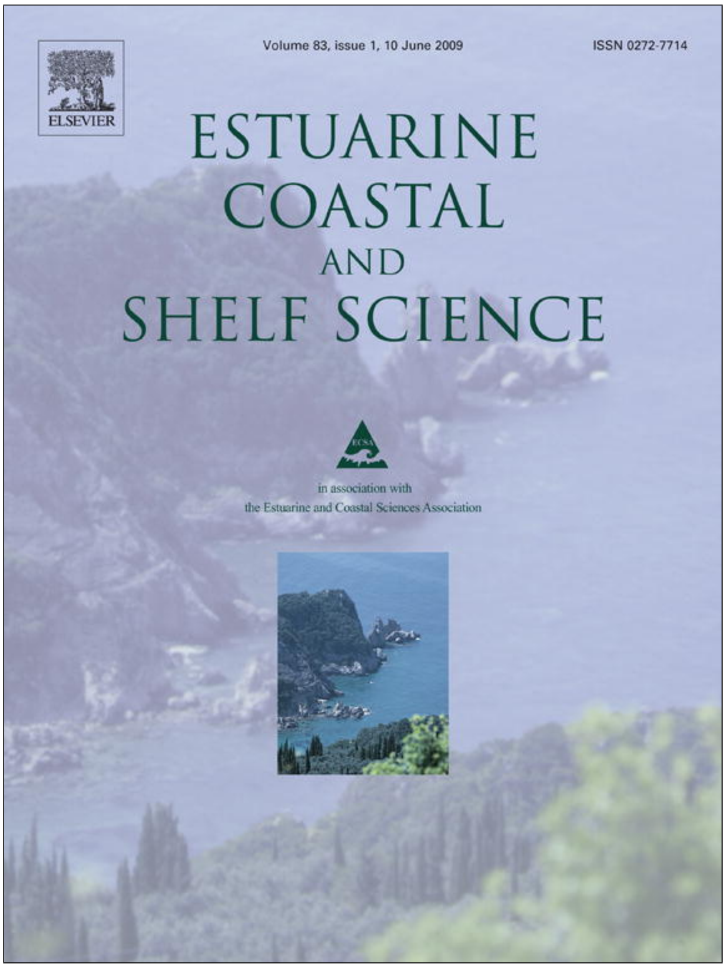
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Low-frequency sea-level change in Chesapeake Bay: Changing seasonality and long-term trends

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ABSTRACT

Long-term sea-level variability in Chesapeake Bay is examined from long tide gauge records in order to assess the influence of climate factors on sea-level changes in this complex estuarine system. A time series decomposition method based on autoregression is applied to extract flexible seasonal and low-frequency components from the tide gauge records, allowing to analyse long-term sea-level variability not only by estimating linear trends from the records, but also by examining fluctuations in seasonal and long-term patterns. Long-term sea-level variability in Chesapeake Bay shows considerable decadal variability. At the annual scale, variability is mainly determined by atmospheric factors, specifically atmospheric pressure and zonal wind, but no systematic trends are found in the amplitude of the annual cycle. On longer time scales, precipitation rate, a proxy for river discharge, is the main factor influencing decadal sea-level variability. Linear trends in relative sea-level heights range from 2.66 $\pm$ 0.075 mm/year (at Baltimore) to 4.40 $\pm$ 0.086 mm/year (at Hampton Roads) for the 1955–2007 period. Due to the gentle slope of most of the bay margin, a sea-level increase of this magnitude poses a significant threat in terms of wetland loss and consequent environmental impacts.

1. Introduction

Sea-level variations occur over a wide range of time scales, from millennia to minutes. However, records of precise measurements of sea-level cover less than 200 years. Tide gauges are the only source of historical sea-level measurements (with some records going back to the 19th century) and thus are the basis of studies of long-term (over the instrumental period) sea-level variations.

Chesapeake Bay is the largest estuary in the United States and a complex estuarine system, surrounded by a dense network of tributaries. Tide gauge measurements of sea-level have been routinely performed in the Bay since the early 20th century. Some of the very long historical tide gauge records from Chesapeake Bay have been analysed in the frame of global and regional studies of sea-level seasonal and long-term variability (e.g. Pattullo et al., 1955; Tsimplis and Woodworth, 1994; Douglas, 1991, 1995; Holgate and Woodworth, 2004; Barbosa et al., 2006; Jevrejeva et al., 2006; Barbosa et al., 2008a,b). Sea-level variability in Chesapeake Bay has also been intensively studied in order to understand estuarine hydrodynamics and meteorological influences on the estuarine circulation (Wang, 1979; Garvine, 1985; Goodrich, 1988; Paraso and Valle-Levinson, 1996; Valle-Levinson et al., 2001; Bosley and Hess, 2001; Pasternack and Hinnov, 2003; Salas-Monreal and Valle-Levinson, 2008). These studies of subtidal sea-level variability in Chesapeake Bay typically focus on the analysis of hourly tide gauge records up to a few years.

The aim of this work is to link these two perspectives in studying sea-level variability at Chesapeake Bay. On one hand, the goal is to study long-term (over the instrumental record) sea-level variability, by analysing long and continuous monthly tide gauge records. On the other, the objective is to also provide a more detailed description of long-term sea-level variability rather than just the estimate of a linear trend, in order to assess the influence of climate parameters on sea-level variations.

Climate change at the global and regional scale is expected to influence variability at the ecosystem level, impacting highly vulnerable estuarine and coastal areas (Preston, 2004). Sea-level rise is one of the most obvious effects of climate change and can impact considerably a complex estuarine system such as Chesapeake Bay, including land loss by erosion and inundation of low-lying lands, wetland loss and salt water intrusion. It is therefore particularly relevant to quantify long-term sea-level variability and how it is influenced by climate parameters.

