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Large eddy simulation of the Ekman transport in a stratified coastal sea: A case study of the Persian Gulf

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ABSTRACT

Ekman transport is a key factor in the coastal upwelling regimes in the northern coastal region of the Persian Gulf. In this paper, the Ocean Module of Parallelized Large-Eddy Simulation Model (PALM) was utilized so as to investigate the Ekman layer and estimate the water mass transport in the Persian Gulf for the first time. In order to take into account the effect of the topography on the Ekman transport, three experiments with the same initial and boundary conditions and different topographies were carried out. The results indicated that, in the vicinity of the shoreline and in shallow waters Turbulent Kinetic Energy (TKE) is 10 times stronger than in the offshore area. It was concluded that in the presence of the shoreline the vertical velocity increases and in the onshore area, the upwelling speed is 3–4 times larger than in the offshore area. It was revealed that the Ekman transport reached a steady state at the end of the simulation, and reached a constant value of about 250 kg/ms.

1. Introduction

Ekman transport in the vicinity of shore boundaries can cause the “Upwelling-Downwelling” phenomenon. According to the continuity equation, when the cross-shore component of the Ekman transport moves the surface water away from the shore, deep water should replace surface water. This cross-shore Ekman transport can be used as an upwelling index (Kämpf and Chapman, 2016). Numerous studies have been carried out on the properties of the Ekman layer, because of its importance in air-sea interactions (e.g. Ashkenazy et al., 2015; Deusebio et al., 2014; Pham and Sarkar, 2014; Skyllingstad et al., 2016).

In addition to the wind condition, the bathymetry and shoreline orientation have significant effects on coastal upwelling. Estrade et al. (2008) concluded that both the location of the upwelling and the scale of the divergence zone (defining upwelling intensity) vary with topography. They did not consider stratification in the simulations and as the authors pointed out, this assumption is the most constraining hypothesis. The introduction of stratification into the numerical model modifies the upwelling structure. Lentz (2001) suggested that in presence of stratification, the upwelling and downwelling phenomena are confined to a region the near the coast. He found that the presence or absence of stratification had a profound influence on the wind-driven, cross-shelf circulation. In the stratified water column, the observed near-surface and near-bottom cross-shelf transports are approximately equal to the stress-driven Ekman transports. Also, the results showed that when the water column is not stratified, the observed near-surface and near-bottom cross-shelf transports are smaller than the Ekman transports for moderate to strong wind or bottom stresses.

Chen et al. (2013) performed a series of idealized numerical experiments to examine the upwelling response to wind and shelf slope. They suggested that it was necessary to combine the effects of wind stress with bottom slope for studying coastal upwelling systems. Their results showed that steeper slope leads to a narrower cross-shore width of upwelling area and larger vertical velocity, whereas stronger alongshore wind stress induces broader upwelling area and larger vertical velocity. Accordingly, considering the bathymetry and shoreline is necessary for the investigation of the coastal upwelling and the Ekman transport.

Research on the coastal upwelling phenomenon using numerical simulations has frequently been undertaken (e.g. Bai et al., 2016; Chen et al., 2013; Jing et al., 2009), and most of these studies have been carried out with a focus on the regional scale (hundreds to thousands of kilometers) in annual or seasonal periods, hence small-scale turbulent currents and eddies have not been considered directly, and these are significant elements in Ekman layer dynamics and coastal areas. Also, there is another group of researchers who used high resolution Direct Numerical Simulation (DNS) or Large Eddy Simulation (LES) to

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investigate Ekman layer features (e.g. Coleman et al., 1992; Grötzbach, 1987; Shingai and Kawamura, 2002).

DNS is more accurate, and capable of capturing all motion including at fine scales; however, due to the high computational time, it is only applicable for low Reynolds number or small model domain. Taylor and Sarkar (2008) used both DNS and LES to study a steady Ekman layer with a thermally stratified outer flow, and compared the results of the two approached. Their findings showed that the low resolution LES was not able to resolve small-scale motions meaning that the turbulent heat flux in the boundary layer was significantly under-predicted in comparison with DNS. They suggested increasing the LES resolution to solve this problem.

Zikanov et al. (2003) studied a surface turbulent Ekman layer created by a steady wind near the water surface using LES. They showed that the classical Ekman model does not adequately describe the mean current. Taylor and Sarkar (2008) carried out a comprehensive study on the bottom Ekman layer under external stratification. The results showed that the boundary layer thickness is strongly limited by the outer layer density stratification. Note that the vertical wall boundaries were not counted in the respective fields.

Studying and estimating small scale vertical turbulent motion may have several implications in marine ecology. Patterns of vertical circulations and eddy-like motions can affect ecological processes, debris and particle trajectories, pollution spread, and sediment transport. Such patterns may be controlled by dynamic (e.g. ocean current, wind stress or thermocline convection) or topographic features. Different marine life forms such as phytoplankton, fish, marine mammals and birds are found to alter their distributions in the presence of such flow patterns.

1.1. Ekman theory

Ekman (1905) considered a steady wind stress over an infinitely deep and infinitely broad ocean (i.e. no bottom friction and no horizontal boundaries) with no pressure gradients or density inhomogeneity. He assumed a balance among the Coriolis force, viscous friction, and the pressure gradient, adopting the approximation of constant vertical eddy viscosity A_z and derived a solution, currently known as the Ekman spiral. The Ekman model implies a spiral current which at the surface travels at 45° to the right of the wind in the northern hemisphere, in which the Coriolis force is balanced everywhere by the friction (Liss and Slinn, 2012).

