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Observations of a tidal intrusion front in a tidal channel

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ABSTRACT

A visible front indicated by a surface colour change, and sometimes associated with foam or debris lines, was observed in a tidal channel during neap tide. This is an example of a tidal intrusion front occurring in the absence of sudden topographical changes or reversing flows, typically reported to be associated with such fronts. Detailed Acoustic Doppler Current Profiler and conductivity/temperature/depth measurements were taken on repeated transects both with fronts apparent and with fronts absent. The results indicated that the front occurred as a result of stratification, which was sustained by the buoyancy flux and the weak tide-induced mixing during neap ebb tide. The stronger tide-induced mixing during spring tide restrained stratification, leading to the absence of a front. The mechanism of the frontogenesis was the density gradient between the stratified water formed during neap ebb tide, and the more mixed seawater during neap flood tide; thus, the water on the landward (southwestern) side of the front was stratified, and that on the seaward side (northeastern) of the front was vertically well mixed. Gradient Richardson number estimates suggest that the flow between the stratified and mixed water was near the threshold 0.25 for shear instability. Meanwhile, the density gradient would provide an initial baroclinic contribution to velocity convergence, which is indicated by the accumulation of buoyant matter such as foam, grass, and debris into a sharply defined line along the surface. The front migrates with the flood current, with a local maximum towards the eastern side of the channel, leading to an asymmetrical shape with the eastern side of the front driven further into the Tiaozhoumen tidal channel.

1. Introduction

Tidal intrusion fronts are often formed when dense water flows into a basin of less dense water and retains its character as a separate, underflowing dense layer (Largier, 1992). Take an estuary for example, a tidal intrusion front is formed when the tidal inflow of dense seawater floods and prevents a simultaneous buoyant outflow in or near the estuary mouth during flood tide (Thain et al., 2004; Uncles, 2011). The fronts are often visible at the surface due to the presence of debris and foam caused by the strong surface convergence, or/and colour differences between the marine and estuarine water masses along the plunge line (Largier, 1992).

These fronts have been observed in many estuaries around the world, including Port Hacking Estuary in Australia, the Palmiet and Qora estuaries in southern Africa, and the Dart estuary in the UK. Most of them are associated with morphological features consisting of a large and sudden change in depth or width (Clifton et al., 1973; Huzzey, 1982; Largier, 1986; Largier and Taljaard, 1991; Uncles and Stephens, 1997; Thain et al., 2004; Booth, 1987). Brubaker and Simpson (1999) gave a schematic figure of a tidal intrusion front associated with a depth increase. When the tidal flood current flows over the sill, the inflow undergoes a hydraulic jump due to the change in depth, which decelerates the flow. At this point, the inflow no longer has sufficient velocity to resist the outflow and the flow stratifies, resulting in the formation of a front. For this type of tidal intrusion front, it is the topography associated with regions of minimal channel cross sectional area, such as a sill or width constriction, which triggers their formation. For more details, see Brubaker and Simpson (1999). The dynamics of these types of fronts have been successfully described by the internal hydraulic theory of Farmer and Armi (1986) and Armi and Farmer (1986).

However, tidal intrusion fronts do not always depend on a controlling morphological feature. An example has been described by Simpson and Nunes (1981) in the Seiont River of North Wales, UK. Here, when the flood tide flows in, the surface flow on either

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side of the water mass moves in a reversing direction towards it, resulting in a front. A significant feature of this type of front is a characteristic "V" formation at the surface and a strong point convergence at its apex. For more details of this tidal intrusion front see Simpson and Nunes (1981).

In this study, a tidal intrusion front was observed in a tidal channel, which is not related to a constriction as in the first category of tidal intrusion described above, or following the characteristic shape of the latter one. When the front was present, sampling with an Acoustic Doppler Current Profiler (ADCP) on repeated transects across the front, and conductivity/temperature/depth (CTD) station sampling provided information on the structure of the flow field and density distribution near the front. Additionally, when the front was absent, repeated transects in the Tiaozhoumen tidal channel were undertaken and showed that this tidal intrusion front is strongly associated with stratification during the neap-spring transition.

2. Study area

2.1. Topography

Tiaozhoumen Channel is located between the islands of Liuheng and Xiazhi, in Zhejiang Province, China (Fig. 1). The southwestern side of the channel is the coastline of Liuheng Island, while the northeastern side of the channel are open to several entrances to the Xiazhimen Channel. Based on bathymetric data, the channel can be divided into three segments according to their topographic features. First, in the lower channel segment there are a large number of islands. The terrain here is irregular, and the channel has several entrances. Second, the middle channel is relatively flat, with 10–20 m depth contours running approximately parallel to the coastline, and reaching a maximum depth of 30 m. Third, in the upper channel segment there are many reefs and shoals, and the underwater topography is irregular. The main channel in this segment shows a north-south direction, inconsistent with the shore-parallel channel in other segments. Therefore, the tidal channel in this study area forms a bend, keeping parallel to the shoreline of Liuheng Island.