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Characterisation of long-term variability from a time series of observational variables requires flexible methods to extract the low-frequency components. While a linear trend is often a first good approximation for describing low-frequency variability, its descriptive power is very limited, constraining the examination of eventual influencing factors. By the same token, the detection of subtle climate changes in seasonal patterns requires adequate approaches in order to discriminate between long-term changes in the mean and in the seasonal pattern (Pezzulli et al., 2005; Barbosa et al., 2008a; Barbosa, in press). In this work, autoregressive-based decomposition is applied to obtain flexible, time-varying descriptions of sea-level long-term variability in Chesapeake Bay.

The structure of the paper is as follows. The tide gauge data and the statistical approach are described in Section 2. Results of long-term sea-level variability in terms of seasonal and low-frequency sea-level patterns are presented in Section 3. The results are discussed in Section 4 and concluding remarks are given in Section 5.

2. Data and methods

2.1. Sea-level and climate data

Monthly tide gauge records for Chesapeake Bay (Fig. 1, Table 1) are obtained from the permanent service for mean sea-level (PSMSL) (Woodworth and Player, 2003). Small gaps in the records (<3 months) are filled-in using cubic splines (Lancaster and Salkauskas, 1986). Longer gaps are closed by Holt–Winters exponential smoothing (Holt, 1957; Winters, 1960). The resulting time series of relative sea-level heights (RSLH) are shown in Fig. 2.

Ancillary climate data are further considered. Monthly time series of atmospheric pressure, precipitation rate, zonal wind and meridional wind since year 1948 were obtained from the NCEP/NCAR reanalysis project (Kistler et al., 2001). Data are extracted from the 2.5° reanalysis grid for the point at latitude 37.5°N and longitude 285°E. Sea surface temperature (SST) at gridpoint 38°N, 284°E is obtained from the NOAA Extended Reconstructed SST V2 dataset (Reynolds et al., 2002).

The use of ancillary data from gridded climate datasets in this study yields an obvious constraint in terms of spatial resolution, hindering the comparison of sea-level values from tide gauges, influenced by very local atmospheric and oceanographic conditions, and gridded climate variables, representing more regional conditions. However, gridded data are spatially limited but temporally advantageous due to the availability of long and homogeneous time series. Furthermore, for the analysis of sea-level variability on long time scales and eventual climate influences, the analysis of regional factors, although not optimal, is a good first approximation.

2.2. Time series decomposition

A time series decomposition approach based on the dynamic linear representation of an autoregressive process (West, 1997) allows to extract from a given time series a non-stationary and time-varying description of periodic and long-term components. The method and its application to the analysis of sea-level records is described in Barbosa et al. (2008a) and the reader is referred to this work and references therein for the mathematical details. The approach is implemented in the R language (R Development Core Team, 2008) and the software (R-package ArDec) and accompanying tutorial is freely available, under GPL license, at http://cran.r-project.org.

The basic concept on which the method is based is that any autoregressive process of a given order p, modelling the behaviour of a time series X_t as a linear combination of its past values $X_t, X_{t-1}, \ldots X_{t-p}$ and a Gaussian white noise $\epsilon_t \sim N(0, \sigma^2)$,

$$X_t = \sum_{j=1}^{p} \phi_j X_{t-j} + \epsilon_t \quad (1)$$

can be written as

$$X_t = \sum_{j=1}^{p} \gamma_t^j. \quad (2)$$

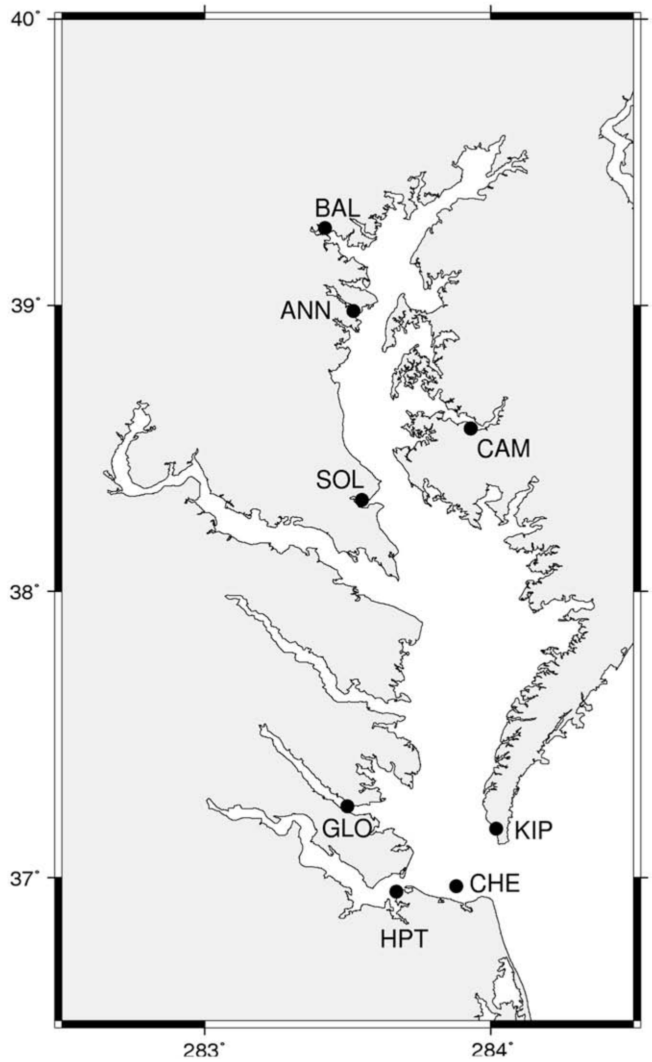

Fig. 1. Study area (Chesapeake Bay) and tide gauge locations. The acronyms are defined in (Table 1).

