CFD MODELLING AND UNCERTAINTY ANALYSIS IN THE ESTIMATION OF THE WIND DRIFT FACTOR

Ricardo Sbragio[1], Marcelo Ramos Martins[2]

University of São Paulo, Naval Architecture and Ocean Engineering Department, Analysis, Evaluation and Risk Management Laboratory – LabRisco

ABSTRACT

The estimation of an oil spill trajectory is essential for a risk analysis in order to plan and to establish the correct mitigation procedures of a postulated event. The trajectory is strongly influenced by the sea surface currents. Among the causes of the sea surface currents, the wind plays an important role. The sea surface wind induced velocity is estimated in several works using a wind drift factor that is normally set to be between 1% and 6%. Its estimation is usually based either on experience or on random sampling. In this work, the procedure for determining the wind drift factor through a series of two dimensional CFD simulations of the wind acting on a wavy sea surface and its associated uncertainty are presented, with the purpose of reducing the subjectivity in its estimation.

1. INTRODUCTION

In the analysis of the consequences of an oil spill, the estimation of the oil path is needed to plan and to establish the best mitigation actions. The path of a surface oil spill is influenced by the sea surface currents. One of the origins of these currents is the wind, which induces shear stress and pressure effects on the wavy water surface.

The relation between the wind induced sea surface speed and the 10m wind speed is called wind drift factor. This parameter is used in oil spill trajectory determination and is commonly estimated based on experience or by random sampling. To reduce the subjectivity in the estimation, this factor is evaluated in this paper through a series of CFD Eulerian two-dimensional simulation of a biphasic flow, composed of air and water in the presence of surface waves. The estimation is object of an uncertainty analysis. The mean free surface velocity and the mean 10m wind speed on the domain are used to determine the wind drift factor.

The estimation of the wind drift factor follows a general procedure. However, the wind, water and air data used in the CFD model are for a specific region where a real oil spill occurred (Point Wells oil spill case [1, 2]), as its results are going to be applied in an ongoing consequence analysis research related to this case.

This paper is organized as follows: this first section presents the introduction with the objective of the estimation of the wind drift factor in a risk analysis of an oil spill. Section 2 describes the methodologies used in the CFD estimation of the wind drift factor, in the significant wave estimation and in the uncertainty analysis. Section 3 shows the sea surface velocity and the wind drift factor results from the CFD simulations. Section 4 presents the discussion on the results. Finally, section 5 shows the conclusions.

2. DESCRIPTION OF THE METHODOLOGY

The wind acting on a water surface transfers momentum and energy to the water, inducing a current velocity. This velocity is due to the shear stress and to the pressure effects on a wavy free surface. The non-linear waves generated by the wind also cause a drift as the particle trajectory does not follow a closed circle, which is known as Stokes drift. This effect is analytically derived by [3] and is not included in this CFD simulation of the wind induced velocities, as its analytical estimation is straight forward. Hence, the waves

1 PhD, Naval Engineer – University of São Paulo, Naval Architecture and Ocean Engineering Department, Analysis, Evaluation and Risk Management Laboratory – LabRisco
2 PhD, Naval Engineer – University of São Paulo, Naval Architecture and Ocean Engineering Department, Analysis, Evaluation and Risk Management Laboratory – LabRisco

used in the CFD modelling are linear waves, such that they do not produce Stokes drift. Also, the influence of Coriolis acceleration is not included, as the model is two-dimensional.

2.1 Methodology for the CFD Estimation of the Wind Drift Factor

The usual treatment that is found in literature to estimate the wind drift factor is based on experience or in random sampling [e.g. 2, 4-9]. This factor is defined as the ratio between the free surface wind induced velocity and the 10m nominal wind speed. The values of the wind drift factor from literature are in the overall range from 0.01 to 0.06.

In order to reduce the subjectivity in the estimation of the wind drift factor, a series of CFD simulations were conducted using ANSYS Fluent solver [10, 11]. The domain model is two-dimensional (figure 1). The simulation is transient and biphasic with air as primary phase and water as secondary phase. The governing equations are the continuity equation and the momentum equation with Newton's viscosity law.

Fig.1 – Two-dimensional CFD domain, with water and air phases.

