Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Modeling of Wind Effects on Stratified Flows in Open Channels: A Model for the Istanbul Strait (Bosphorus)

To cite this article: A.H. Bilge *et al* 2016 *J. Phys.: Conf. Ser.* **738** 012069

Modeling of Wind Effects on Stratified Flows in Open Channels: A Model for the Istanbul Strait (Bosphorus)

A.H.Bilge(1), **G.Kirkil**(1), **S.Burak**(2), **M. Incegul**(1)

(1)Faculty of Engineering and Natural Sciences, Kadir Has University, (2) Institute of Marine Sciences and Management, Istanbul University

E-mail: `ayse.bilge@khas.edu.tr`

Abstract. Stratified flows in open channels arise as a result of density or surface level differences. If the channel is connected to a basin at one or both ends, strong winds originating from the basin cause the "wind setup" effect that increases the water level at the entrance of the channel. On the other hand, along the channel, persistent winds in the upper layer flow direction lead to an increase of the drift velocity and to a decrease in upper layer flow depth. The Istanbul Strait (Bosphorus) connecting the Black and the Marmara Seas, is characterized by a stratified flow caused by the surface level and salinity difference between these basins, consisting of a southward upper layer flow and a northward lower layer flow. Along the strait, there are three hydraulic control points; the north sill, a midway contraction reach and the south sill. Under wind effects, the northern and southern entrances of the strait behave as an estuary whereas the midway reach to the south of the contraction acts as as an open channel. In winter, when the sea level difference is relatively low, the wind setup due to southerly winds may cause a blockage and even reversal of the upper layer flow. On the other hand in spring when there is excessive river discharge, northerly winds increase the influx of Black Sea waters into the strait and may lead to a blockage of the lower layer. We claim that strong northerly winds may cause a decrease of the upper layer depth beyond the contraction and we propose a simple model for its estimation in terms of the wind and water flow speeds.

1. Introduction

Sea basins connected by straits have been the subject of many research papers, e.g. [5] [6] [16] [2]. Salinity, temperature and/or surface level differences between the basins lead to stratified currents, such as in the Gibraltar Strait connecting the Atlantic Ocean and the Mediterranean, the Istanbul Strait (Bosphorus) connecting the Black Sea and the Marmara, the Kerch Strait connecting the Azov Sea to the Black Sea [9] . In these stratified flows, the Atlantic Ocean, the Black Sea and the Azov Sea act as low salinity basins. Perturbations to the main flow regime can arise as a result of tides, sea level differences or winds.

The exchange flow regime of the Istanbul Strait has important effects on the delicate ecological balances in the Black and the Marmara Seas. The effects of strong winds are one of the major causes of perturbations. The well known effects are the blockage and even reversal of the upper layer under the effect of southerly winds and the blockage of the lower layer under the effect of northerly winds [1], [3], [7], [8], [10],[11].

The Istanbul Strait (Bosphorus) is a 31 km long narrow channel in the north-south direction joining the Black Sea and the Marmara Sea basins. It has a width of 3.329 km and 2.826 km at the north and south entrances respectively. The Black Sea's water level is about 30 cm higher than the Marmara Sea, due to high influx from rivers into the Black Sea, causing a net southward flux throughout the year. The more saline (36-38 psu) Mediterranean water flows at the bottom layer from south to north while the less saline (18-22 psu) Black Sea water flows at the top layer in the reverse direction. The south and north exits of the strait are marked by sills at depths 33 and 61 meters, respectively, forming hydrological control sections. There is a third control section about 10 km north of the southern entrance, caused by a "contraction".

In this work we point out a possible effect of northerly winds on the flow of the upper layer. It is well known that strong northerly winds cause a wind set up at the north entrance of the strait, that increases the sea level difference and the upper layer flux. As a result, the northern section of the strait is filled completely with Black Sea waters and this leads to a complete blockage of the lower layer current at the Contraction zone. As one moves to south beyond the Contraction, the flow speed of the upper layer increases considerably and there is more or less horizontal interface layer up to the south entrance. Motivated by a result in the literature on wind effects measured at the Ishikari river estuary [15], we suggest that strong northerly winds may cause a decrease in the thickness of the upper layer current along the section of the strait between the Contraction and the south entrance. Experimental work that supports this argument is given in [12]

2. The Model

Wind effects on open channel flows are studied within the framework of an experimental single layer flow setup [12], [14]. In this work, the authors have found if the wind blows for a sufficiently long period of time, a new flow regime is set up and the flow depth decreases, by momentum transfer between the wind and the water.

We propose a simple model for the decrease in the fluid level due to wind induced drift under the assumption of constant flux. For this computation we integrate the vertical drift velocity profile up to the unknown, the new lower level equilibrium height h and determine h from the constant flux assumption. To our knowledge there is no discussion of the wind induced open channel drift in the Bosphorus.