Table 1
Analysed monthly time series of mean sea-level from tide gauge stations in Chesapeake Bay.

Station	Acronym	λ (°E)	ϕ (°N)	period	% missing
Annapolis	ANN	283.52	38.98	1929–2007	4.22
Baltimore	BAL	283.42	39.27	1903–2007	0.16
Cambridge	CAM	284.07	38.57	1971–2007	3.15
Chesapeake Bay Bridge Tunnel	CHE	284.12	36.97	1985–2007	0.37
Gloucester Point	GLO	283.5	37.25	1951–2002	7.85
Hampton Roads	HPT	283.67	36.95	1928–2007	0.00
Kiptopeke	KIP	284.02	37.17	1952–2007	0.74
Solomon's Island	SOL	283.55	38.32	1938–2007	3.10

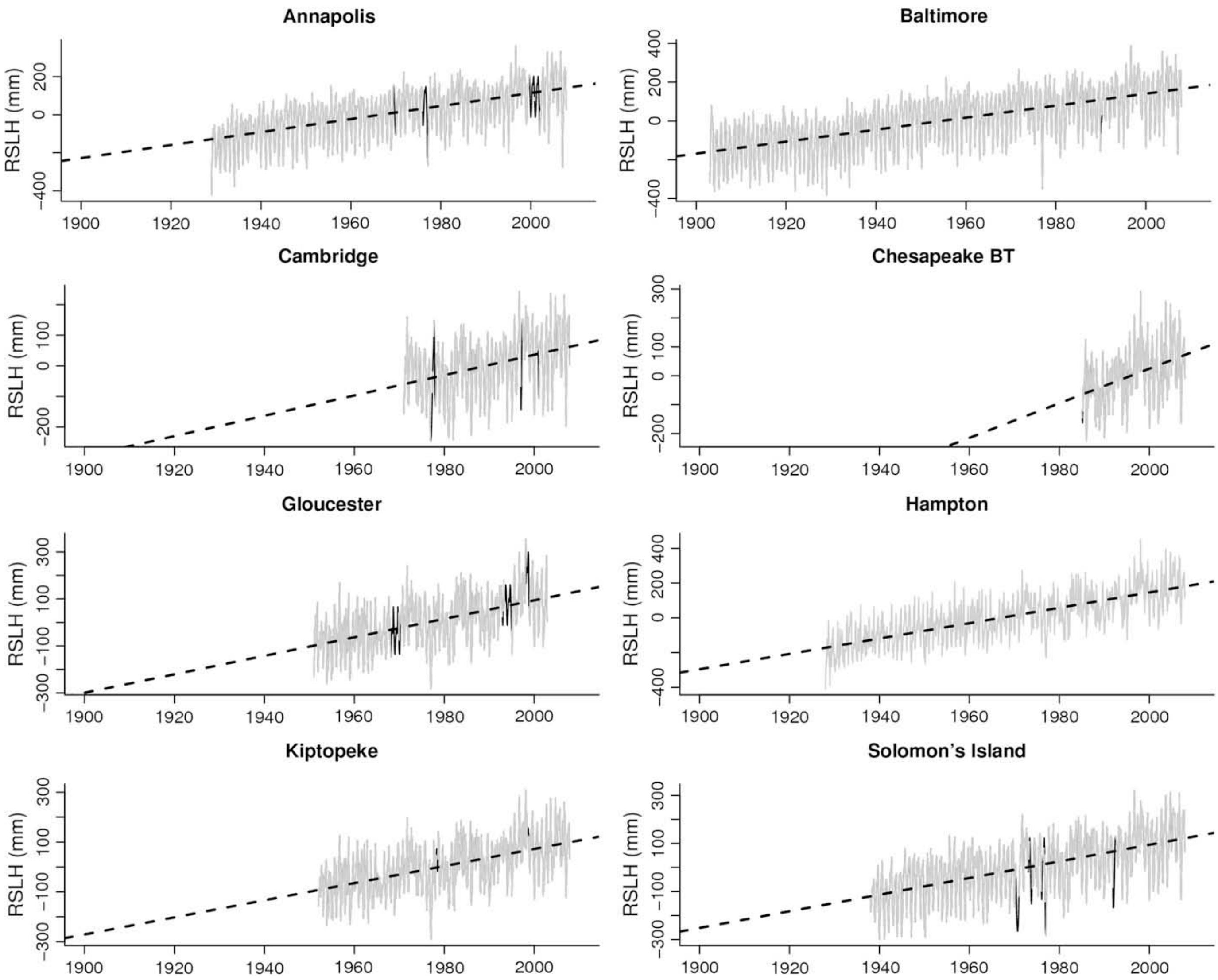

Fig. 2. Monthly tide gauge records of relative sea-level heights (RSLH). Interpolated values are represented in black. The dashed line depicts the linear trend estimated for each record by ordinary least squares (Table 4).

where each component γ_t^j, $j = 1,\ldots, p$ is either an autoregressive process (1) of order $p = 1$, corresponding to a trend component, or a process of order $p = 2$, corresponding to a periodic component. The components γ_t^j are derived by eigen-analysis of the matrix constructed from the autoregressive parameters ϕ_j (see Barbosa, in press for details).

This time series decomposition approach has a strong physical motivation, being very close to the first order linear treatment of a system's dynamics in classical physics. Its main advantage is to provide a time-varying description of trends and periodic signals (the γ_t^j components), allowing to examine changes in the amplitude and phase of the periodic signals, and to investigate fluctuations in the trend patterns, yielding a more flexible and realistic description of long-term sea-level variability.

