Cesar H. A. Ribeiro - Joanna J. Waniek Jonathan Sharples

# Observations of the spring-neap modulation of the gravitational circulation in a partially mixed estuary

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Abstract The long-term variability of the non-tidal circulation in Southampton Water, a partially mixed estuary, was investigated using 71-day acoustic Doppler current profiler (ADCP) time series. The data show evidence that the spring-neap tidal variability of the turbulent mixing modulates the strength of the non-tidal residual circulation, with subtidal neap tide surface flows reaching 0.12 m s<sup>-1</sup> compared to <0.05 m s<sup>-1</sup> at spring tides. The amplitude of the neap-tide events in this nontidal circulation is shown to be related to a critical value of the tidal currents, illustrating the strong dependence on tidal mixing. The results suggest that the dominant mechanism for generating these neap-tide circulation events is the baroclinic forcing of the horizontal density gradient, rather than barotropic forcing associated with ebb-induced periodic stratification. While tidal turbulence is thought to be the dominant control on this gravitational circulation, there is evidence of the additional effect of wind-driven mixing, including the effects of wind fetch and possibly wave development with along-estuary winds being more efficient at mixing the estuary than across-estuary winds. Rapid changes in atmospheric pressure also coincided with fluctuations in the gravitational circulation. The observed subtidal flows are shown to be capable of rapidly flushing buoyant material out of the estuary and into the coastal sea at neap tides.

Keywords Gravitational circulation - Net transport -Tidal mixing - Stratification

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#### 1 Introduction

The net flow of water into and out of estuaries influences the exchanges with the surrounding coastal region, thus playing a role in controlling the estuarine environment by regulating the transport of, for instance, nutrients, sediments, planktonic organisms and pollutants. Temporal variability of the net flow is therefore a key parameter in estuarine ecology and environmental management.

The longitudinal density gradient is a main characteristic of many estuaries, extending from the less dense riverine freshwater to the denser seawater. The gravitational circulation is driven by this gradient, and is characterised by a surface current flowing seaward and a landward near-bed flow. This bidirectional flow will act to induce stratification, competing against tidal mixing to determine the vertical structure of the estuarine water column. Changes in the tidal currents on the springneap tidal cycle can modulate the tidally driven turbulent mixing above and below the critical rate required to prevent stratification. The resulting fortnightly modulation of stratification has been observed in partially mixed estuaries (Haas 1976), in fords (Winter 1973), in shallow coastal gulfs (Nunes and Lennon 1987) and shelf regions of freshwater influence (Simpson et al. 1990). Turbulence induced by wind stress on the surface can also contribute to the controls on stratification (Goodrich et al. 1987: Van de Kreeke and Robaczewska 1989).

While the increased gravitational currents may not be observed, the effects of the currents can be seen in the subsequent increase in stratification. The direct observation of the response of the gravitationally driven currents to modulated mixing is more difficult. The link can be inferred from the theoretical analysis of Hansen and Rattray (1965). Assuming a tidally averaged condition, Officer (1976) derived the profile of the gravitationally driven flow as:

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