The wind speed boundary condition at the inlet is given by equation 1 [12], where W_{10} is the nominal value of the wind velocity at 10m height, y is the vertical coordinate, measured upwards from the flat sea surface (with $y < 20m$ [10]) and W is the wind speed at coordinate y. This inlet velocity boundary condition is applied in the CFD Fluent solver with the user defined function (UDF) shown in figure 2.

$$W_{10} = W(y)(10/y)^{1/7} \ . \tag{1}$$

```
/***************************
InletVelocity.c
****************************/
#include "udf.h"

DEFINE_PROFILE(inlet_x_velocity2, thread, position)
{
  real x[ND_ND];
  real y;
  real W10;
  face_t f;

  begin_f_loop(f, thread)
     {
      F_CENTROID(x,f,thread);
      W10 = 7.0;
      y = x[1];
      if (y>0)
          F_PROFILE(f, thread, position) = W10/pow((10.0/y),1./7.);
     }
  end_f_loop(f, thread)
}
```

Fig.2 – User defined function for inlet velocity boundary condition (in this case, W_{10} is set to be 7.0 m/s).

A monochromatic linear Airy wave with specified wavelength and wave height, according to the Sverdrup-Munk-Bretschneider (SMB) procedure [12-15], is also used at the inlet boundary condition.

The boundary conditions at the top and bottom were zero shear slip wall. The outlet is a zero pressure boundary condition.

Simulations were performed with two sets of domain dimensions, shown in table 1, such that the wind induced significant waves (determined following the procedure described in item 2.2) could be suitably modeled. The free surface cells were refined using dynamic adjust, based on the gradient of the water phase volume fraction. This procedure allows a better discretization of the waves at the surface. The time step is 0.03s.

Tab.1 – Domain characteristics

Wind speed	Length	Water depth	Air column	Cell number
≤ 7m/s	500m	20m	10m	592k to 843k
> 7 m/s	900m	45m	15m	564k to 663k

The open channel model is set for the two-phase flow and the Volume of Fluid formulation [16] is used for interface tracking. The solver setup used Green Gauss Cell Based for spatial discretization of the gradient equation, PRESTO! discretization scheme for the pressure, QUICK scheme for the momentum, Compressive scheme for the volume fraction and Second Order Upwind for the turbulent kinetic energy and turbulent dissipation rate. The transient formulation used a Bounded Second Order Implicit Scheme. Coupling between pressure and velocity used PISO method. The relaxation parameters were maintained as the solver default.

The seawater density is $1018.77\,kg/m^3$ calculated based on [17, 18] for the average seawater temperature (6.71°C) and salinity (23.99 psu), using the data provided by [19], which was obtained according to the model described in [20-23], at the time and region of Point Wells oil spill [1, 2]. The seawater dynamic viscosity is 1.504e-3Pa.s, obtained using the correlations presented in [24]. The surface tension of seawater is 7.54e-2 N/m, following the procedure presented in [25]. Air temperature varies from 0.1°C to 4.4°C [26], with an average density of $1.282\,kg/m^3$ and an average viscosity of 1.7264e-5 Pa.s.

The simulation procedure comprises monitoring the average velocity of the seawater free surface and of the 10m wind at the CFD domain in 60s intervals, until convergence. The wavy free surface is tracked by setting a water volume fraction of 50% at the domain cells. The average velocity at this 50% volume fraction is the water free surface velocity, which ratio to the average velocity of the 10m wind, determines the wind drift factor.

2.2 Methodology for the Estimation of the Significant Wave used in the CFD Simulations

The monochromatic linear Airy wave, applied at the domain inlet, is determined by the Sverdrup-Munk-Bretschneider (SMB) method [12-15]. As the data obtained from the wind drift factor estimation are part of a simulation of a real case of oil spill in a bounded region (described in [1, 2]), the wave is considered to be fetch limited, with an assumed fetch length of 40km, as suggested in [27]. The SMB method establishes that the spectral significant wave height H_m, the period of the spectral peak T_m and the duration t of the wave development relate to the fetch F and to the wind stress factor W_a by equations 2 to 4 [12]. In these equations, g is the acceleration of gravity.