3. Results

Most of the variance in the monthly tide gauge records (Fig. 2) is explained by long-term trends and by the annual seasonal cycle. This is evident in the cumulative periodograms for the sea-level time series from Chesapeake Bay (Fig. 3). The cumulative periodogram is a statistical tool based on the common periodogram definition used in standard spectral analysis, but the cumulative version makes it considerably easier to visually infer the existence of periodicities, characterised by sudden jumps in the cumulative curve. Thus Fig. 3 shows that for most records the cumulative periodograms are dominated by a sudden jump at the frequency of 1 cycle/year (corresponding to the annual seasonal cycle) and also by sharp increases in cumulative power at very low-frequencies, corresponding to long-term variability. The annual cycle is stronger for the inner locations (Annapolis, Baltimore, Cambridge and Solomon's Island), while the semi-annual component is stronger for the locations closer to the Bay mouth (Chesapeake BT, Hampton, Gloucester and Kiptopeke). Very low-frequency variability is stronger at Hampton.

The time series decomposition approach described in Section 2.2 is applied to each tide gauge record. First an autoregressive model (1) is fitted to each time series, yielding the autoregressive parameters ϕ_j (the order p of the process is estimated using the Akaike Information Criterion). Then the eigen-analysis of the matrix of autoregressive parameters yields p components γ_t^j. From these p components, only the ones corresponding to the highest

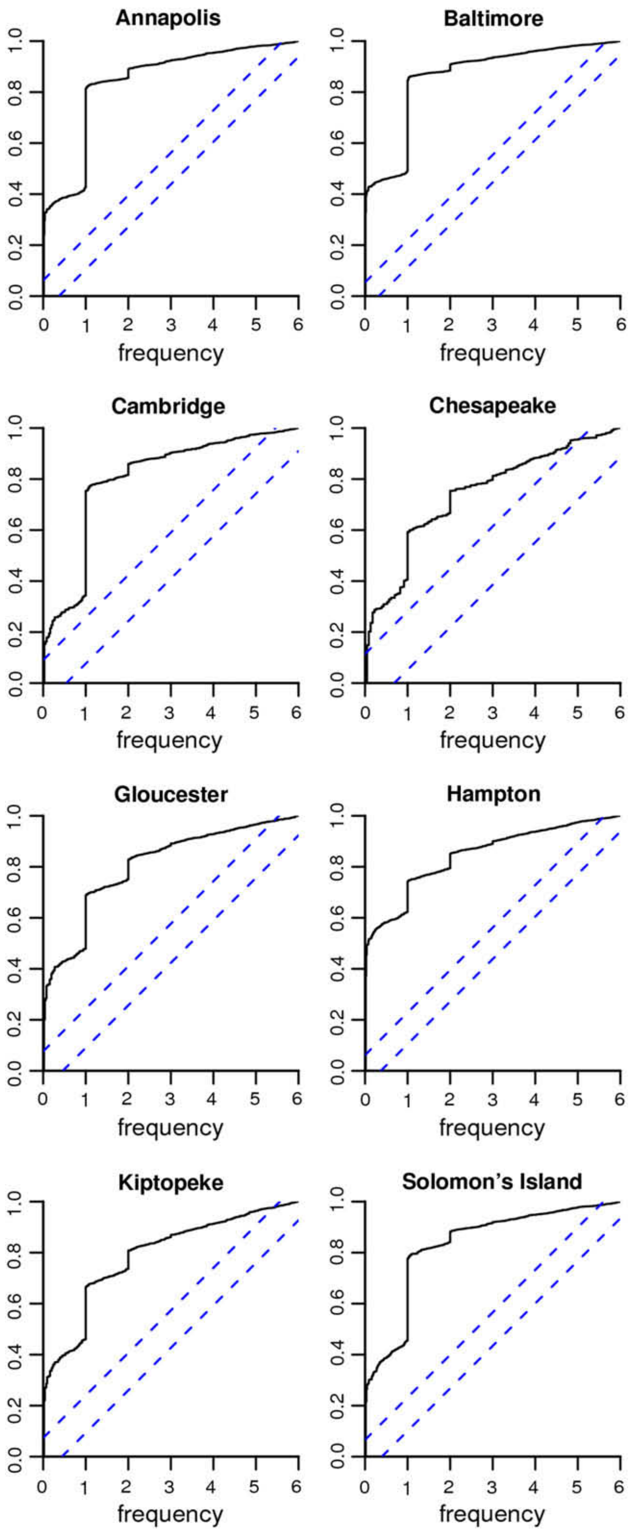

Fig. 3. Cumulative periodograms (frequency is in units of cycles/year). A cycle at a given frequency is captured in the cumulative periodogram as a sudden jump in the curve. The dashed lines represent 95% confidence intervals for white noise.

eigenvalues are relevant. In this case these correspond to two components, a periodic γ_t^1 time series, representing the annual cycle, and a trend component γ_t^2 representing long-term variability. These components are shown in Fig. 4 and further described in Sections 3.1 and 3.2, respectively.

3.1. Annual variability

The annual components (Fig. 4 (left)) are represented in Fig. 5 by means of monthplots. The horizontal lines in the monthplots indicate the mean value of the annual component for each month over the period spanned by the record, and the value of the annual component for each individual year is superimposed to each monthly average (grey lines). Thus for each month it is represented (in grey) the value of the annual component for that month, from the first to the last year of the record. The annual cycle has a minimum in February/March and peaks in August/September for the locations closer to the Bay entrance (Chesapeake BT, Hampton, Gloucester and Kiptopeke) while for locations in the inner part of the Bay (Annapolis, Baltimore, Cambridge and Solomon's Island) relative sea-level heights are lowest in January/February and peak in July/August.