We combine experimental results of [12], [13] and [8] to choose a realistic drift velocity profile. In [13], the authors analyze wind driven and density currents in the Petrozavodsk Bay of Onega Lake, between the Baltic Sea and the White Sea. This paper reports measurements of the drift current (Figure 1a in [13]) due to wind effects. The wind induced flow is confined to the upper 1/6th of the 23 meter depth. It drops from about 50 cm/sec on the surface to zero sharply. The lower level density current in the reverse direction is more or less uniform and it has values around 6-8 cm/sec. Finally, in [8] we have detailed velocity profiles under various conditions at the south entrance.

Flow velocities are taken from [6], where the authors report current and salinity measurements along the Bosphorus, during early September in 1994 (days 250 to 260), over a period quite atmospheric conditions. The surface flow speed is 0.2 at the north entrance and it increases to 0.6-0.8 around the Contraction.

Vertical profile of streamwise velocity for open channel flows can approximately be represented by a power law [4]:

$$u(z) = U_{max} \, (z/h)^{1/N} \, , \quad 0 \leq z \leq h,$$

where h is the channel depth, z is the vertical distance from the bottom of the channel, $u(z)$ is the flow velocity and U_{max} is its maximum. The power law parameter N usually changes between 4 and 12, depending on the boundary friction. The most commonly used value is

$N = 7$. If the open channel flow is stratified with densities ρ_1 and ρ_2 ($\rho_1 > \rho_2$) and the flows are in opposite direction (as in the case of Istanbul Strait); velocity profiles of lower and upper layers each follow a power law with a smooth transition in between them (Figure 1).

When the wind blows on the free surface, in the direction of the flow, with a velocity V, an increased shear stress cause an increase in the flow speed of via a momentum transfer mechanism resulting in a new velocity profile $u'(z)$. This increase in the flow velocity induced by the wind dies out exponentially with depth. Nevertheless, if the discharge is constant, this leads to a reduction in the flow height to h'. Assuming constant cross-section and constant discharge, the flow heights h and h' are related by

$$q = \int_0^h u(z)\, dz \;=\; \int_0^{h'} u'(z)\, dz. \tag{1}$$

This is the effect that has been reported in an experimental setup in [12].

We study a problem where two layers in an open channel stratified flow flowing in opposite directions (Figure 1). The flow velocity at the interface layer is 0. With no wind effect on the free surface, the lower layer has a height of h_1 and maximum velocity of $U_{max,1}$ to the right and upper layer has a height of h_2 and maximum velocity of $U_{max,2}$ to the left. We assume that the flux of the upper layer is constant, the total fluid height is constant and and the interface layer acts as a movable boundary. When wind blows on the free surface, in the direction of the upper layer flow, with a velocity V, the height of the upper layer decreases to h'_2, as discussed above. Since the total height is assumed to be constant the lower level height increases to h'_1. these values being related by

$$h_1 + h_2 = h'_1 + h'_2.$$

We assume furthermore that the effect of wind on the open channel flow is limited to the upper layer only. The lower layer velocity profile is slightly adjusted to match with the new velocity profile in the upper layer. Then, Eqn(1) is still valid for a double layer flow.

The assumption of constant total height is valid in the reach at the south of the Contraction; the increases on the water levels are confined to the entrances of the Istanbul Strait. The validity of the constant flux assumption is supported by the existence of the Contraction. The mechanism leading to the increase of the height of the lower level may be either reduced velocity or increased flux, but the cause is practically irrelevant for the purposes of our analysis.

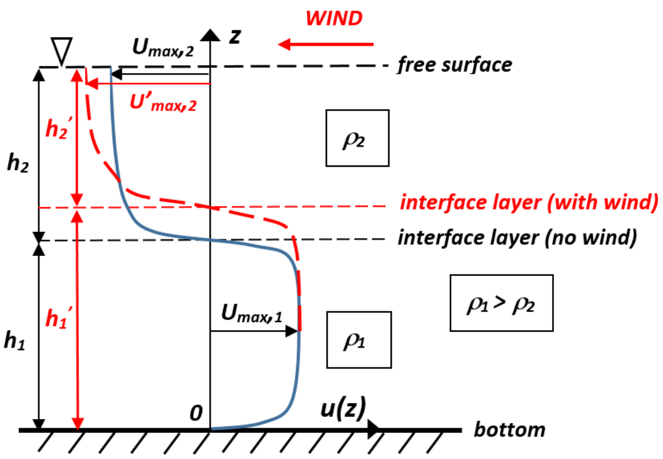

Figure 1. Bi-directional open channel flow (solid curve) and the wind induced velocity profile (dashed curve).

