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Sea-level rise and other influences on decadal-scale salinity variability in a coastal plain estuary

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ABSTRACT

The response of salinity in the Delaware Estuary to climatic variations is determined using statistical models and long-term (1950-present) records of salinity from the U.S. Geological Survey and the Haskin Shellfish Research Laboratory. The statistical models include non-parametric terms and are robust against autocorrelated and heteroscedastic errors. After using the models to adjust for the influence of streamflow and seasonal effects on salinity, several locations in the estuary show significant upward trends in salinity. Insignificant trends are found at locations that are normally upstream of the salt front. The models indicate a positive correlation between rising sea levels and increasing residual salinity, with salinity rising from 2.5 to 4.4 per meter of sea-level rise. These results are consistent with results from 1D and dynamical models. Wind stress also appears to play some role in driving salinity variations, consistent with its effect on vertical mixing and Ekman transport between the estuary and the ocean. The results suggest that continued sea-level rise in the future will cause salinity to increase regardless of any change in streamflow.

1. Introduction

Salinity influences both the physical properties of an estuary and the characteristics of its ecosystem. For example, salinity is the dominant factor regulating stratification. Even small changes in the salinity of an estuary can have a significant impact on the estuary's ecosystem. For example, salinity influences the spread of oyster disease (Powell et al., 1992), the distribution and diversity of ammonia-oxidizing bacteria (Bernhard et al., 2005), and the development of phytoplankton blooms (Gallegos and Jordan, 2002). Understanding and mitigating the impacts of changing salinity are particularly important because climate change and other human activities have already stressed many estuarine ecosystems (Kennish, 2002).

Many climatic and oceanic factors, including streamflow, sea level, oceanic salinity, and wind stress, have an influence on the salinity and water quality of an estuary. Streamflow determines the amount of fresh water entering the estuary. Elevated streamflows are typically associated with fresher water in the estuary; lower streamflows are associated with increased salinity in the estuary. Higher sea levels increase salinity by bringing more salt water into the estuary. Variations in oceanic salinity alter the salinity of water circulating into the estuary. Finally, wind stress may influence salinity through vertical mixing, Ekman transport and upwelling (Banas et al., 2004), and other mechanisms.

Climate change has the potential to cause changes in all of these variables. Precipitation amounts, frequencies, and intensities are expected to change in many areas as a result of anthropogenic climate change, and the associated effects on streamflow may be complicated by land use and evaporation changes (Krakauer and Fung, 2008). Global mean sea level has risen significantly during the twentieth century and is expected to rise at an increasing rate through the twenty-first century (Rahmstorf, 2007; Vermeer and Rahmstorf, 2009; Church et al., 2013). Meanwhile, changes in

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land use and large-scale atmospheric circulation have slowed winds over much of the Northern Hemisphere land area (Jiang et al., 2009; Vautard et al., 2010), although wind speeds have also increased in some areas (Hartmann et al., 2013).

Regardless of the causes, salinity change could be detrimental to many estuaries. This study focuses on the salinity of the Delaware Estuary on the United States East Coast. Over 8 million people live within the Delaware River basin (Sanchez et al., 2012), and the estuary contains the largest freshwater port in the United States (Philadelphia) (Kauffman et al., 2011). The Delaware River and Estuary provide a significant amount of freshwater to New York City and Philadelphia. Salt intrusion into the Philadelphia area water supply can occur during periods of high salinity (Hull and Titus, 1986). These factors prompt the Delaware River Basin Commission to carefully regulate the position of the salt front in the estuary. In addition, species in this estuary are typically sensitive to salinity; and interactions between parasites and hosts, as well as predators and prey, are often influenced by salinity. For instance, eastern oysters, a keystone species in the estuary, are host to two parasites that cause important diseases: *Perkinsus marinus* (dermo disease) and *Haplosporidium nelsoni* (MSX disease). The distribution of both parasites, as well as that of the oyster, is restricted by low salinity, but oysters can tolerate much lower salinity than either parasite, thereby providing low-salinity refuges from disease in the upper estuary (Haskin and Ford, 1982; Bushek et al., 2012; Ford et al., 2012).

Because of the importance of the estuary and river for shipping, drinking water, and fishing, a number of studies have examined the physical properties of the estuary. Salinity is higher in the center of the estuary and lower near the shores. The estuary is weakly to partially stratified, and the lateral salinity difference is typically greater than the vertical difference (Wong and Münchow, 1995; Wong, 1995). However, significant vertical stratification can occur in the main channel (Aristizábal and Chant, 2013). The estuary experiences two tides per day as a result of a large principal lunar semidiurnal (M_2) constituent (Wong, 1995). Salinity variability in the estuary produced by tidal advection is larger than the variability caused by streamflow (Garvine et al., 1992). Sea level and circulation also vary on the subtidal time scale primarily as a result of wind forcing (Wong and Garvine, 1984).

