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Form drag is a major component of bed shear stress associated with tidal flow in the vicinity of an isolated sand bank, Torres Strait, northern Australia

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ABSTRACT

Tidal current and elevation data were collected from five oceanographic moorings during October 2004 in Torres Strait, northern Australia, to assess the effects of large bedforms (i.e., sand banks) on the drag coefficient (C_D) used for estimating bed shear stress in complex shallow shelf environments. Ten minute averages of tidal current speed and elevation data were collected for 18 days at an on-bank site (<7 m water depth) and an off-bank site (<10 m). These data were compared to data collected simultaneously from two shelf locations (<11 m) occupied to measure regional tidal behaviour. Overall C_D estimates at the on- and off-bank sites attained $7.0 \pm 0.1 \times 10^{-3}$ and $6.6 \pm 0.1 \times 10^{-3}$, respectively. On-bank C_D estimates also differed between the predominant east–west tidal streams, with easterly directed flows experiencing $C_D = 7.8 \pm 0.18 \times 10^{-3}$ and westerly directed flows $C_D = 6.4 \pm 0.12 \times 10^{-3}$. Statistically significant differences between the off-bank and on-bank sites are attributed to the large form drag exerted by the sand banks on the regional tidal currents, and statistically significant differences between the westward and eastward flows is ascribed to bedform asymmetry. Form drag from the large bedforms in Torres Strait comprises up to 65% of the total drag coefficient. When constructing sediment transport models, different C_D estimates must therefore be applied to shelf regions containing steep bedforms compared to regions that do not. Our results extend the limited inventory of seabed drag coefficients for shallow shelf environments, and can be used to improve existing regional seabed mobilisation models, which have direct application to environmental management in Torres Strait.

1. Introduction

Internationally, environmental management of continental shelf seas has evolved from a crisis-oriented, discipline-based reaction to alarming trends (e.g., measured depletion of fisheries) or perceived threats to endangered species, to a more proactive, science-based discipline involving geographic information systems (GIS) and modelling of processes at multiple spatial–temporal scales. A key underlying capability needed for science-based management is the ability to predict the environmental response to perturbations of either a natural or anthropogenic origin. Models of continental shelf processes (physical, biological and chemical), at spatial–temporal resolutions tailored to address specific management issues, are increasingly being used to provide support for decision-making. Examples of the broad range of model applications include predicting the fate of dredge spoil (e.g., Jørgensen and Edelvang, 2000), the dispersal of marine pests (e.g., Dight et al., 1990) and to provide an estimate of the connectivity of different locations on the continental shelf, as sources or sinks of larvae (Condie et al., 2005).

In the tide-dominated shelf of Torres Strait, northeastern Australia, modelling work has attempted to address environmental issues involving the dispersal of river-supplied mining waste and its possible impact on coral reefs and seagrasses (e.g., Hemer et al., 2004). Major impediments to modelling the hydrodynamics and sediment transport processes in such areas are the lack of sufficient bathymetric and bed roughness data. In this case, the bathymetry of the region is complicated by the presence of coral reefs and wide-spread fields of mobile sand banks (Harris, 1988; Daniell and Hughes, 2007). These features act as roughness elements of the seabed and they must be accounted for in hydrodynamic models that attempt to represent processes that act over a comparable length scale.

Of paramount importance to sediment transport and resulting seabed dynamics is the bed shear stress. For a steady unidirectional flow, the total bed shear stress τ_b can be calculated using the quadratic stress law:

$$\tau_b = \tfrac{1}{2}\rho C_D U^2 \tag{1}$$

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where ρ is the water density, C_D is a drag coefficient, and U is the time-averaged flow velocity. In shelf environments dominated by cohesionless bed sediments (grain size $>64\,\mu m$), τ_b can be partitioned into three components related to different roughness types: (1) skin friction, (2) form drag, and (3) an apparent roughness due to sediment movement as bedload (e.g., Dyer, 1986; Wright, 1995). This partitioning is largely handled through employing different values for the drag coefficient, depending on requirements. For example, in the case of regional scale numerical models of tidal currents, a drag coefficient representative of the sum of all three roughness types is appropriate to correctly account for frictional energy dissipation (e.g., Wolanski et al., 1995; Saint-Cast, 2008). Alternatively, in the case of sediment entrainment, a drag coefficient representative of only the skin friction component is appropriate (e.g., Dyer and Soulsby, 1988).

The methods and field measurements used for estimating values of C_D must be sympathetic to the research goals. The skin friction component of the bed shear stress and related C_D can be estimated using one of two methods. The first involves measurement of the vertical profile of time-averaged horizontal velocity in the logarithmic or constant-stress part of the boundary layer, which usually occupies the first 1–3 m above the seabed on shallow shelves (e.g., Smith and McLean, 1977; Cacchione and Drake, 1982). The second method involves measurements of the three-dimensional turbulence at a single elevation anywhere within the constant-stress part of the boundary layer (e.g., Grant et al., 1984; Huntley, 1988). To estimate the total bed shear stress and related drag coefficient representing all three roughness contributions, the dynamic momentum balance can be used, which requires measurements of the depth-averaged flow velocity and horizontal pressure gradient (e.g., Huntley et al., 1993; Williams, 1995). While most studies require either the total bed shear stress or only the skin friction component, it is often necessary to consider the form drag component either implicitly or explicitly, because when present, it is typically the largest roughness contributor. For example, sediment transport modelling based on the total bed shear stress may be close to the mark in the absence of bedforms, but may be grossly over-estimated when form drag over the bedforms is significant.