The annual amplitude is computed as the difference between the maximum and minimum values of the annual component for each calendar year and represented in Fig. 6. The average amplitude (Table 2) is smaller for the tide gauges nearest to the coast and increases towards the head of the Bay, as a result of a natural seiche mode (Wang and Elliot, 1978). Although the standard deviations for the annual amplitudes are fairly stable, 3.5 cm (the higher value for Chesapeake BT results from the much shorter length of the record), the amplitude of the annual cycle exhibits considerable temporal variability, as shown in Fig. 6. Particularly evident is the decrease in the annual amplitude at all locations in the late 1990's. This decrease is mainly the result of a year (1998) for which the annual amplitude of sea-level is anomalously low. The physical reason for this drop in the annual amplitude is unclear.

In order to examine the source of this variability in the amplitude of the annual cycle, the annual variability in sea-level is compared with the annual variability in ancillary climate variables, including atmospheric sea-level pressure (SLP), precipitation rate (PR), zonal (E–W) wind (Uwnd) and meridional (N–S) wind (Vwnd). Annual components are extracted for these variables as for sea-level and the Spearman's rank correlation coefficient is computed for describing the correlation between fluctuations in the annual amplitude of sea-level and of the climate variables (Table 3). At all locations the changes in the amplitude of the annual cycle of sea-level are correlated with concurrent changes in the annual amplitude of zonal wind, and anti-correlated with variations in the annual amplitude of atmospheric pressure. At Annapolis and Solomon's Island, the annual cycle is also influenced by precipitation rate. No significant correlation was found between annual fluctuations in the annual cycle of sea-level and sea surface temperature (from the gridded dataset).

Although the amplitude of the annual cycle shows variability associated with atmospheric factors, the amplitude of the annual cycle (Fig. 6) does not exhibit a systematic (statistical significant) trend at any of the locations.

3.2. Long-term variability

Long-term sea-level variability in Chesapeake Bay is characterised by a large increasing trend around 3 mm/year (Table 4, Fig. 2). The largest trend of nearly 6 mm/year at Chesapeake BT results from the much shorter length of this record. Sea-level is known to exhibit considerable decadal variability, and estimated trends are very dependent on the period considered for the analysis (e.g. Holgate, 2007). Therefore, sea-level trends estimated from very short records need to be viewed with caution. Large trends in relative sea-level height are also found in the southern end of the Bay, at Hampton Roads and Gloucester Point.

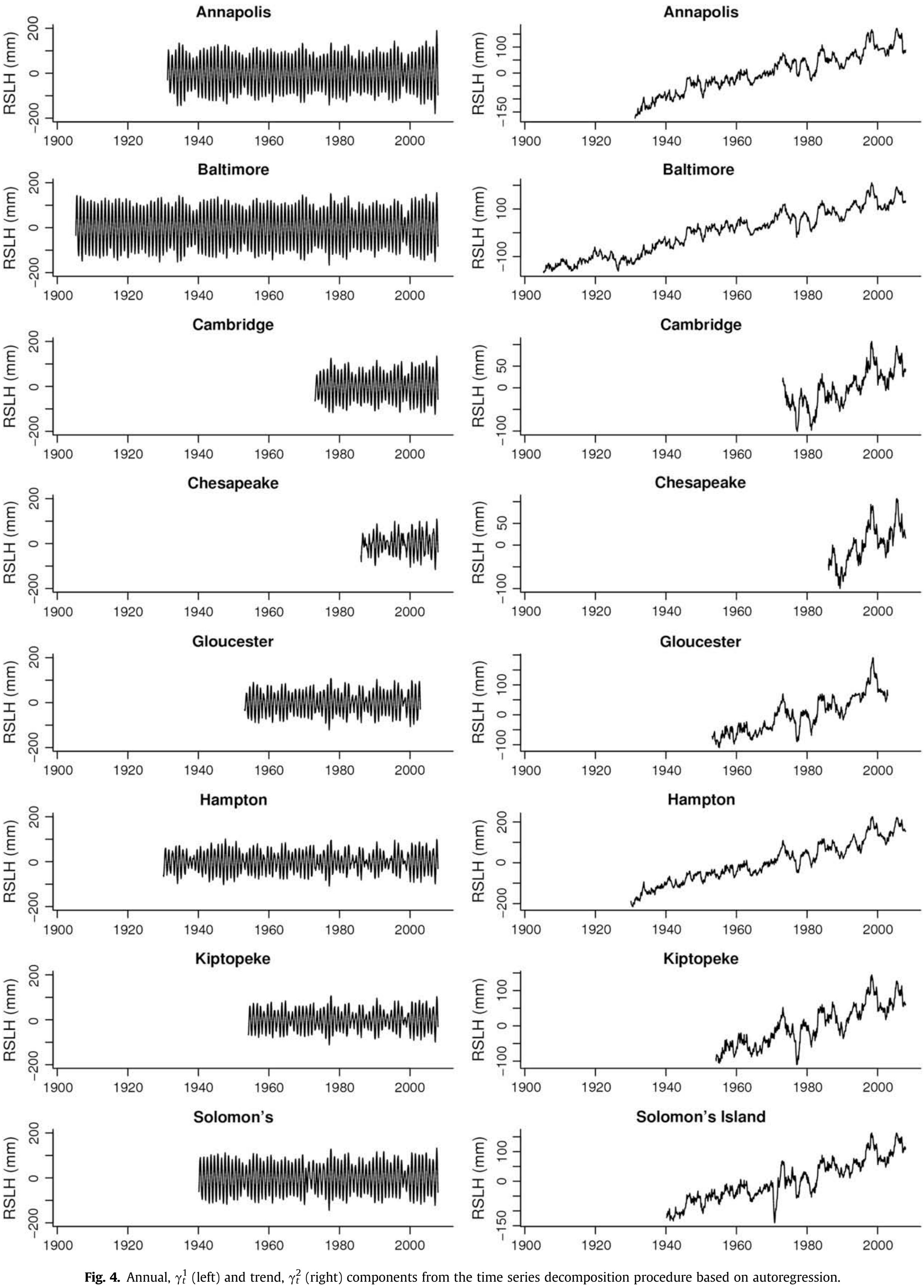

Fig. 4. Annual, γ_t^1 (left) and trend, γ_t^2 (right) components from the time series decomposition procedure based on autoregression.