3. Simulation of Wind Effects

We consider a bi-directional flow in a channel with constant cross-section. Let h_1 and h_2 be the heights of the lower and upper levels respectively and let z denote the vertical distance from the channel bottom. The fluid velocities of these layers are respectively $u_1(z)$ (in the negative direction) and $u_2(z)$ (in the positive direction) with boundary conditions,

$$u_1(0) = 0, \quad \frac{du_1}{dz}(0) = \infty, \quad \frac{du_2}{dz}(h) = 0.$$

A general model that would fit these boundary conditions are

$$\text{For} \quad 0 \leq z \leq h_1: \quad u_1(z) = -Az^{\alpha}[h_1 - z]^{\beta},$$

$$\text{For} \quad h_1 \leq z \leq h_1 + h_2: \quad u_2(z) = B[z - h_1]^{\gamma}\,[h_1 + h_2(1 + \delta/\gamma) - z]^{\delta},$$

where A and B are positive and the exponents α, β, γ, δ are in the range $(0, 1)$. The smoothing of the first derivative at the interface can be achieved by spline interpolations at the boundaries of mixing layers say $h_1 - a$ and $h_1 + b$, by matching velocities and their derivatives, but this will be omitted in the present work.

In our simulation, we choose the following normalized values for fluid layers.

$$h = h_1 + h_2 = 1, \quad h_1 = 5/8h, \quad h_2 = 3/8h, \quad A = -1/2, \quad B = 1, \quad \alpha = \beta = \gamma = \delta = 1/7.$$

With these values, the velocity profile of the upper layer is practically constant up to a reasonable depth and in the calculation of wind effects on the upper layer height, we assume that $u_2(z)$ is approximately equal to U_{max}. As mentioned above, the wind effect is considered to die out as a Gaussian pulse, hence we propose a wind induced velocity profile in the form

$$v(z) = V_{max} e^{-k^2\left(\frac{h-z}{h_2}\right)^2}.$$

Let h'_1 and h'_2 be the layer heights under wind effects. The constant discharge equation is expressed as

$$\int_{h-h_2}^{h} u_2(z)\, dz = \int_{h-h'_2}^{h} u_2(z)\, dz + \int_{h-h'_2}^{h} v(z)\, dz.$$

Approximating $u_2(z)$ by U_{max}, we get

$$U_{max}(h_2 - h'_2) = V_{max} \int_{h-h'_2}^{h} e^{-k^2\left(\frac{h-z}{h_2}\right)^2}\, dz.$$

After a change of variable $s = (h - z)/h_2$, we obtain

$$U_{max}(h_2 - h'_2) = V_{max} \frac{h_2}{k} \int_0^{k\ h'_2/h_2} e^{-s^2}\, dz.$$

Since

$$\int_0^x e^{-t^2} dt = \frac{\sqrt{\pi}}{2} Erf(x),$$

after dividing both sides by h_2, we obtain the relation

$$U_{max}\left(1 - \frac{h'_2}{h_2}\right) = V_{max} \frac{\sqrt{\pi}}{2k} Erf(\left(\frac{k\ h'_2}{h_2}\right).$$

This gives a relation between the ratios h'_2/h_2 and V_{max}/U_{max}. We evaluate V_{max}/U_{max} numerically in terms of h'_2/h_2 in the range $(0.5, 1)$ and plot their relation for $k = 2, 3, 4, 5$. The results are presented in Figure 2a,b where we show the steady state (no-wind) velocity profile together with wind induced velocities (Figure 2a) and the reduction in the upper layer height h'_2/h_2 as a function of the relative wind speed V_{max}/U_{max} (Figure 2b) for the values of $k = 2, \ldots 5$.