$$gH_m/W_a^2 = 0.0016(gF/W_a^2)^{0.5}, \tag{2}$$

$$gT_m/W_a = 0.2857(gF/W_a^2)^{1/3}, \tag{3}$$

$$gt/W_a = 68.8(gF/W_a^2)^{2/3}. \tag{4}$$

Equations 2 to 4 are valid up to the limits of the fully developed wave, given by $gH_m/W_a^2 = 0.2433$, $gT_m/W_a = 8.134$ and $gt/W_a = 71500$ [12]. In order to obtain the wind stress factor W_a, one shall first obtain the effective wind speed W_{ef} from the measured wind speed W, by applying the corrections due to anemometer elevation (as shown in equation 1), duration-averaged wind speed, air-sea temperature difference and anemometer location. For the CFD estimation of the wave characteristics, the 10m height wind speed W_{10} averaged over the CFD domain is used as the best value of the effective wind speed W_{ef}, with only the anemometer elevation correction being applied on the simulation. The wind stress factor W_a, used to determine the significant wave, accounts for a nonlinear relation between the wind stresses and wind speed and is obtained from the effective wind speed W_{ef} by equation 5 [12]:

$$W_a = 0.71{W_{ef}}^{1.23} \ \ (W_{ef} \text{ in m/s}) \ . \tag{5}$$

The wavelength λ is obtained using the dispersion relation for a short wave (equation 6), assuming large depth:

$$\omega^2 = kg \ , \tag{6}$$

where k is the wave number ($k = 2\pi/\lambda$) related to the wavelength λ, and ω is the circular frequency ($\omega = 2\pi/T$) related to the wave period T. Evaluating equation 6 leads to the wavelength equation (equation 7), being the period T determined from equation 3:

$$\lambda = \frac{gT^2}{2\pi} \ . \tag{7}$$

2.3 Methodology for the Estimation of the Simulation Numerical Uncertainty

The CFD model used in the analysis of the wind drift factor is subjected to imprecisions. Hence, it is fundamental that it is submitted to a verification process to determine its simulation numerical uncertainty. The verification procedure is based in the guidelines of ITTC [28] for CFD analysis, which follows [29, 30].

The verification procedure assesses the simulation numerical uncertainty U_{SN}, through convergence studies due to a single input parameter refinement. In this paper, three solutions (fine, medium and coarse) are used to verify the convergence of each parameter. The simulation numerical uncertainty U_{SN} is determined by equation 8.

$$U_{SN}^2 = U_I^2 + U_G^2 + U_T^2 + U_P^2 \ , \tag{8}$$

where U_I is the uncertainty due to iteration, U_G is the uncertainty due to grid size, U_T is the uncertainty due to time step and U_P is the uncertainty due to other parameters.

For the CFD simulations of this research, the contributions due to the grid size and to the time step were the main parameters in the calculation of the simulation numerical uncertainty. Other sources of uncertainties that were tested, like uncertainty due to iterations (small due to convergence of the simulations) or due to data (e.g. water and air density and viscosity), are of secondary order.

For the grid size uncertainty, the grid refinement ratio r_G is defined as the ratio of the cell linear dimensions (in the x- and y-directions) of the medium over the fine meshes and of the coarse over the medium meshes. It is set to be constant and equal to $\sqrt{2}$.

The time step uncertainty U_T is determined by performing three transient simulations using the fine grid. The time steps are set to be 0.03s, 0.04243s and 0.06s, corresponding to a time step refinement ratio r_T of $\sqrt{2}$.

Convergence is defined by the convergence ratio R_k (equation 9), calculated based on the three solutions for each parameter k (in this case, k is the grid size or the time step). In equation 9, ε_{k21} is the difference between the medium solution S_{k2} and the fine solution S_{k1} ($\varepsilon_{k21} = S_{k2} - S_{k1}$) and ε_{k32} is the difference between the coarse solution S_{k3} and the medium solution S_{k2} ($\varepsilon_{k32} = S_{k3} - S_{k2}$).

$$R_k = \varepsilon_{k21}/\varepsilon_{k32} \ . \tag{9}$$

For a monotonic convergence ($0 < R_k < 1$), the generalized Richardson extrapolation (RE) [28-30] is used to estimate the uncertainty. The error estimative $\delta_{RE\ k}^*$ of the generalized Richardson extrapolation for parameter k is calculated by equation 10.

$$\delta^*_{RE\ k} = \frac{\varepsilon_{k21}}{r_k^{p_k} - 1}\,, \tag{10}$$

with:

$$p_k = \frac{\ln(\varepsilon_{k32}/\varepsilon_{k21})}{\ln(r_k)}\,. \tag{11}$$

The uncertainty U_k of parameter k is estimated by multiplying the error estimative of the RE (equation 10) by a factor of safety $F_s = 1.25$, recommended for careful grid studies (3 or more grids) [28, 31], as shown in equation 12.