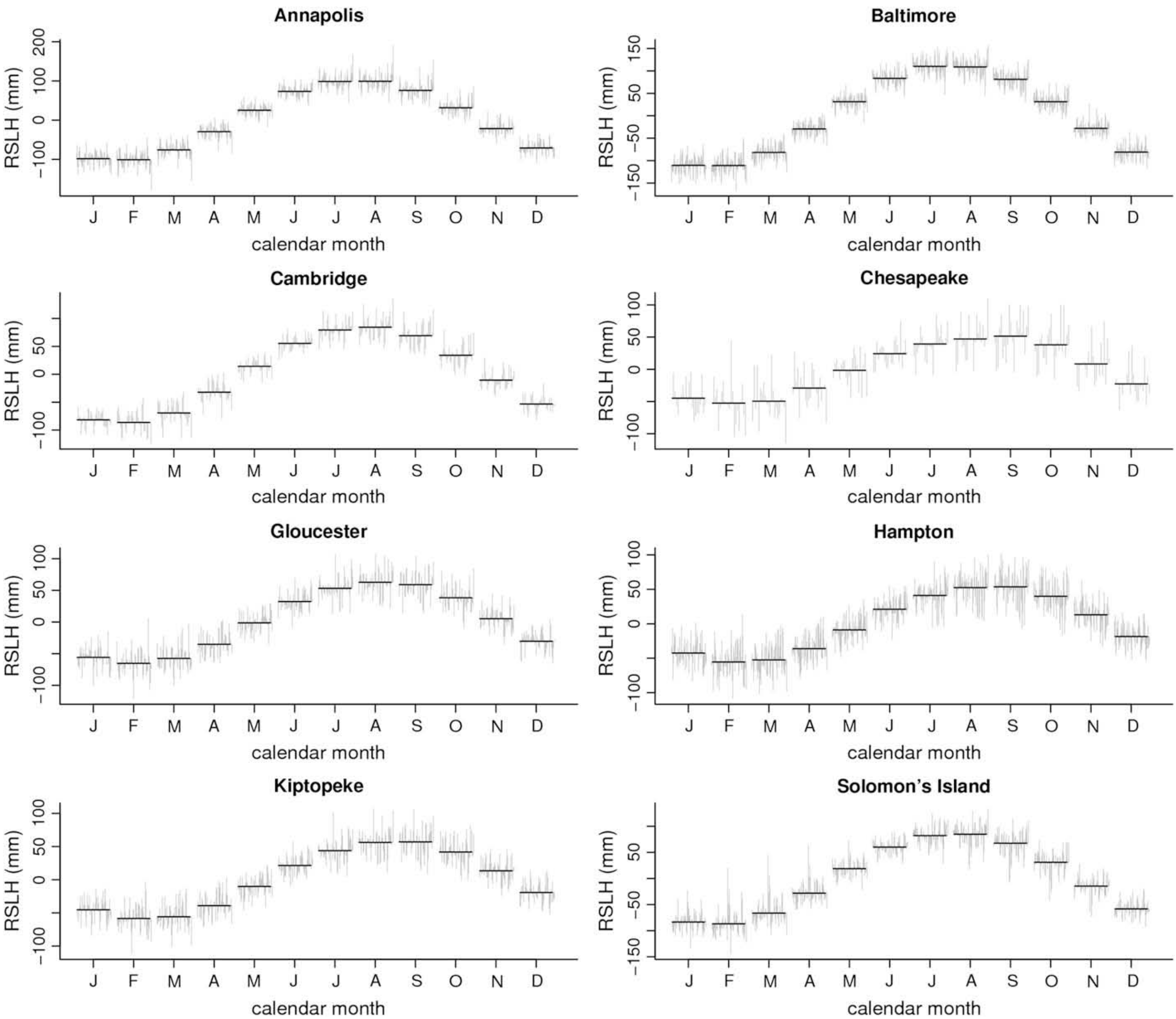

Fig. 5. Monthplot representation of the annual components (γ_t^1) obtained with the time series decomposition procedure. The horizontal lines indicate the mean value of the annual component for each month over the period spanned by the record. The value of the annual component for each individual year, from the first to the last year of the record (gravy lines), is superimposed to each monthly average.

Beyond the monotonous increasing trend, long-term sea-level variability in Chesapeake Bay displays appreciable fluctuations and considerable inter-annual variability, with the trend components (Fig. 4, right side) exhibiting similar temporal patterns at most stations (e.g. the ''double trough'' around 1980, or the peak in the late 90's). Considering an EOF analysis of the five records for which data are available for the common period 1955–2002, the first principal component time series (Fig. 7) is able to explain 96.5% of the variability in the dataset of trend components.

