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Physical properties and processes in the Bristol Channel and Severn Estuary

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ABSTRACT

This article firstly describes the physical properties of the Bristol Channel and Severn Estuary in the context of its adjacent seas. These properties include tidal ranges and tidal phases at mean spring tides, storm surge characteristics, wind-driven currents and water levels, and frontal evolution. Simulated data on peak current speeds within the Channel at mean spring and mean neap tides are then presented, together with simulated data on annual mean wind speeds and wave heights. Analyses of observed data are described in the second part of the article. The analyses cover elements of three topics: the influences of tides, topography, runoff, salinity, wind and atmospheric pressure on residual currents and mean water levels; the identification of mechanisms involved in residual water, salt and suspended particulate matter (SPM) transport; and the identification of an exceptionally strong estuarine turbidity maximum (ETM) in the upper reaches of the Severn. Gravitational circulation was evident and strong spring-neap variations in near-bed, mid-depth and upper water column residual currents were identified that demonstrated the importance of non-linear tidal generation due to advection of momentum. Near-bed and mid-depth wind-driven residuals generally were oppositely directed to the wind in the central and inner Channel. A combination of data analyses, analytical modelling of vertical current structure and depth-averaged hydrodynamic modelling was used to interpret features of the data. Analyses of the mechanisms driving residual water, salt and SPM transport at a station in the lower Severn during neap tides showed that vertical shear mechanisms were relatively unimportant to salt and SPM transport. The residual advection and tidal pumping transport mechanisms were quantified.

1. Introduction

The Severn Estuary and Bristol Channel constitute a large, partially enclosed body of tidal waters in southwest Britain. The system is ca. 250 km long, is slowly flushed (ca. 200 days) and becomes increasingly tidal and turbid from its mouth to its upper reaches, increasing in tidal range from ca. 7 to 12 m at mean spring tides and ca. 0.001–50 g l^{-1} of suspended particulate matter (Uncles et al., 2002). Fast tidal currents produce strong horizontal and vertical mixing and large bed stresses. These lead to pronounced horizontal dispersion (Uncles and Radford, 1980; Uncles, 1979, 1982b), near vertical homogeneity in salinity, temperature and phytoplankton (Uncles and Joint, 1983) and tide-dominated bed sediment transport, sediment distributions and benthic faunal communities (Warwick and Uncles, 1980). The area has received considerable attention from coastal oceanographers in the past, both because of the theoretical interest arising from its tidal range, which is amongst the largest in the world, and the interest in tidal energy propagation, dissipation and power generation (e.g. Shaw, 1987; Uncles and Jordan, 1994; BERR, 2009). Much of our understanding of its tidal and residual (tidally averaged) circulation has been derived from numerical, three-dimensional hydrodynamic models (Owen, 1980; Stephens, 1986; Wolf, 1987) and one- and two-dimensional hydrodynamic models and their comparisons with data (Uncles, 1981a,b, 1982a,b, 1983, 1984, 1991; Uncles and Jordan, 1979, 1980, 1994). Circulation models have also been used for early studies of the region's water quality (Radford et al., 1981; Rattray and Uncles, 1983), ecology (Radford and Uncles, 1980; Uncles and Joint, 1983) and meteorological forcing (Proctor and Flather, 1989). Considerable information is available on the distribution and behaviour of suspended fine sediments (Kirby and Parker, 1982, 1983; Collins, 1983; Joint, 1983; Kirby, 2010).

Although there appears to have been no new reviews on the Channel-wide hydrodynamics of the region in the last 25 years, there has been a large amount of scientific work on various aspects of the Channel's water quality and ecology (see SEP, 2008, for numerous presentations of recent work). Some of this newer work has included hydrodynamic modelling, as well as models of estuarine morphology and catchment-wide nutrient and bacterial distributions (Wolf, 1987; Lin and Falconer, 2001; Harris et al., 2004; Bockelmann-Evans et al., 2007; Jones et al., 2007; Phillips, 2007; Schnauder et al., 2007). Over the last 20 years, considerable

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research has been undertaken into the behaviour of the Severn's intertidal areas. This research has included the mechanisms of bed-form generation and the sedimentation properties of mudflats and saltmarshes and their dependence on meteorological variables and tides (e.g. Allen and Rae, 1988; Lee, 1996; Allen and Duffy, 1998a,b; O'Brien et al., 2000; Haslett et al., 2001; Allen et al., 2006; Allen and Haslett, 2006, 2007; Williams et al., 2006, 2008; Allen and Dark, 2008; Kirby and Kirby, 2008). Research on waves in the Channel, including catastrophic waves, has received some attention in recent years (e.g. Davies and Glorioso, 1999; Jones, 2000; Bryant and Haslett, 2007). The effects of rising sea level over the Holocene have been discussed by Bell (2004).

