in salinity, temperature, turbidity, dissolved oxygen, and many other parameters that can be linked to regional climate change and variability. Climate, hydrological, and ecosystem modeling studies are another approach to understanding climate impacts. For example, there are growing efforts to project estuarine response to elevated greenhouse gas concentrations (Najjar et al., 2010) some using downscaling methods that link global climate and regional models (Hostetler et al., 2011). Because instrumental records are usually limited to the last few decades, a third approach employs paleoclimatic and

paleoecological reconstructions, obtained from geochemical, physical, or biological proxies recovered from sediment cores (Cronin and Walker, 2006; Gooday et al., 2009). Paleo-reconstructions provide direct evidence for past climate impacts and prehistorical baseline conditions for ecosystem restoration, impact assessment, and planning.

Identifying climate impacts on modern estuaries is complicated by multiple environmental stresses from a wide range of local and regional anthropogenic activity such as land use changes associated with urbanization, agriculture, and other activities (Willard and Cronin, 2007; Canuel et al., 2010). These factors can make the attribution of observed changes in estuarine environments to specific causes very challenging.

This chapter summarizes climate impacts on estuaries during the mid-Holocene to late Holocene interglacial period (the last ~7,000 years), which is the period since postglacial sea-level rise stabilized and modern coastal systems took their modern form. Thus, this chapter applies to both prehistorical natural climate variability and climate change since the onset of the Anthropocene, sometimes defined as the period since the industrial revolution beginning ~1750–1800 CE (Common Era) (Gale and Hoare, 2012). Climate impacts can be grouped into five broad, interconnected categories: regional precipitation, sediment processes, temperature (global and regional), biogeochemical processes, and sea-level rise.

Regional precipitation

Climate change has direct impacts on estuaries through its effects on regional rainfall patterns. Seasonal and/or mean annual precipitation in watersheds is often highly correlated with river discharge into estuaries, which in turn affects salinity patterns and circulation. For example, in a partially mixed, microtidal estuary like Chesapeake Bay, river discharge, along with wind and tidal forcing, affects buoyancy-driven circulation, stratification, the development of a pycnocline, and oxygen exchange between upper and deeper layers (Schubel and Pritchard, 1986).

As a consequence, river discharge affects nutrient influx, phytoplankton blooms, dissolved oxygen, water quality, and ecosystem functioning such that excess nutrient loading coupled with greater river discharge has led to estuarine eutrophication on a global scale (Diaz and Rosenberg, 2008; Kemp et al., 2009; Howarth et al., 2011).

Internal modes of climate variability

The term “internal modes of climate variability” is often used to refer to climate changes that are not forced by radiative forcing from GHGs and solar and volcanic activities but rather interactions between the atmosphere, oceans, and ice sheets. The most widely recognized climate patterns are called the El Niño-Southern Oscillation

(ENSO), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO). Many studies have demonstrated a strong connection between internal modes of climate variability over interannual to multidecadal timescales and estuarine circulation, salinity, and dissolved oxygen (DO). Using a global dataset, Gilbert et al. (2010) could identify a secular pattern of decreasing DO between 1976 and 2000 that was more evident in coastal regions than in the open ocean. However, they also stressed that when interpreting the twentieth century patterns of oxygen concentrations, decadal climate variability can impose large-amplitude oscillations larger than the overall linear trend (see Garcia et al., 2005). Some examples of climate variability impacting regional rainfall, river discharge, estuarine salinity, and, in some cases, nutrient flux include studies of the PDO (Xu et al., 2012), the NAO (Cronin et al., 2005; Prasad et al., 2010), ENSO (Swart et al., 1996; Schmidt et al., 2001; Cronin et al., 2002), and the AMO (Enfield et al., 2001).

There are also well-established links between climate variability and marine biological systems (Mantua et al., 1997; Drinkwater et al., 2003; Pershing et al., 2005; Greene and Pershing, 2007). Cloern et al. (2010) showed that biological communities in San Francisco Bay are sensitive to ocean currents, temperatures, and coastal upwelling connected to PDO variability and North Pacific gyre circulation. Paerl et al. (2013) showed that climate-driven changes in river discharge to North Carolina estuaries altered the composition and biomass of phytoplankton communities. ENSO- and NAO-connected climate variability also influences outbreaks of infectious diseases on a global scale (Lafferty, 2009; Morand et al., 2013) and, in particular, viruses, bacteria, and infectious disease outbreaks in coastal waters (Lipp et al., 2001; Rose et al., 2001).

