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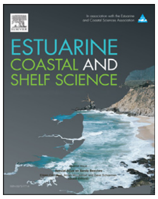

Fortnightly tides and subtidal motions in a choked inlet

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ABSTRACT

Amplitudes of semi-diurnal tidal fluctuations measured at an ocean inlet system decay nearly linearly by 87% between the ocean edge of the offshore ebb-tidal delta and the backbay. A monochromatic, dynamical model for a tidally choked inlet separately reproduces the evolution of the amplitudes and phases of the semi-diurnal and diurnal tidal constituents observed between the ocean and inland locations. However, the monochromatic model over-predicts the amplitude and under-predicts the lag of the lower-frequency subtidal and fortnightly motions observed in the backbay. A dimensional model that considers all tidal constituents simultaneously, balances the along-channel pressure gradient with quadratic bottom friction, and that includes a time-varying channel water depth, is used to show that that these model-data differences are associated with nonlinear interactions between the tidal constituents that are not included in non-dimensional, monochromatic models. In particular, numerical simulations suggest that the nonlinear interactions induced by quadratic bottom friction modify the amplitude and phase of the subtidal and fortnightly backbay response. This nonlinear effect on the low-frequency (subtidal and fortnightly) motions increases with increasing high-frequency (semi-diurnal) amplitude. The subtidal and fortnightly motions influence water exchange processes, and thus backbay temperature and salinity.

1. Introduction

As tidal waves propagate from the ocean through an inlet and into the backbay (lagoon), amplitudes decrease and phase lags develop relative to the oceanic sea-surface elevation fluctuations. If the amplitude reduction is large, the system is considered tidally choked. Tidal choking influences the amount of flushing from the lagoon to the ocean, which is important to coastal ecology, water quality, and sedimentation. Coastal lagoons have been divided into three categories (choked, restricted, and leaky) based on the ability of the lagoon to flush water (Kjerfve, 1986). Tidal choking occurs if there is a relatively long, narrow, or shallow channel connected to a backbay with a large surface area (Brown, 1928; Bruun et al., 1978; Hill, 1994) (Fig. 1). Most observations of tidal choking are associated with shallow coastal lagoons that typically are found in microtidal regimes with flat coastal plains (Kjerfve, 1986). Tidal choking also is observed in larger, deeper, narrow channel inlet systems with backbays (e.g. Indian River Inlet, DE, USA (Wong and Lu, 1994) and Fleet Lagoon, English Channel, UK (Robinson et al., 1983)).

The channel of a tidally choked inlet system acts like a hydraulic low-pass filter between the ocean sea-surface fluctuations and the backbay response (Di Lorenzo, 1988; Kjerfve and Knoppers, 1991). There is relatively greater damping of high-frequency, large amplitude tidal motions than of low-frequency, small amplitude tidal motions, and the phase difference between the ocean and backbay sea-surface fluctuations decreases with decreasing frequency (Keulegan, 1967). A number of relatively simple tidal (choking) models exist that describe the tidal amplitude decay and temporal lag in the backbay forced by oceanic tidal amplitudes and phases at the entrance of the inlet without (Keulegan, 1967; Stigebrant, 1980) and with (Hill, 1994) tidally varying channel water depths. In these models the ocean is connected to the backbay via a prismatic channel, resulting in linear amplitude decay along the channel owing to bottom friction (Fig. 1).

Models that account for a time-varying water depth suggest that the frictional effect decreases during flood tides and increases during ebb tides (Hill, 1994). This frictional asymmetry allows water to flow more easily into the backbay than out to the ocean,

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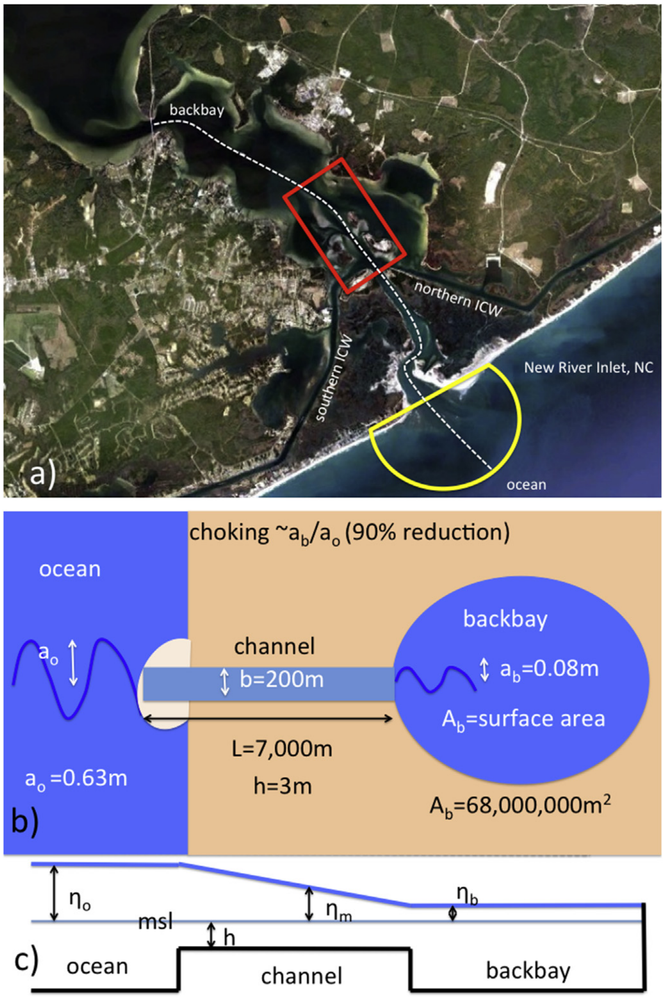