Similarly as in Section 3.1, the climate variables were subject to a similar decomposition as the one carried out for the sea-level records in order to examine the correlation between the corresponding trend components. The autoregressive-based decomposition approach was unable to extract a significant long-term component for meridional and zonal winds, suggesting that wind variability over the analysed period does not exhibit a significant trend. No statistically significant association is found between long-term variability in sea-level and atmospheric pressure, and between sea-level and sea surface temperature. However, the first principal component of the sea-level trend components (Fig. 7) is correlated (correlation coefficient $= 0.54 \pm 0.055$) with the long-term component of precipitation rate. Precipitation rate, a proxy for river discharge, is able to explain 31% of the long-term variability in sea-level.

Table 2
Statistics of the annual cycle of mean sea-level.

	Minimum	Maximum	Mean (cm)	Std dev (cm)
Annapolis	January/February	July/August	20.7	4.1
Baltimore	January/February	July/August	22.9	3.6
Cambridge	January/February	July/August	17.6	3.8
Chesapeake BT	February/March	August/September	12.9	4.7
Gloucester Point	February/March	August/September	13.6	3.6
Hampton Roads	February/March	August/September	12.0	3.9
Kiptopeke	February/March	August/September	12.4	3.7
Solomon's Island	January/February	July/August	17.9	3.6

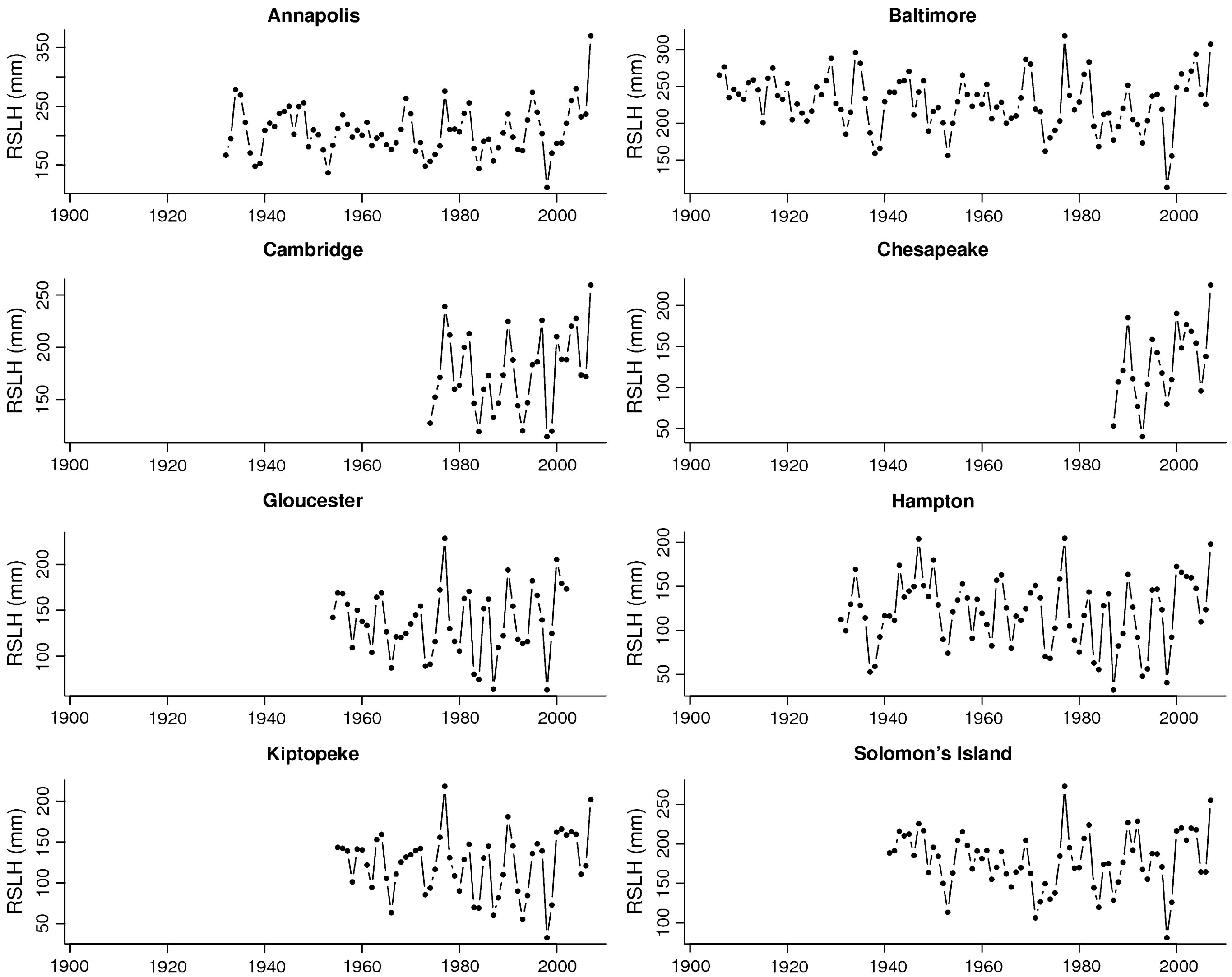

Fig. 6. Temporal evolution of the annual amplitude, computed as the difference between the maximum and minimum values of the annual component (γ_t^1) for each calendar year.

4. Discussion

The autoregressive-based approach to time series decomposition allows to extract flexible, time-varying long-term components from long tide gauge records. In this way, it is feasible to analyse long-term sea-level variability not only by estimating linear trends from the records, but also by examining fluctuations in seasonal and long-term patterns.

Sea-level variability in Chesapeake Bay shows considerable variability on seasonal and longer time scales. At the annual scale, variability is mainly determined by atmospheric factors, specifically atmospheric pressure and zonal (E–W). Zonal wind is more important than meridional wind in determining seasonal sea-level variability since a eastward wind drives water out of the Bay and off the coast, and a westward wind drives water onshore and inflow into the Bay, while N–S winds have an opposing effect at the inner Bay and the coast (e.g. Wang, 1979). No systematic trends are found in the amplitude of the annual cycle of sea-level. On longer time

Table 3
Spearman's rank correlation coefficient between annual amplitudes of sea-level and climate variables (SLP: sea-level pressure; PR: precipitation rate; Uwnd: zonal wind; Vwnd: meridional wind) for the common (1955–2007) period.