Two specific aspects of climate that deserve attention are extended droughts or wet periods and extreme events such as tropical cyclones. Evidence from tree-rings, corals, sediments, molluscan isotopes, and speleothems shows that droughts are an inherent part of Holocene climate. Quantitative reconstructions of precipitation show that North America (Cook et al. 2014) and Europe (Büntgen et al., 2010) have experienced decadal, continent-scale droughts over the past millennium. Multiple paleo-reconstructions based on several proxies show that droughts frequently affected mid-Atlantic climate and Chesapeake Bay watershed (Stahle et al., 1998; Cronin et al., 2005; Saenger et al., 2006; Harding et al., 2010). Precipitation changes over centennial timescales also affected coastal systems, such as changes in runoff and productivity in Chilean fjords during the latter part of the Little Ice Age from ~1600 to the 1800s (Rebolledo et al., 2008).

Although specific weather events cannot be directly linked to climate change, there is nonetheless concern that changing climate might increase the frequency and

intensity of tropical storms (Nicholls et al., 2007), which can severely impact estuaries. In one of the first intensive studies of hurricane impacts, the June 1972 storm *Agnes* in the eastern United States, there were widespread, long-lasting effects on Chesapeake Bay circulation, salinity, water quality, and ecosystems (Bailey et al., 1975; Davis et al., 1977). Similarly, three hurricanes that hit coastal North Carolina in 1999 caused 50- to 500-year floods, lowered salinity, and enhanced nitrogen loading to Pamlico Sound, which together had multiyear effects on coastal ecosystems (Paerl et al., 2001). Large storms also affect coastal wetlands notably through the impacts of storm surge, wind, and freshwater flushing on wetland soil dynamics and elevation (Cahoon, 2006).

Modeling precipitation changes and impacts

One challenge in estuarine research is predicting future precipitation/streamflow changes due to higher CO₂ concentrations. In the mid-Atlantic region of the eastern United States (Chesapeake Bay, the Delaware Bay, and Hudson River Estuary), impacts on streamflow ranged from a decrease of 40 % to an increase of 30 %, although results varied by season (Najjar et al., 2009). In a study of San Francisco Bay, Knowles and Cayan (2002) found that changes in winter snowpack and reduction in spring runoff would lead to elevated salinity (see Cloern et al., 2011). Future progress in this emerging field will come from linking downscaled climate models with watershed and estuarine hydrodynamic models, especially as improvements are made in predicted precipitation response to future climate change.

Global and regional temperature

Compared to precipitation-driven changes, the impacts of changing temperature may be less obvious in the short term, but nonetheless aquatic temperatures are important in estuarine functioning and ecosystems. Global mean annual and regional ocean temperatures are expected to rise over future decades to centuries due to elevated atmospheric CO₂ concentrations (Najjar et al., 2009), and in theory, this warming might lead to poleward range shifts in temperature-sensitive species (Helmuth et al., 2002; Przeslawski et al., 2012). Moreover, there is indisputable evidence that the world's oceans have been warming for at least the last 50 years (Levitus et al., 2012), and paleoclimate records show that marine species experienced large climate-driven biogeographic range shifts over 10⁴–10⁷ year timescales. These shifts are best documented in marine sediment records of major microfossil groups (diatoms, dinoflagellates, foraminifera, radiolarian, ostracodes) during glacial-interglacial cycles of the 500,000 years when Earth's mean annual temperature fell ~5 °C during glacial periods (Kucera et al., 2005). In addition to open-ocean sea faunal and floral biogeographic shifts, paleo-records from estuaries and coasts also show Holocene temperature-induced biogeochemical

and productivity changes such as the sedimentary record of LIA cooling in Kagoshima Bay, Japan (Kuwae et al., 2007).

