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On the impact of wind curls on coastal currents

Wolfgang Fennel*, Hans Ulrich Lass

Institut für Ostseeforschung Warnemünde an der Universität Rostock D-18119 Warnemünde, Germany

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Abstract

Studies of upwelling and coastally-trapped wave theory, as developed over the past thirty years, have largely neglected effects of cross-shelf variation in wind stress and the resulting wind stress curl. However, recent satellite-based observations (QuikSCAT) of global wind stress patterns show significant and persistent wind stress curls extending well offshore in some coastal regions including the Benguela System. Motivated by this example, we use a relatively simple analytical model to investigate explicitly the impact of cross-shelf variation in wind stress on the structure of the coastal currents.

The model is based on the linear Boussinesq equations of a stratified, flat bottomed coastal ocean on a *f*-plane (southern hemisphere), bounded by a straight vertical wall. The model includes a wind mixed layer and a linear friction rate. The model equations are solved using the method of Green's functions.

There are two mechanisms imposing divergencies of the Ekman transport, (1) coastal inhibition and (2) wind stress curl. In the first case the coastal flows are affected significantly by Kelvin waves, due to the waveguide properties of boundaries. In the second case, the wind stress curl generates vertical motion and hence horizontal pressure gradients, where the associated geostrophic flows are limited by friction only. As a result, complex flow patterns with counter-currents can emerge. In order to highlight the role of wind stress curls, the responses of the coastal ocean to different cross-shore variations of the alongshore wind stress are compared with the baseline case of no wind curl.

Keywords: Wind stress curl; Coastal jets; Upwelling; Kelvin waves; Green's-functions; Benguela upwelling system

1. Introduction

Oceanic upwelling is generated by divergences of Ekman-transport imposed by wind curls, coastal boundaries or ice edges, e.g. McCreary and Chao (1985), McCreary et al. (1987), Sjøberg and Mork (1985), Fennel and Johannessen (1998). Coastal boundaries imply inhibition and, therefore, strong divergences of the offshore transport for alongshore winds with the coast to the right/left at the northern/southern hemisphere. As a consequence, the near-surface isopycnals slope upward and generate cross-shore pressure gradients which drive geostrophically balanced coastal jets, e.g. Gill (1982). Owing to the waveguide properties of boundaries, coastal upwelling can significantly be reduced by coastally trapped waves. Coastally-trapped wave theory, as developed over the past thirty years, has largely neglected effects of cross-shelf variation in wind stress and the resulting wind stress curl. For an idealized model ocean of constant depth, bounded by a straight wall, the relevant coastally trapped waves are Kelvin waves, which propagate across the wind band and

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* Corresponding author.
E-mail address: wolfgang.fennel@io-warnemuende.de (W. Fennel).

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reduce the coastal upwelling, arrest the coastal jets, generate alongshore pressure gradients and undercurrents, see e.g. McCreary (1981). Away from ocean boundaries, the responses to wind curls are not affected by waves due to the absence of waveguides. An interesting question is how the coastal response is modified when wind stress curls due to cross-shore variation in wind stress near a boundary exist and the two mechanisms interact.

A theoretical study of the role of wind stress curls on the three-dimensional structure of the California Current was presented in McCreary et al. (1987). The variation of the wind curl was estimated from wind records near the coast and 100 km offshore. It was indicated that the wind curl might be a reason for coastal currents flowing against the local winds, McCreary et al. (1987). The influence of large scale wind curls on the Benguela upwelling system was analyzed by Fennel (1999), using wind stress curls estimated by Bakun and Nelson (1991). In Bakun and Nelson (1991), maps of wind stress curls were generated with 1° resolution for the eastern ocean boundaries of the North and South Atlantic and of the South Pacific, based on composites of maritime data from a large number of years. The new generation of the SeaWind scatterometer on the QuikSCAT satellite, provided opportunities to map spatial wind patterns with an unprecedented resolution and sampling frequency. As shown by Chelton et al. (2004), spatial structures of winds (divergences and curls) are often surprisingly persistent.

This paper refers to the Benguela system as an example region where the QuikSCAT observation show a well established, persistent wind stress curl near the ocean boundary. An example of the wind variations is shown in Fig. 1, in terms of the monthly averaged meridional wind stress of March 2003.

The typical patterns of the alongshore wind-stress show the general features of the wind field in the Benguela inferred from classical wind observations, e.g. Shannon (1985), but reveal more detailed structures. Basically, there are three centers of strong meridional wind-stress, with insignificant cross-shore variations, located near Cape Frio, (17°S), near Lüderitz, (27°S), and off the area of the western Cape, (34°S). The centers are separated by two bands of low meridional wind-stress near the coastal boundary. The bands are about 100 km wide and extend about 500 km alongshore. Within these bands, strong wind-stress curls exist due to the increasing meridional winds in offshore direction. These patterns are remarkably persistent, apart from some seasonal variations at its northern and southern ramps, and some interannual variations in the overall intensity of the wind-stress, see Hardman-Mountford et al. (2003).

Observations of the three-dimensional coastal currents in the Benguela system are relatively rare. However,

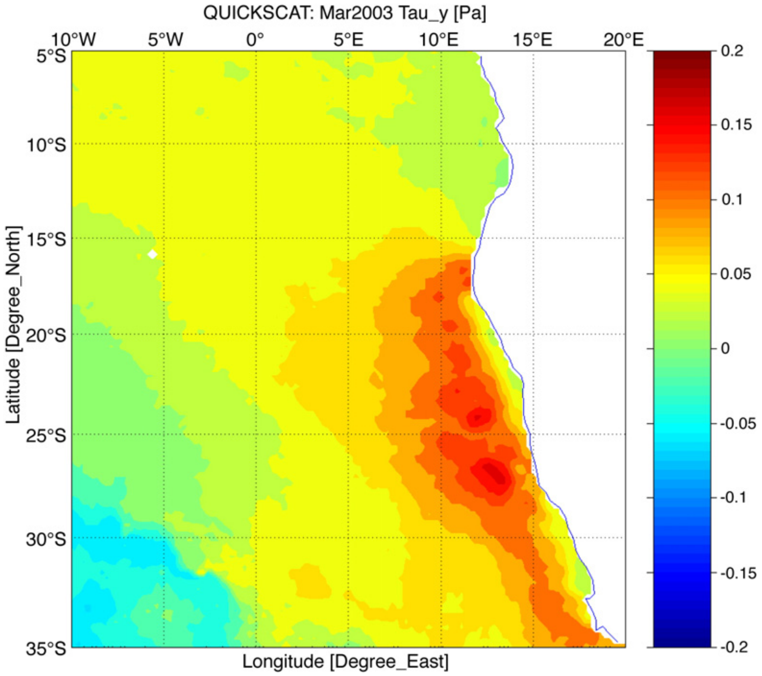

Fig. 1. Monthly average of the northern wind stress component for March 2003, derived from QuikSCAT data.