$$U_k = F_s|\delta^*_{RE\ k}|\,. \tag{12}$$

For oscillatory convergence ($R < 0$), the uncertainty U_k is based on the oscillation maximum solution $S_{k\ max}$ and minimum solution $S_{k\ min}$ of parameter k (equation 13).

$$U_k = 0.5(S_{k\ max} - S_{k\ min})\,. \tag{13}$$

3. RESULTS

3.1 Results of the estimation of the significant wave

The significant wave height (equation 2) and wavelength (equation 7) for a 40km fetch and wind speeds up to 11m/s are presented in figures 3 and 4, respectively. The values of the wavelength and wave height are used at the inlet of the open channel model in the CFD software ANSYS Fluent as boundary condition.

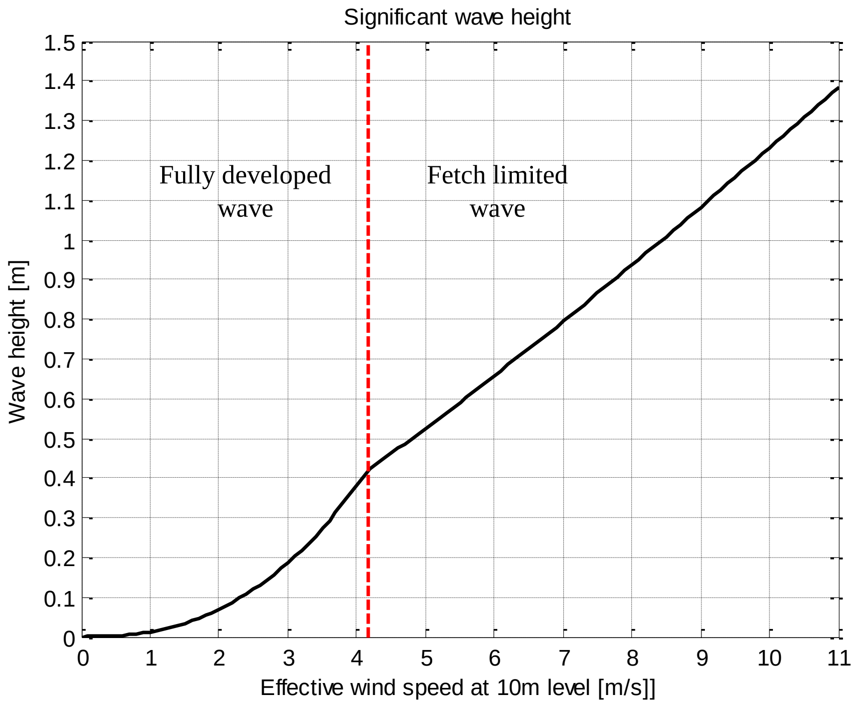

Fig.3 – Significant wave height for short waves for a 40km fetch (the red dotted line indicates the limit of the fully developed wave and the fetch limited wave).