In addition to large-scale range shifts, several indirect impacts of rising temperatures deserve mention: reduced sea ice, especially in marginal subarctic seas; coral bleaching; expanded geographic ranges of harmful algal bloom species; and mangrove species expansion among others (Nicholls et al., 2007). Case studies include the Bering-Chukchi Seas (Grebmeier, 2012), the Changjiang River Estuary (Ma et al., 2009), Mediterranean coastal systems (Bensoussan et al., 2010), Narragansett Bay, Rhode Island (Nixon et al., 2009), and the Gulf of Mexico (Bianchi et al., 2013).

Sediment processes

Coastal sedimentary processes influenced by climate include erosion (in the watershed and estuary), transport (in suspension and along river and estuarine bottoms), and deposition in an estuary, bay, or fjord. However, deciphering climate impacts on sedimentation is difficult due to large-scale anthropogenic activities. On the global scale, Syvitski et al. (2005) estimate that humans account for 2.3 ± 0.6 billion metric tons per year but that sediment retention in reservoirs, totaling 100 billion metric tons (bmt) in recent decades, reduces the sediment reaching the world's coasts by 1.4 ± 0.3 bmt per year (see Milliman and Farnsworth, 2011). On a regional scale, Saenger et al. (2008) found that postcolonial agricultural land clearance in the Chesapeake Bay watershed increased sediment accumulation rates by several times, but there were complex leads and lags related to climatic factors.

Nonetheless, preindustrial climate changes are known to affect sediment flux to coastal systems. For example, in subpolar fjords in Svalbard, Szczucinski et al. (2009) found that post-Little Ice Age temperature increase and glacier retreat had large impacts on sediment accumulation.

Within an estuary or bay, sediment affects a variety of factors including turbidity, light penetration, and the distribution of submerged aquatic vegetation (including sea grasses). This applies both to clastic sediment, often referred to as mineral matter, and particulate organic material, much of which is produced by algal productivity fueled by high nutrient concentrations. Sediment also plays an important role in the development of estuarine turbidity maximum zones (ETM, also called turbidity maximum zones, TMZ), a characteristic feature of many estuaries. It has long been known that trapping of suspended material in ETMs can be enhanced by increased vertical stratification due to large freshwater influx (Geyer, 1993). The physics of circulation near these salinity gradients are such that they trap clastic sediment and phytoplankton-derived organic material that has been transported to or resuspended within the ETM, resulting in high nutrient concentrations (Uncles et al., 2006;

Doxaran et al., 2009). As zones of complex salinity variability, nutrient dynamics, planktonic productivity, and fish spawning and growth, ETMs are important estuarine features forced by climate, river discharge, salinity, and sediment transport.

Despite the complexity of processes controlling sediment, land-to-estuary sediment flux, estuaries will continue to be vulnerable to future changes in climate, including the incidence and intensity of extreme storm events.

Biogeochemical processes

In addition to biogeochemical changes related to nutrient and oxygen dynamics discussed above, changes in ocean carbonate chemistry due to the uptake of anthropogenic CO₂ by the world's ocean, often referred to as "ocean acidification" (OA), pose complex, taxon-specific, and still poorly understood impacts on marine life (Hendriks et al., 2010; Wittmann and Pörtner, 2013; Kroeker et al., 2013). It is estimated that mean global ocean pH has been lowered by 0.1 pH units since ~1750 and may decrease by 0.3–0.4 pH units by 2100 (Pelejero et al., 2010). For comparison, glacial-interglacial cycles of the last 400 ka may have experienced changes of between 0.15 and 0.3 pH units. Although anthropogenic driven pH changes cannot be directly compared to natural events due to differing rates and boundary conditions, paleoclimate studies show that over multimillion year timescales, past natural acidification events had large effects on marine organisms (Kump et al., 2009; Pelejero et al., 2010; Hönlisch et al., 2012).