The objectives of this article are twofold. First, to provide an account of our current knowledge of the physical, water-column properties of the Bristol Channel and Severn Estuary (the Channel) and place these in the context of the system's geographical environment, from shelf and coastal sea to tidal river. The variables of concern are water, salt, heat and suspended particulate matter (SPM) transport. To this end, the aim of Section 2 is to demonstrate the relationship between Channel and coastal-sea variables (tides, storm surges, wind-driven currents, fronts) and then present other aspects of the data within the Channel where greater spatial detail is necessary (tidal currents, winds and waves). The second objective, and the aim of Sections 3 and 4, is to present some new aspects of data from observations that have been made at stations in the Channel, in particular the effects of winds and density gradients on residual currents and to investigate the dominant mechanisms for residual salt and SPM transport. The very strong estuarine turbidity maximum (ETM) that exists within the Severn's tidal river is illustrated using survey data. A review of the underlying processes affecting the Channel's overall hydrodynamics, mixing and salinity was given by Uncles (1984) and that review does not appear to have been superseded. It concluded by noting that the effects of wind on the residual circulation were unknown. It is therefore the intention of this article to illustrate different aspects of the data, update findings where more recent simulations of the physical properties have been computed, and use archived data to present new insights into the Channel's physical behaviour, including wind effects.

2. Review of physical water-column properties of the Bristol Channel

Physical water-column properties are illustrated for the Bristol Channel and its adjacent coastal seas at a large spatial scale. A finer spatial scale is used for the presentation of data within the Channel.

2.1. The Channel in its shelf-wide context

The shelf area considered here includes the Bristol Channel, English Channel, Celtic Sea and the St. George's Channel entrance to the Irish Sea (Fig. 1). This wider region illustrates the interdependence of the adjacent coastal seas and the Channel's tidal range and tidal phase, meteorological forcing (storm surges and steady wind-driven currents and water levels) and frontal behaviour. Although these shelf data are usually treated as boundary conditions across the Channel's mouth, their presentation helps to place the Channel in its shelf-wide context.

2.1.1. Mean spring tidal ranges and phases

Sinha and Pingree (1997) and Pingree and Griffiths (1981, 1987) have presented data for the main semi-diurnal tidal constituents over the shelf in this region: M_2, S_2 and N_2. In this article, mean spring and neap tidal ranges are presented rather than individual tidal constituents. The mean spring tidal range at a location, MSTR, is defined as the difference in water-levels between mean high-water springs and mean low-water springs. Contours of MSTR for the Bristol Channel and its adjacent coastal seas (Fig. 1A) illustrate that the range increases from ca. 3 m near the shelf break, to more than 12 m in the upper Severn Estuary (HO, 1996). Co-tidal lines are drawn through locations of equal Mean High Water Interval (MHWI) and are shown in Fig. 1B. MHWI is defined as the mean time interval between the passage of the moon over the Meridian of Greenwich and the time of the next high water (HW) at the place concerned. MHWI increases from ca. 3.5 h close to the shelf break to more than 5.5, 7 and 10 h near the St. George's Channel entrance of the Irish Sea, the upper Severn Estuary of the Bristol Channel, and the eastern English Channel, respectively (HO, 1996, Fig. 1B). More recently produced maps of spring tidal range in the region also are available on the web (see BERR, 2004).

2.1.2. Storm surges

Storm surges are caused by strong winds and associated low atmospheric pressure during storms. A contour map of storm surge elevations in water level for a 50-year return period (Flather, 1987) is shown in Fig. 1C. Elevations increase from approximately 0.5 m close to the shelf break to between 0.75 and 1.25 m near the St. George's Channel entrance to the Irish Sea and exceed 1.5 m in the Bristol Channel. A contour map of the maximum storm surge current speeds associated with the surge elevations shown in Fig. 1C, i.e. for a 50-year return period (Flather, 1987), is shown in Fig. 1D. Maximum speeds increase from approximately 0.2 m s^{-1} near the shelf break to approximately 0.4 m s^{-1} in the central Celtic Sea, before decreasing again to 0.2 m s^{-1} near the St. George's Channel and the Bristol Channel. The arrows in Fig. 1D indicate the direction of maximum surge current in those regions that show a directional preference.

2.1.3. Wind-driven currents

Currents driven by a steady, uniform wind-stress on the shelf seas around the British Isles have been modelled by Pingree and Griffiths (1980). Their numerical model superimposes the wind on an accurate model of the average tide, so that the steady, wind-driven currents are estimated when simulated currents computed with and without wind are subtracted. Steady winds from the southwest that correspond to a stress of 0.16 Pa (ca. 10 m s^{-1}) produce depth-averaged residual currents to the southeast (of magnitude a couple of cm s^{-1}) close to the shelf break and across the Celtic Sea (Fig. 2A). A north-flowing current is formed along the north Cornwall and Devon coasts and across the mouth of the Bristol Channel (typically a few cm s^{-1}) and a south-flowing return flow occurs in the central reaches of the St. George's Channel. Water levels that correspond to the southwest wind are shown in Fig. 2B. These are very small close to the shelf break and across the Celtic Sea and show an increase from 0.025 m in the St. George's Channel to over 0.1 m in the Bristol Channel.

Steady winds from the southeast that correspond to a stress of 0.16 Pa produce depth-averaged residual currents that flow to the northwest (of magnitude a couple of cm s^{-1}) close to the shelf break and across the Celtic Sea (Fig. 2C). However, a north-flowing current is again formed along the north Cornwall and Devon coasts and across the mouth of the Bristol Channel (again, typically a few cm s^{-1}) but in this case there is no south-flowing return flow in the central reaches of the St. George's Channel. Water levels that correspond to the southeast wind are shown in Fig. 2D. These are less than 0.025 m close to the shelf break and increase to more than 0.05 m in the St. George's Channel. Levels decrease to zero in the inner Bristol Channel and Severn.

Although uniform and steady wind conditions may rarely occur in nature, a southwest or west-southwest wind approximates to