Isolated sand banks with superimposed dunes are ubiquitous on the Torres Strait shelf. They are expected to act as significant roughness elements influencing shelf currents and ultimately sediment transport pathways. Their detailed role in the shelf sediment budget is still unknown, yet those involved in regional marine planning and management require modelled (if not measured) estimates of the sediment budget as soon as possible (Harris et al., 2008). The aim of this paper is to contribute towards the facilitation of this regional modelling by determining the differences in tidal flow between a site located on an isolated sand bank and an adjacent site free from any direct influence of a sand bank. The comparison is specifically focussed on quantifying any impact that the sand bank has on the drag coefficient used to estimate total bed shear stress. This is partly motivated by the need to improve existing models that predict seabed mobilisation in Torres Strait, but currently ignore the contribution of form drag to the modelled bed shear stress (Hemer et al., 2004). In a broader context, this research complements similar studies conducted on shelves displaying extensive bedform fields rather than the isolated sand banks investigated here (e.g., Huntley et al., 1993, 1994; Williams, 1995). Finally, this research extends the limited inventory of seabed drag coefficients currently available for shelf environments (see Soulsby, 1997).

The following section describes the physiography of the Torres Strait shelf. A description of the field data and processing methods are presented in Section 3. The results section (Section 4) compares the measured current behaviour between an instrument station located on a sand bank and one located off the sand bank, and utilises both to estimate drag coefficients representative of the total bed shear stress using the dynamic momentum balance. A discussion of implications for regional scale numerical modelling of flows and sediment transport on the Torres Strait shelf follow in Section 5 and conclusions in Section 6.

2. Regional description

Torres Strait is located between Cape York Peninsula (northern Australia) and Papua New Guinea, bounded to the east by the northern limit of the Great Barrier Reef and Coral Sea and to the west by the Arafura Sea. It is a political boundary between Australia, Papua New Guinea and Indonesia, and a major shipping route between the northern ports of Australia, Southeast Asia and the Pacific. It also contains valuable fisheries and sensitive seagrass habitats that support dugong and green turtle populations (Williams and Staples, 1990).

In the direction of the tidal stream, the Strait is approximately 500 km long (east–west) and 300 km wide (north–south). It includes a chain of islands and patch reefs extending north–south, many with fringing reefs that are elongated up to 18 km in an east–west direction (Fig. 1; Woodroffe et al., 2000). These reefs form natural boundaries to intervening channels that are typically 1–3 km wide. The seabed throughout the Strait is shallow with large areas in the range 6–9 m deep, but including navigable shipping channels 15–25 m deep (Wolanski et al., 1988; Harris, 1994; Hemer et al., 2004). The Strait is a sedimentological mixing zone, sandwiched between the largest modern tropical carbonate province on Earth (Great Barrier Reef) and a continental margin delivering vast amounts of terrigenous sediment to the ocean (Papua New Guinea). Sands and gravels dominate the carbonate fraction and are made up of the skeletal remains of benthic foraminifers, molluscs, bryozoans and coral. *Halimeda* is locally important. The terrigenous fraction is largely relict quartz sands and silts and clays (Maxwell, 1968; Harris and Baker, 1991).

Widespread areas of the seabed in Torres Strait are covered with mobile sand and gravel bedforms. Large-scale sand banks are numerous, principally located in the west between the islands, and exhibit a variety of forms that are related to the availability of

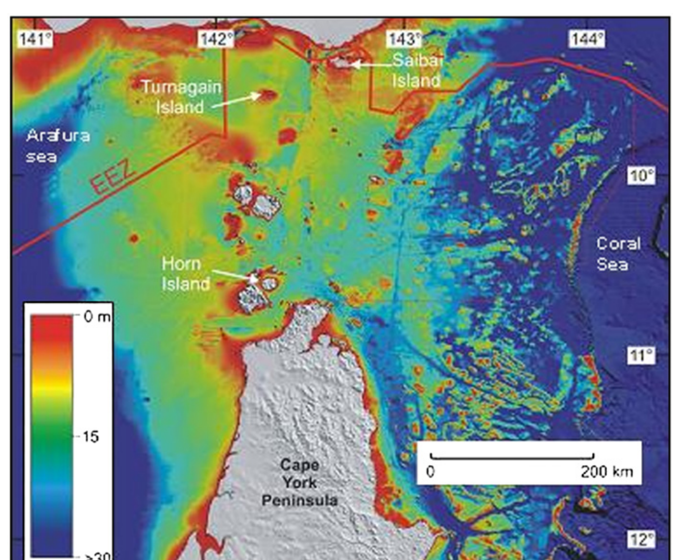

Fig. 1. Regional map of Torres Strait showing the location of Turnagain Island where the current metres were deployed, and Horn Island where wind data were recorded.