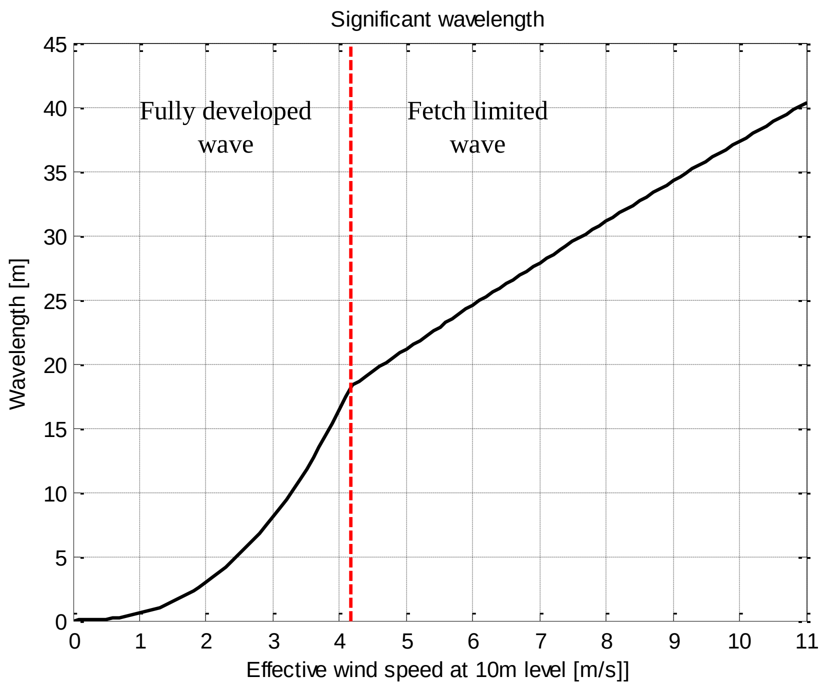

Fig.4 - Significant wavelength for short waves for a 40km fetch (the red dotted line indicates the limit of the fully developed wave and the fetch limited wave).

3.2 Results of the estimation of the free surface velocity

The average wavy free surface velocity, determined from the CFD simulations as a function of the domain averaged 10m wind speed, is presented in figure 5.

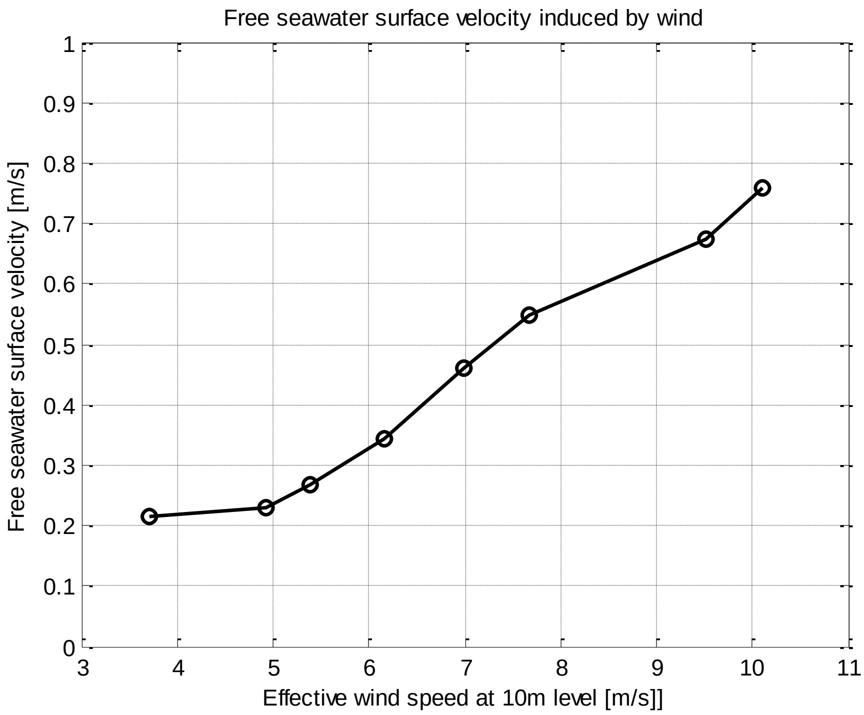

Fig.5 – Domain averaged free surface velocity.

The uncertainty analysis for the average free surface velocity is estimated by a variation on the grid size (figure 6) and a variation on the time step of the simulations (figure 7).