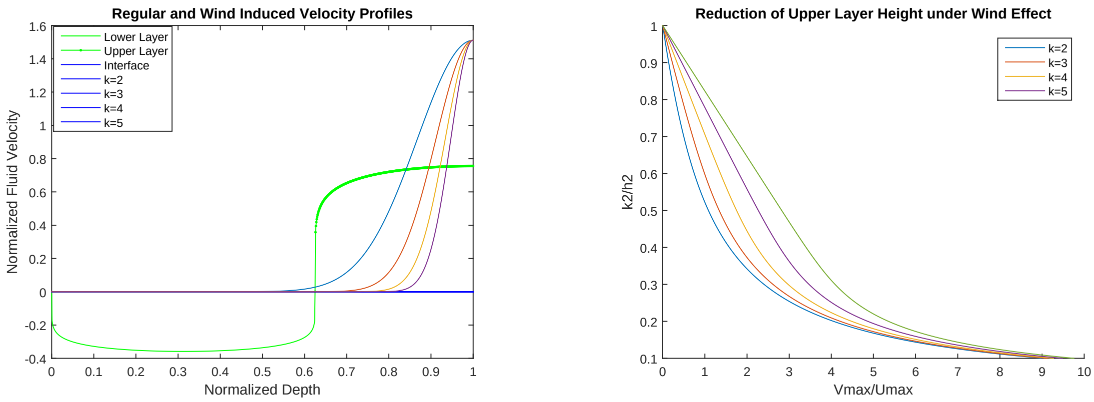

Figure 2 (a) Bi-directional velocity profile $u(z)$ and wind induced Gaussian velocity $v(z) = V_{max}e^{-k^2\left(\frac{h-z}{h_2}\right)^2}$ for $k = 2, \dots, 5$ (b) k_2/h_2 as a function of the relative wind speed V_{max}/U_{max}, where $U_{max} = u(h)$, k_2 and h_2 are respectively upper layer heights with and without wind effects.

References

[1] H. Altiok, A.Aslan, S. vezN. Kiratli, S. Tas, A.E. Muftuoglu, K.I. Sur, E. Okus, Influence of the extreme conditions on the water quality and material exchange flux in the strait of Istanbul, Journal of Marine Systems, 139, (2014) 204-215.

[2] A.Andersen, F. Jakobsen, B. Alpar, The water level in the Bosphorus Straight and its dependence on atmospheric forcing, Deutsche Hydrographische Zeitschrift , German Journal of Hydrography, vol. 49, (1997) N. 4.

[3] S. Burak, Evaluation of Pollution Abatement Policies in the Marmara Sea with Water Quality Monitoring, Asian Journal of Chemistry Vol. 20, No. 5 (2008), 4117-4128.

[4] H. Chanson, The Hydraulics of Open Channel Flow: An Introduction, Elsevier, (2004).

[5] Farmer, D.M., Armi, L., 1986. Maximal two-layer exchange over a sill and through the combination of a sill and contraction with barotropic flow. J. Fluid Mech. 164, 5376.

[6] M.C. Gregg, E. Ozsoy and M.A. Latif, Quasi-steady exhange flow in the Bosphorus, Geophysical Research Letters, Vol. 26, No 1, pp. 83-86, (1999)

[7] M.C. Greg, E. Ozsoy, Flow, water mass changes and hydrolics in the Bosphorus, Journal of Geophysical Research, vol 107, No. C3, 10.1029/2000JC000485, (2002).

[8] I. Guler, Y. Yuksel, A.C. Yalciner, E. Cevik, C. Ingerslev, Measurement and evaluation of the hydrodynamics of secondary currents in and near a strait connecting large water bodies- A field study, Ocean Engineering, vol 33, (2006) 1718-1748.

[9] V. A. Ivanov , L. V. Cherkesov, T. Ya. Shulga Analysis of the influence of water exchange through the Kerch Strait on the surge processes and currents in the Azov Sea, Physical Oceanography December 2010, Volume 20, Issue 4, pp 239-250 Translated from Morskoi Gidrofizicheskii Zhurnal, No. 4, pp. 314, JulyAugust, 2010.) Strait. J. Geophys. Res. 116, C08038. http://dx.doi.org/10.1029/2010JC006861.

[10] Jarosz, E.W., Teague, J., Book, J.W., Beiktepe, ., 2011b. Observed volume fluxes in the Bosphorus Strait. Geophys. Res. Lett. 38, L21608. http://dx.doi.org/10.1029/ 2011GL049557.

[11] T. Oguz, E. Ozsoy, M. Latif, H. Sur, U. Unluata, 1990: Modelling of hydraulically controlled exchange flow in the Bosphorus Strait. J. Phys. Oceanogr., 20, 7, 945-965.

[12] E.J. Plate and C.R. Goodwin, The influence of wind on open channel flow, Coastal Engineering Report

[13] B.I. Samolyubov and I.N. Ivanova, The evolution of velocity profiles and turbulant viscosity in a system of urrents with wind induced and density flows, Physics of the Earth, Atmosphere and Hydrosphere, Fizika, 2014, No 5. pp. 60-66

[14] J. Wu, An estimation of wind effects on dispersion in wide channels, Water Resources Research, Vol. 3, no.5, 1097-1104, (1969).

[15] K. Yokoo, S. Yoshida, C.P. Caulfield, P.F. Linden, I. Ito, Effect on wind on highly stratified flow, in WIT Transaction on the Built Environment, Coastal Engineering VII, Vol 78, Coastal Engineering, Paper DOI 10.2495/CE050031.

[16] H. Yuce, 1996. Mediterranean water in the Strait of Istanbul (Bosphorus) and the Black Sea exit. Estuar. Coast. Shelf Sci. 43, 597616