2.2. Oceanography

A number of recent studies investigating currents through Tiaozhoumen Channel have been undertaken by the Second Institute of Oceanography, State Oceanic Administration, China (e.g. Li et al., 1994; Yang et al., 2004). Based on the observational data accumulated since 1994, the general oceanographic setting of the study area is described as follows:

The flow in the tidal channel is dominated by semi-diurnal tidal currents. The study area has a variable spring-neap tidal range, with a 3.1 m mean spring range and a 1.4 m mean neap range. Waves are not significant for most of the year, with a mean wave height of 0.3 m, increasing to 2.5 m only under typhoon conditions (usually between July–September) (Li et al., 1994).

The current flow is affected by the local topography and shoreline morphology. In general, reciprocating flows dominate in the main channel, but in the lower channel segment, the appearance of a number of islands results in a characteristic flow rotation. The flow directions in the upper, middle and lower channel segments differ as a result of the curvature of the coastline of Liuheng

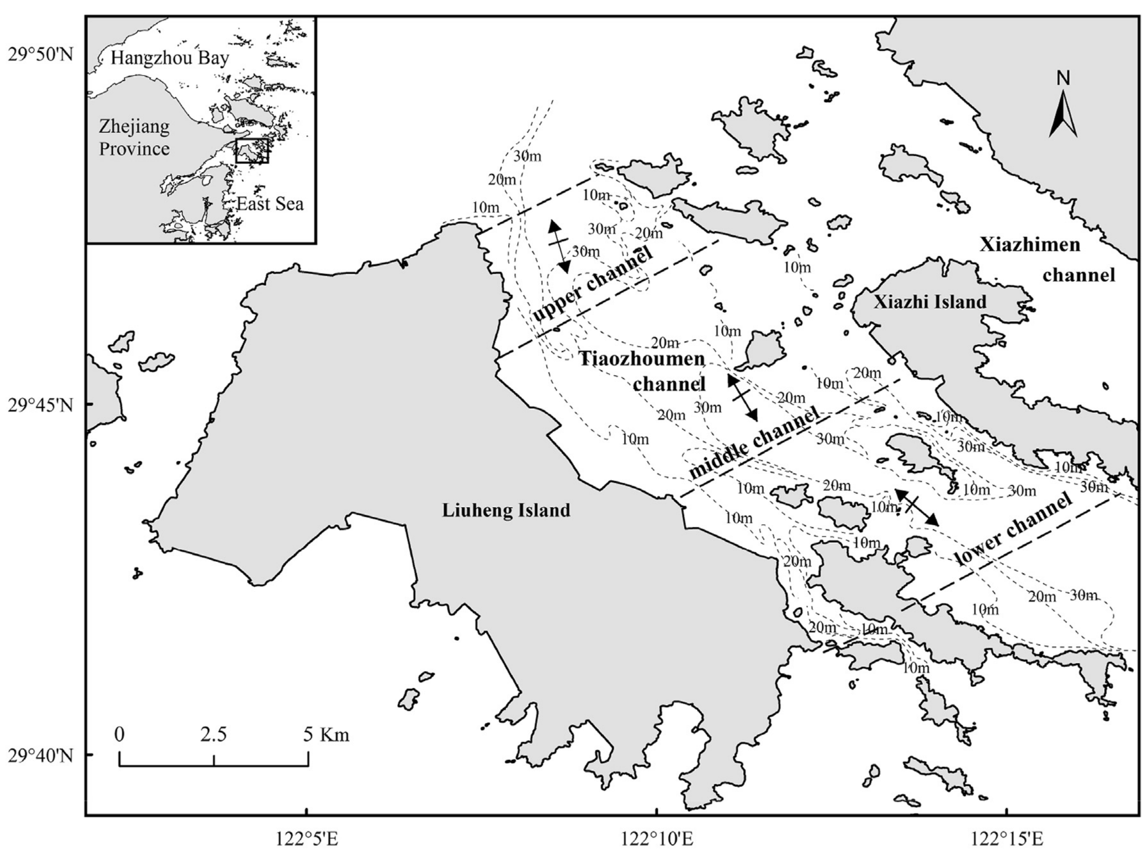

Fig. 1. The study site of Tiaozhoumen tidal channel, in the lower channel segment there are several islands and a rotation of the flow, in the middle channel segment the topography is flat and the flow is reciprocating, in the upper channel segment there are many reefs and shoals, with a predominantly reciprocating flow.