Available online at www.sciencedirect.com
ScienceDirect
Progress in Oceanography 70 (2006) 255–270
Progress in Oceanography
www.elsevier.com/locate/pocean

Sediment distribution and transport across the continental shelf and slope under idealized wind forcing

Scott A. Condie [a,*], Christopher R. Sherwood [b,1]

[a] CSIRO Marine and Atmospheric Research, GPO Box 1538, Hobart, Tasmania 7001, Australia
[b] U.S. Geological Survey, Coastal and Marine Geology, 384 Woods Hole Road, Woods Hole, MA 02543-1598, USA

Received 1 November 2004; received in revised form 5 May 2005; accepted 27 July 2005
Available online 27 June 2006

Abstract

Resuspension, transport, and deposition of sediments over the continental shelf and slope are complex processes and there is still a need to understand the underlying spatial and temporal dynamical scales. As a step towards this goal, a two-dimensional slice model (zero gradients in the alongshore direction) based on the primitive flow equations and a range of sediment classes has been developed. The circulation is forced from rest by upwelling or downwelling winds, which are spatially uniform. Results are presented for a range of wind speeds and sediment settling speeds. Upwelling flows carry fine sediments (low settling speeds) far offshore within the surface Ekman layer, and significant deposition eventually occurs beyond the shelf break. However, coarser sediments quickly settle out of the deeper onshore component of the circulation, which can lead to accumulation of bottom sediments within the coastal zone. Downwelling flows are more effective at transporting coarse sediments off the shelf. However, strong vertical mixing at the shelf break ensures that some material is also carried into the surface Ekman layer and returned onshore. The concentrations and settling fluxes of coarse sediments decrease offshore and increase with depth under both upwelling and downwelling conditions, consistent with trends observed in sediment trap data. However, finer sediments decrease with depth (upwelling) or reach a maximum around the depth of the shelf break (downwelling). It is shown that under uniform wind conditions, suspended sediment concentrations and settling fluxes decay offshore over a length scale of order $\tau_s/\rho f|w_s|$, where τ_s is the wind stress, ρ the water density, f the Coriolis parameter, and w_s is the sediment settling velocity. This scaling applies to both upwelling and downwelling conditions, provided offshore transport is dominated by wind-driven advection, rather than horizontal diffusion.

Keywords: Sediment transport; Shelf; Upwelling; Downwelling; Settling; Resuspension; Deposition

* Corresponding author. Tel.: +61 3 6232 5025; fax: +61 3 6232 5053.
E-mail addresses: scott.condie@csiro.au (S.A. Condie), csherwood@usgs.gov (C.R. Sherwood).
[1] Tel.: +1 508 457 2269; fax: +1 508 457 2310.

0079-6611/$ - see front matter
doi:10.1016/j.pocean.2005.07.003

1. Introduction

Sediment transport across the continental shelf and slope is central to our understanding of marine geological processes, as well as having important implications for the distribution of particle reactive nutrients and pollutants, water column productivity, benthic ecology, and the global carbon budget. There is a wide range of physical processes responsible for this transport, including wind-driven flows, internal waves, wave-orbital flows, and buoyant plumes (see review by Nittrouer and Wright, 1994). However, there has been surprisingly little investigation of the underlying dynamics controlling the distribution of sediments on continental shelves. Even the ubiquitous decline in turbidity with offshore distance (McCave, 1972) has only been explained loosely in terms of offshore diffusion. This study focuses on the important role of wind forcing by modeling the sediment distributions and transport in both upwelling and downwelling systems.

The approach adopted here is to develop a vertical-slice cross-shelf model (zero gradients in the alongshelf direction) incorporating a simple shelf–slope bathymetry. Idealized wind and wave fields were applied to this system, generating bottom stresses capable of resuspending bottom sediments. The circulation generated in similar systems by upwelling winds has been investigated by Hamilton and Rattray (1978), Foo (1981), Kundu (1984), Allen et al. (1995), and Austin and Lentz (2002). The corresponding downwelling circulation was considered by Allen and Newberger (1996) and Austin and Lentz (2002), while Xing et al. (1999) examined the impact of time varying seasonal winds and surface heat fluxes. Since these studies have already described the dynamics of the water movement in considerable detail, the main focus here will be on the sediment transport dynamics.

Amin and Huthnance (1999) have used a steady-state cross-shelf model to investigate the role of horizontal and vertical diffusion on cross-slope sediment distributions, while neglecting the role of advection. However, Harris and Wiberg (2001) have since used their own cross-shelf model to show that time-dependence and horizontal advection play a strong role in determining sediment transport, resuspension and deposition patterns. This is particularly true in shelf systems where Ekman boundary layer dynamics can significantly complicate the vertical structure of the horizontal advection pattern (e.g. Csanady, 1982) with major implications for sediment movements (Kachel and Smith, 1989). One potential limitation of the sediment transport models of both Harris and Wiberg (2001) and Shapiro (2004) was the use of idealized flow fields with zero vertical advection and the absence of stratification effects on vertical mixing profiles. Three-dimensional stratified circulation models have recently been used to investigate sediment transport in the vertical-slice cross-shelf geometry under a range of forcing conditions, including barotropic and baroclinic tides, imposed along-shelf flows, and upwelling and downwelling winds (Davies and Xing, 2002; Davies et al., 2002). These studies have started to demonstrate the potential range of interactions between cross-shelf circulation cells and the resuspension and settlement of sediments. A similar modeling approach has therefore been adopted here, with a particular focus on understanding and quantifying the dynamical effects of wind-stress and sediment settling rates on the scales of sediment transport.

2. Model description

Flow fields and sediment distributions were calculated over a two-dimensional vertical slice, orientated perpendicular to the coastline and extending offshore over an idealized shelf–slope bathymetry. The water depth increased linearly from 20 m at the coast to 80 m at the shelf-break 12 km offshore, then more rapidly to 500 m over a linear slope of width 20 km. The domain then extended a further 12 km offshore over flat bathymetry. The Coriolis parameter was assumed to have a constant value of $f = 1 \times 10^{-4}\ \mathrm{s}^{-1}$. The water column was initially stratified with the temperature profile shown in Fig. 1, without any horizontal gradients and an uniform salinity of 35 psu.

Boundary conditions were periodic in the alongshore direction, ensuring zero alongshore gradients in all flow properties. Free-slip conditions were applied at the coastal boundary, while the offshore boundary was open. The temperature and salinity profiles at the open boundary were held fixed at their initial values (Fig. 1). The free surface height at the offshore boundary was also clamped at its initial value. In reality, the offshore boundary conditions are established by basin-scale processes, and the modeled circulation near this boundary may not be universally representative. A sponge layer with horizontal viscosity increasing expo-