	SLP	PR	Uwnd	Vwnd
Annapolis	−0.43*	0.34*	0.45*	<|0.3|
Baltimore	−0.47*	<|0.3|	0.62*	<|0.3|
Cambridge	−0.64*	<|0.3|	0.70*	<|0.3|
Chesapeake BT	−0.54*	<|0.3|	0.62*	<|0.3|
Gloucester Point[a]	−0.40*	<|0.3|	0.56*	<|0.3|
Hampton Roads	−0.49*	<|0.3|	0.67*	<|0.3|
Kiptopeke	−0.46*	<|0.3|	0.63*	<|0.3|
Solomon's Island	−0.32*	0.37*	0.49*	<|0.3|

*Denotes statistical significant values, for a 95% confidence level.
[a] 1955–2002.

Table 4
Linear trends and corresponding standard errors for the complete period (as in Table 1) and for the common (1955–2007) period.

	Complete period (mm/year)	1955–2007 period (mm/year)
Annapolis	3.17 (±0.038)	3.01 (±0.069)
Baltimore	3.03 (±0.026)	2.66 (±0.075)
Cambridge	3.18 (±0.14)	–
Chesapeake BT	5.10 (±0.30)	–
Gloucester Point	3.69 (±0.088)	–
Hampton Roads	4.19 (±0.044)	4.40 (±0.086)
Kiptopeke	3.17 (±0.073)	3.16 (±0.075)
Solomon's Island	3.19 (±0.055)	3.33 (±0.080)

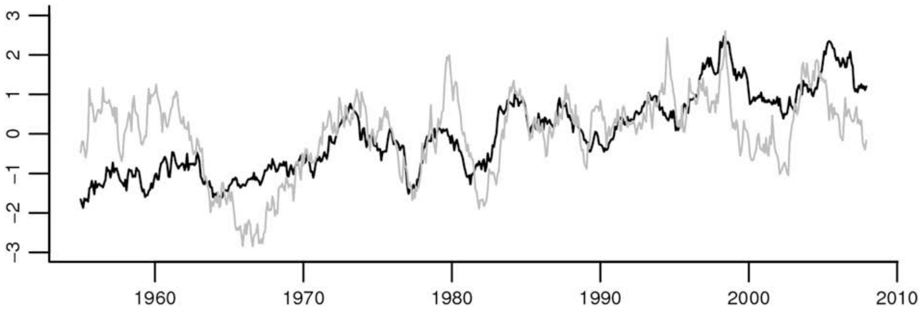

Fig. 7. First principal component time series from the five sea-level trend components available for the 1955–2007 period (black) and trend component of reanalysis precipitation rate (grey).

scales, precipitation rate, which can be considered a proxy for river discharge, is the main factor influencing decadal sea-level variability in Chesapeake Bay.

Sea-level trends in Chesapeake Bay, around 3 mm/year, are larger than the global estimate of 1.5–2 mm/year (Church and White, 2006), as a result of land subsidence. Local subsidence is caused by groundwater extraction (Gornitz and Seeber, 1990) while regional subsidence of the entire Mid-Atlantic coast results from post-glacial adjustment (Peltier, 1996). The very large trends in relative sea-level heights in the southern end of the Bay, at Hampton Roads and Gloucester Point, can result from enhanced subsidence through sinking of the filling of a large buried impact crater (Koeberl et al., 1996). Differential subsidence of the Exmore breccia would cause a differential lowering of the ground surface and bay floor over the crater, contributing an additional component to relative sea-level heights in the area (Poag et al., 2004).

5. Conclusions

Sea-level rise in Chesapeake Bay is not only determined by global sea-level rise associated with global climate change, but also influenced by local effects, such as subsidence associated with tectonic effects and fluid withdrawal from coastal aquifers, as well as by climate variability, particularly atmospheric effects (pressure and zonal winds) at the seasonal scale and hydrologic effects (associated with precipitation and river discharge) on longer time scales.

Linear trends in relative sea-level heights for the 1955–2007 period range from 2.66 ± 0.075 mm/year (at Baltimore) to 4.40 ± 0.086 mm/year (at Hampton Roads). Although trends of 3 mm/year may be unimpressive at face value, a sea-level increase of this magnitude poses a significant threat in terms of wetland loss and consequent environmental impacts due to the gentle slope of most of the bay margin. Coastal marshes are very susceptible to sea-level rise since their vertical accretion rates are limited (FitzGerald et al., 2008). Sea-level rise, can result in a state change in a marsh, generally over the course of decades (Alber et al., 2008). Under regimes of high sea-levels, marsh lands can be submerged if they are unable to migrate quickly enough up shore, and brackish marsh can convert into salt marsh, affecting the associated ecosystems. Other processes associated with sea-level rise such as erosion and accretion can have profound cumulative effects that are not yet predictable (Williams et al., 2009).

Sea-level rise not only inundates low-lying coastal regions, but perhaps more importantly, enhances the effect of waves and storm surges. A higher mean sea-level value means a higher level upon which surges build, causing storm surges to penetrate farther inland (Gönnert, 2004; Kleinosky et al., 2007). Since sea-level in Chesapeake Bay is strongly influenced by atmospheric pressure and winds, the atmospheric effects will be superimposed to surge propagation, enhancing the potential danger of storms, as suggested by model experiments (Shen et al., 2006).

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