Several numerical modeling studies have examined the response of salinity to sea-level rise (Hull and Tortoriello, 1979; U.S. Army Corps of Engineers Philadelphia District (1997); Kim and Johnson, 2007). These studies found that salinity should increase in response to sea-level rise in most of the estuary. Numerical models have produced similar results in other estuaries, including the Chesapeake Bay (Hilton et al., 2008) and the San Francisco Bay (Cloern et al., 2011).

Although numerical model simulations can be informative, they are also subject to potentially restrictive assumptions and are no substitute for long-term observations of salinity trends. For example, all modeling studies to date assume that sea-level rise has no influence on bottom topography, even though it is likely that sea-level rise causes increased shoreline erosion, which increases sediment deposition (Cronin et al., 2003). Thus, empirical methods are an essential complement to numerical models for determining the effects of climate change and sea-level rise on salinity.

Ordinary linear regression is commonly applied to empirically model salinity. For example, Garvine et al. (1992) and Wong (1995) used linear regression to model the response of the salt intrusion length to streamflow in the Delaware Estuary. Marshall et al. (2011) used multiple linear regression to build predictive models of salinity in the Florida Everglades. However, when applying linear regression, care must be taken to account for issues such as correlation among data (autocorrelation), non-constant variance (heteroscedasticity), and non-linearity that are commonly found in water quality data (including salinity data).

Autoregressive models have been applied to empirically model salinity by taking advantage of the highly autocorrelated nature of most water quality data. Using autoregressive models, Gibson and Najjar (2000) predicted the response of salinity in the Chesapeake Bay to future changes in streamflow, and Hilton et al. (2008) tested whether sea-level rise has caused significant changes in Chesapeake Bay salinity. Saenger et al. (2006) used autoregressive models to relate river discharge to salinity and to reconstruct Holocene discharge and precipitation in the Chesapeake Bay watershed.

Other studies have applied additive models to empirically model salinity. The additive model and the related generalized additive model expand the traditional linear regression model by modeling the response variable with one or more smooth functions with forms that are nonparametric (i.e., are not defined *a priori*). Several authors have recently applied these models in studies of salinity and other water quality metrics. Jolly et al. (2001) and Morton and Henderson (2008) used additive and generalized additive models to determine changes in river salinity. Autin and Edwards (2010) applied additive models to extract tidal variations from salinity, dissolved oxygen, and temperature data and found that the additive methods performed better than multiple regression.

Neither additive nor autoregressive models offer a complete solution to the problems of autocorrelation, non-linear relationships, and heteroscedasticity commonly found in water quality data. Additive models are not typically robust against correlated or heteroscedastic errors, and autoregressive models do not handle heteroscedasticity or non-linear relationships between variables.

Additive mixed models (AMMs) offer a solution to the complications commonly encountered when modeling water quality time series. AMMs combine the nonparametric smooth functions of additive models with the ability to handle correlated errors and observations. AMMs are popular in many environmental fields that deal with autocorrelated and non-linear data, such as air pollution (Coull et al., 2001) and paleoclimatology (Simpson and Anderson, 2009). In this work, AMMs are applied to perform a data-driven analysis of the effects of climatic variations on salinity in the Delaware Estuary.

2. Methods

2.1. Study area and data

The Delaware Estuary is located in the Eastern United States to the east of the Chesapeake Bay (Fig. 1a). The Delaware River is the primary source of river discharge to the estuary. The head of tide extends to Trenton. Salt intrusion normally extends through the lower half of the estuary (Garvine et al., 1992).

Salinity in the Delaware Estuary has been measured through many different monitoring programs, including surveys, automated sensors, and boat sensors. However, records with long-term data coverage are rare. The goal of this analysis was to determine which variables have an influence on salinity over long time periods. In addition, the statistical models that were applied perform better with larger amounts of data. As a result, of the many salinity datasets that are available, the automated sensor data from the United States Geological Survey (USGS) and bottom salinity measurements from the Haskin Shellfish Research Laboratory (HSRL) were selected for statistical modeling. Both datasets are suitable for studying long-term trends, as they include a large number of measurements and together cover the period from the 1950s to the present.