According to Ekman's model, the Horizontal momentum equation becomes

$$2\Omega \times u = -\frac{1}{\rho}\nabla p + \frac{1}{\rho}\partial_z \tau(z) \tag{1}$$

where Ω is the Earth's rotation rate, u is the horizontal current, ρ is density, p is pressure, z is vertical coordinate and τ is the turbulent stress. Solving Eq. (1) and considering a steady wind in the x-direction gives:

$$u_E = V_0 \exp(-\pi z/D_E)\cos(\pi/4 + \pi z/D_E) \tag{2}$$

$$v_E = -V_0 \exp(-\pi z/D_E)\sin(\pi/4 + \pi z/D_E) \tag{3}$$

Here u_E and v_E are the components of the mean Horizontal velocity, z is the vertical coordinate directed downwards, $V_0 = \sqrt{2}\pi\tau_0/D_E f\rho$ is the amplitude of the surface velocity, $D_E = \pi(2A_z/f)^{1/2}$ is the Ekman depth of exponential decay, τ_0 is the surface shear stress, and $f = 2\Omega\sin\lambda$ is the Coriolis parameter, with Ω and λ being, correspondingly, the Earth's rotation rate and latitude.

The total mass transport (i.e. integrated over the depth to which the wind-driven currents penetrate-generally taken to be the depth of the mixed layer) is found to be

$$M_x = \int_{-H}^{0} u_E\, dz = \tau_0^y/\rho f, \tag{4}$$

$$M_y = \int_{-H}^{0} u_E\, dz = -\tau_0^x/\rho f \tag{5}$$

where τ_0^x and τ_0^y are wind stress in x and y direction, respectively.

Although the Ekman approach is simple, elegant, and clearly supported by laminar laboratory experiments (Pond and Pickard, 2013), the Ekman assumptions rarely occur completely in nature.

From Eqs. (4) and (5), one can estimate directly the total Ekman transport components from the surface wind stress information (see Alvarez et al., 2008; Blanke et al., 2005; Bravo et al., 2016; Desbiolles et al., 2014; Maeda and Kishimoto, 1970). Pickett and Paduan (2003) estimated upwelling in the California Current system and found that the Ekman transport from alongshore wind stress reaches a maximum in summer of about $0.5 \times 10^{-6} m^3 s^{-1}$. The Ekman transport relation for moderate winds, with a transport per unit width of about $1 m^2 s^{-1}$ has been verified (Chereskin and Price, 2001).

Although this method is suitable for the study of long-term and large-scale coastal upwelling patterns, it cannot be used for the investigation of the immediate response of the sea to atmospheric forcing. Additionally, the availability of high resolution direct and remote sensing measurements for long-term periods is challenging in many marine and coastal areas.

The purpose is to investigate the Ekman transport with an emphasis on the role of bathymetry in coastal upwelling. To this end, three numerical experiments were conducted applying a large eddy simulation model: first, idealized open sea with a flat bottom surface (EXP F); second, semi-enclosed sea with a steep shelf (EXP S); and third, semi-enclosed sea with a vertical boundary (EXP V). The study area, numerical model, and model setup are described in section 2. The results are presented in section 3, followed by a discussion in section 4.

2. Methodology

2.1. Study area

A schematic diagram of circulation in the Persian Gulf (Thoppil and Hogan, 2010) and the study area are presented in Fig. 1. There have been very few studies in the Persian Gulf on Ekman transport despite its importance in the region. Coastal upwelling plays important roles in increasing the productivity of the Persian Gulf as well as the climate modification of the adjacent coastal environment. Therefore, this phenomenon is important from physical and ecological perspectives.

The Persian Gulf contains one of the largest fossil fuel resources in the world, with crucial and crowded waterways that connect to the Gulf of Oman and the Indian Ocean through the Strait of Hormuz.

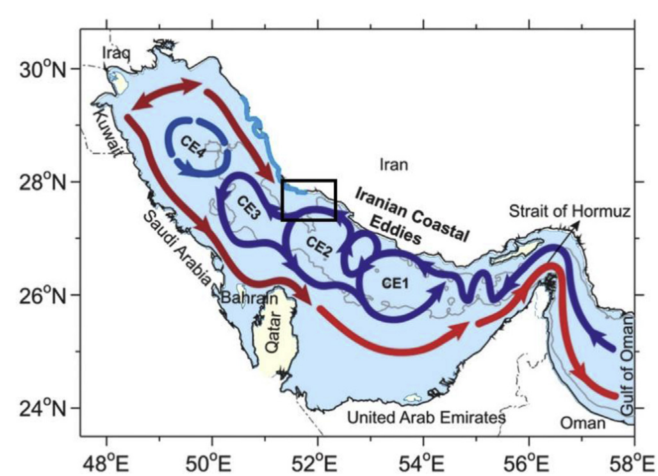

Fig. 1. Schematic diagram showing circulation in the Persian Gulf (Thoppil and Hogan, 2010). The black square shows the study area.