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Review

An 'extreme' future for estuaries? Effects of extreme climatic events on estuarine water quality and ecology

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ABSTRACT

Recent climate observations suggest that extreme climatic events (ECE; droughts, floods, tropical cyclones, heat waves) have increased in frequency and/or intensity in certain world regions, consistent with climate model projections that account for man's influence on the global climate system. A synthesis of existing literature is presented and shows that ECE affect estuarine water quality by altering: (1) the delivery and processing of nutrients and organic matter, (2) physical–chemical properties of estuaries, and (3) ecosystem structure and function. From the standpoint of estuarine scientists and resource managers, a major scientific challenge will be to project the estuarine response to ECE that will co-occur with other important environmental changes (i.e., natural climate variability, global warming, sea level rise, eutrophication), as this will affect the provisioning of important ecosystem services provided by estuaries.

Contents

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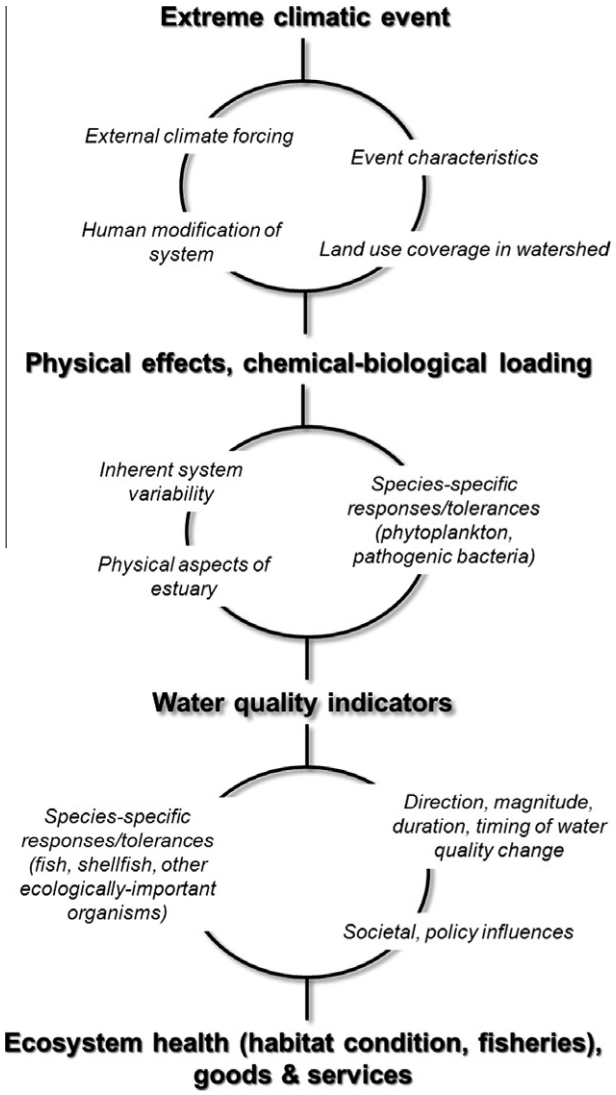

Fig. 1. Schematic representation of the effects of extreme climatic events and potential modulating factors (in italics).

1. Background

Estuaries represent one of the world's most vital aquatic resources, providing food resources and habitat for ecologically and economically important fish and shellfish species, recreational opportunities, scientific and educational experiences, and other important ecosystem services (Costanza et al., 1997; Hobbie, 2000; Pendleton, 2008; Yoskowitz et al., 2010). But estuaries worldwide are being exposed to an increasingly complex suite of environmental perturbations originating in their watersheds (e.g., anthropogenic nutrient loading, land use change, hydrologic modification) and externally from climatic forcings (e.g., tropical cyclones, droughts, global warming, sea level rise). The cumulative effect(s) of these perturbations often includes declining water quality (eutrophication) and deleterious changes in ecosystem structure and trophic dynamics in many estuaries (Cloern, 2001; Paerl et al., 2006; Rabalais et al., 2009). This, in turn, may alter or compromise the quantity and quality of goods and services provided by estuaries.

Climate variability, and specifically extreme climatic events (ECE), strongly influences the delivery of freshwater and associated nutrients and organic matter to the coastal zone (Scavia et al., 2002; Paerl et al., 2006). Despite evidence highlighting large-scale ecological effects of ECE on the coastal zone, our knowledge is limited in terms of mechanistic linkages between particular events and subsequent estuarine water quality and ecosystem responses. This, in turn, hinders the ability of scientists and resource managers to project the trajectory and magnitude of future water quality changes in estuaries and thus effectively manage these vital aquatic resources. Here we summarize the effects of ECE on estuarine water quality and important ecosystem services. We follow a conceptual model that examines effects of ECE on external chemical–biological loading to estuaries as well as effects on estuarine physical dynamics. We then document subsequent impacts on water quality indicators and highlight the cumulative effects of these changes on estuarine ecosystem health, goods and services (especially fisheries), all while attempting to identify important modulating factors (Fig. 1). The emphasis will be on tropical cyclones, floods, drought, and heat waves. We focus on the following questions:

1. How do ECE affect estuarine water quality, and does this depend on the characteristics of a particular event (e.g. timing, duration, trajectory in the case of tropical cyclones)?
2. How long do the water quality changes caused by ECE persist, and does this depend on the tidal regime of affected estuaries?
3. Is there a relationship between land-use coverage in estuarine watersheds and ECE-induced water quality changes?

These questions must be answered to effectively project and plan for the effects of future changes in frequency or intensity of ECE and the eventual impacts on the provisioning of ecosystem services.

2. Effects of extreme climatic events on estuarine water quality

2.1. How do ECE affect estuarine water quality, and does this depend on the characteristics of a particular event?

2.1.1. Tropical cyclones and floods

Tropical cyclones (e.g., Paerl et al., 1998, 2001; Williams et al., 2008) and floods (Wong et al., 2010) can mobilize significant quantities of organic matter and suspended solids which are subsequently deposited in estuaries. The combination of high organic matter loads and stratification caused by the freshwater input can interact to promote hypoxia/anoxia in subpycnocline water and occasionally in the whole water column (Paerl et al., 1998; Mallin et al., 2002; Burkholder et al., 2004; Tomasko et al., 2006). In some cases, freshwater itself may contain relatively low (i.e., hypoxic) oxygen levels that exacerbate these conditions (e.g., Mallin et al., 2002; Tomasko et al., 2006). For example, Hurricanes Fran (Cat. 3) and Bertha (Cat. 2) caused abrupt, adverse changes in the water quality of freshwater and estuarine ecosystems along the US Atlantic coast in 1996. Runoff generated by these storms delivered considerable amounts of terrestrial organic matter, nitrogen (N)-rich organic matter from wastewater treatment facilities, and inorganic nutrients into North Carolina's Cape Fear River (Mallin et al., 1999). This led to hypoxia/anoxia that persisted for nearly 1 month (Mallin et al., 1999, 2002). Large fish kills were reported in the river, and further downstream in the Cape Fear estuary, hypoxic conditions lasted several weeks and had deleterious effects on the benthic invertebrate community (Mallin et al., 1999, 2002). In the nearby Neuse River Estuary, runoff from Fran delivered a large volume of low oxygen, organic matter-rich freshwater to the system, also resulting in development of hypoxic/anoxic conditions and fish mortalities (Paerl et al., 1998).

Tropical cyclones (Bales, 2003; Peierls et al., 2003; Burkholder et al., 2004) and floods (e.g., Magnien et al., 1992; Hickel et al.,