Fig. 1. a) Google Earth image of New River Inlet, NC showing the Atlantic Ocean, the backbay, the northern and southern ICW, the main channel (white dashed curve), the dredge spoil (red box), and the ebb-tidal delta (yellow semi-circle). b) Plan form and c) profile view of the tidal-choking model with dimensional inlet features of New River Inlet, NC. a_o is the ocean M2 tidal amplitude, a_b is the backbay M2 tidal amplitude, b is the channel width, L is the channel length, h is the channel water depth, A_b is the backbay surface area, and η_o, η_m, and η_b are the surface elevations at the ocean, channel, and backbay, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

resulting in a set-up in the backbay sea-surface elevation. Time varying water depths owing to M2 and S2 tides induce a nonlinear fortnightly elevation response in the backbay that depends on the amount of tidal choking and the channel water depth (Hill, 1994).

Here, observations of sea-surface elevation obtained in the large, tidally choked inlet system at New River Inlet, NC, are used to drive a dynamical model to predict the corresponding backbay response, including the long time lags between low-frequency (aperiodic subtidal and periodic fortnightly) motions in the backbay and the ocean. For previous tidal choking models (Keulegan, 1967; Bruun et al., 1978; Stigebrant, 1980; Di Lorenzo, 1988; Hill, 1994; Albrecht and Vennell, 2007) the governing equations were written in a *non-dimensional* form parameterized by the amplitude and period of a single tidal constituent, restricting the application of the governing equations to a single (monochromatic) tidal constituent. Thus, these models cannot simulate the nonlinear interactions between multiple tidal constituents. In contrast, here a *dimensional* tidal choking model applicable to all tidal constituents simultaneously is used in combination with the field observations to investigate the nonlinear effects of the semi-diurnal (M2, S2) and diurnal (K1, O1) tides on the generation and propagation of aperiodic low-frequency subtidal and fortnightly (MSF) motions commonly observed in the ocean (Hill, 1994; Wong and Lu, 1994; amongst others). The influence of the subtidal and fortnightly motions on water temperature and salinity is described.

2. Field observations

Observations were obtained in May 2012 at New River Inlet, NC. This system has an ebb-tidal delta that is approximately 1 km in radius on the ocean side. The channel that connects the ocean to the large surface area (68 km^2) backbay is relatively long (7000 m), narrow (200 m), and shallow (3 m) (Fig. 1a,b). The primary channel and the interconnecting Intracoastal Waterway (ICW) (Fig. 1a) are dredged to maintain shipping navigation. Dredge spoil usually is placed next to the primary channel and in the ICW (Fig. 1a). The placement of the dredge spoil in the backbay increased the length of the tidal channel and has created the appearance of a flood-tidal delta (Fig. 1a, red box). There are additional inlets connecting the ICW to the ocean 12 km to the north and 36 km to the south (not shown). The proximity of these neighboring inlets affects the tidal wave interaction as it propagates into the inlet and then along the ICW (described below).

Short- (~1 day) and long- (~3 weeks) term pressure measurements were obtained using pressure sensors with ±0.5 cm accuracy throughout the ocean, inlet, backbay, and both north and south of New River within the ICW (Fig. 2). The absolute subaqueous pressure signal was corrected for atmospheric pressure fluctuations. A suite of instruments was attached to one of six, easily moved small floating catamarans ("mini-cats") that were anchored to the seabed. A pressure sensor sampling at 1 Hz was attached to the mini-cat anchors to measure sea-surface elevation. Measurements were obtained for $t > 24$ h so that tidal harmonic analysis (T_TIDE, Pawlowicz et al., 2002) could be performed to determine the approximate amplitudes and phases of the diurnal, semi-diurnal, and higher harmonic tidal constituents of the detrended sea-surface elevation observations by a least-squares fit. In addition to the short-term deployments, long-term (~3 weeks) pressure measurements were obtained outside of the ebb-tidal delta in 9-m water depth (inlet km 0, Fig. 3) and in the backbay (inlet km 10, Fig. 3).

3. Field experiment results

3.1. Tidal constituents

At the ocean boundary, the tidal signal is dominated by the M2 tidal constituent (period T = 12.42 h, amplitude a = 0.63 m)(not shown). The other relevant tidal constituents are K1 (lunisolar, T = 23.94 h, a = 0.11 m), S2 (principal solar, T = 12 h, a = 0.08 m), O1 (principal lunar, T = 25.82 h, a = 0.08 m), and MSF (lunar-solar-fortnightly, T = 354.37 h, a = 0.15 m). The tidal constituents represent 93% of the variance, implying that the signal is primarily tidal. The M2 amplitude decreases with distance into the backbay (a = 0.08 m, Figs. 2 and 3), and with distance along the ICW channels (Fig. 2). The amplitude decrease is larger in the southern ICW channel than in the northern ICW channel, possibly owing to the different distances to the neighboring inlets. While the amplitude of the M2 constituent (derived from the short-term estimates) decreases with distance from the ocean (Fig. 2a), the temporal lag increases (Fig. 2b). Lags are larger in the southern ICW channel than in the northern ICW channel, consistent with stronger tidal choking in the southern channel. The southern channel has reduced