Currently, the study of OA impacts on coastal marine organisms is a growing field for corals (Hoegh-Guldberg et al., 2007), molluscs (Talmage and Gobler, 2009; Waldbusser et al., 2011, 2014; Gobler and Talmage, 2013), and other taxonomic groups (Ries et al., 2009; Kroeker et al., 2010). Some case studies suggest that pH has fallen in recent decades in some coastal systems. For example, pH fell from ~8.2 to 7.9 in the last 30 years in Chesapeake Bay (Waldbusser et al., 2011); Feely et al. (2010) estimate that 24–49 % of observed pH lowering in parts of Puget Sound, a deep estuary in the Pacific NW, was due to influx of seasonal upwelled ocean water, that is, global OA, as distinct from in situ remineralization via respiration. Complicating the issue of causality of observed changes in coastal pH, Pelejero et al. (2005) found that pH variation in a southwest Pacific Ocean coral was related to multidecadal climate variability in the Interdecadal Pacific Oscillation. In addition, other factors, such as reduced freshwater influx and higher salinity, may affect estuarine pH.

Sea-level rise

Sea-level rise (SLR) is one of the most challenging yet misunderstood concerns for estuaries and other coastal systems. No fewer than five global and four regional

processes influence relative sea level along any particular coast (Cronin, 2012). Global factors include thermosteric ocean expansion (increase in ocean volume, Willis et al., 2010), melting land-based ice from glaciers (increases ocean mass and mean global sea level), melting parts of the Greenland and Antarctic Ice Sheets (increases ocean mass and sea level, Hanna et al., 2013), reservoir storage (decreases mean sea level), and terrestrial water depletion (increases mean sea level, Konikow, 2011). Regional processes (excluding rapid tectonic movement) include glacio-isostatic adjustment (GIA, Peltier and Fairbanks, 2006) due to viscoelastic response of Earth's mantle to melting large ice sheets since the last glacial period ~20 ka (local GIA can also occur due to glacier melting), elastic deformation of Earth's crust due to changes in gravity and rotation (Tamisiea and Mitrovica, 2011), local groundwater withdrawal, and long-term thermal subsidence of the crust (typically minimal).

The contribution of each factor will vary regionally, but nonetheless, from the standpoint of estuaries and other coastal systems, several points deserve emphasis. Global mean sea level has been rising at rate of 3.1 mm year⁻¹ over the past few decades (perhaps an acceleration over rates averaged for the last century), mostly due to thermosteric expansion and land ice melting. Some studies suggest that SLR is already affecting large estuaries such as Chesapeake Bay (Hilton et al., 2008; Murphy et al., 2011) and coastal wetlands (Cahoon et al., 2006). In addition, although no consensus exists on future SLR, rates are expected to increase and glacier and ice sheet mass balance loss is likely to dominate SLR the rest of the twenty-first century. Consequently, the modeling study by Hong and Shen (2012) on the impacts of future SLR on Chesapeake Bay is illustrative, finding that primary effects on salinity, stratification, circulation, nutrient retention, and dissolved oxygen varied spatially, seasonally, and interannually. In addition, if as expected, tidal ranges and wave heights increase, severe storms would become an even larger concern in some estuaries (Najjar et al., 2010). Finally, geological records show that in the past, SLR rates reached and at times exceeded ~10–15 mm year⁻¹ in the absence of abrupt increase in greenhouse gas forcing. The implication is that, although the many factors that govern coastal ecosystem functioning cannot be oversimplified, the ability of some sensitive systems, notably mangroves, salt marshes, and coral reefs, to "keep up" with SL, that is, to accrete at the same rate of SL rise, remains a major concern.

Summary

Climate changes throughout geological history have influenced estuaries and coastal systems in a variety of ways and over all timescales. Similarly, future climate change will influence estuaries, perhaps at an accelerated rate, notably through effects on salinity and temperature, dissolved oxygen concentrations, nutrient and sediment

flux, biogeochemical processes, and coastal ecosystem functioning. Sea-level rise, altered rainfall patterns leading to extreme droughts and wet periods, and biogeochemical changes associated with ocean acidification are among the most important research topics associated with climate that will likely see great progress in the next few years.

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COASTAL BARRIERS

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Definition

A “coastal barrier” is a barrier that lies between a sea/lake/lagoon and some landform or feature that is non-coastal or at least more landward than the immediate modern or Holocene coastal landform or group of landforms. It may



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