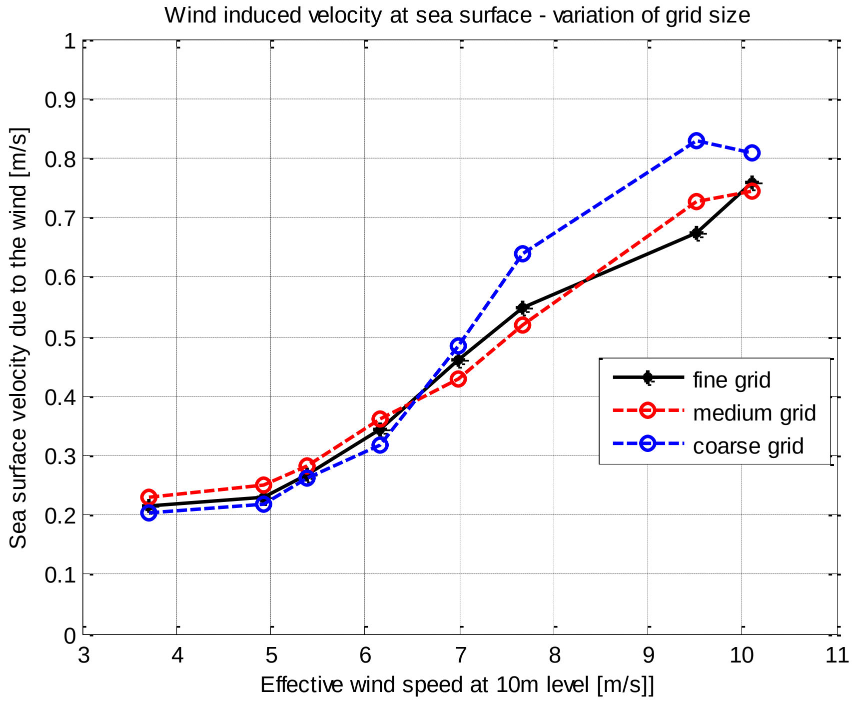

Fig.6 – Results of the average free surface velocity due to the variation of the grid size.

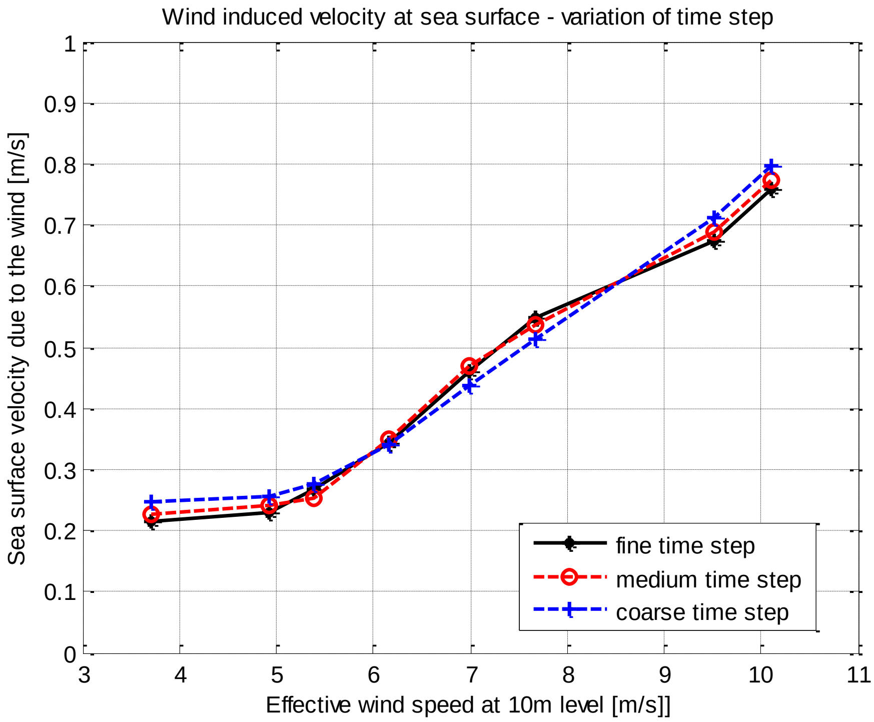

Fig.7 – Results of the average free surface velocity due to the variation of the time step.

From the results presented in figures 6 and 7, the uncertainties due to the grid (U_G) and due to the time step (U_T) are calculated by equations 12 or 13, depending on the type of convergence. The simulation numerical uncertainty (U_{SN}) is calculated by equation 8. The uncertainties are expressed as a percentage of the free surface velocity and are shown in table 2.

Tab.2 – Percentage uncertainty of the free surface velocity due to grid size (U_G), due to time step (U_T) and simulation numerical uncertainty (U_{SN})

Wind speed (m/s)	Free surface velocity (m/s)	U_G	U_T	U_{SN}
3.70	0.216	6.13%	4.38%	7.53%
4.92	0.231	6.44%	6.58%	9.21%
5.39	0.268	3.67%	4.16%	5.55%
6.17	0.344	6.21%	1.11%	6.31%
7.00	0.460	6.23%	3.68%	7.24%
7.67	0.548	10.94%	2.67%	11.27%
9.52	0.674	10.94%	3.16%	11.39%
10.10	0.758	4.14%	8.94%	9.85%

3.3 Results of the estimation of the wind drift factor

The wind drift factor is obtained by the ratio between the average sea surface velocity and the average wind speed measured at the CFD domain. The results are shown in figure 8.

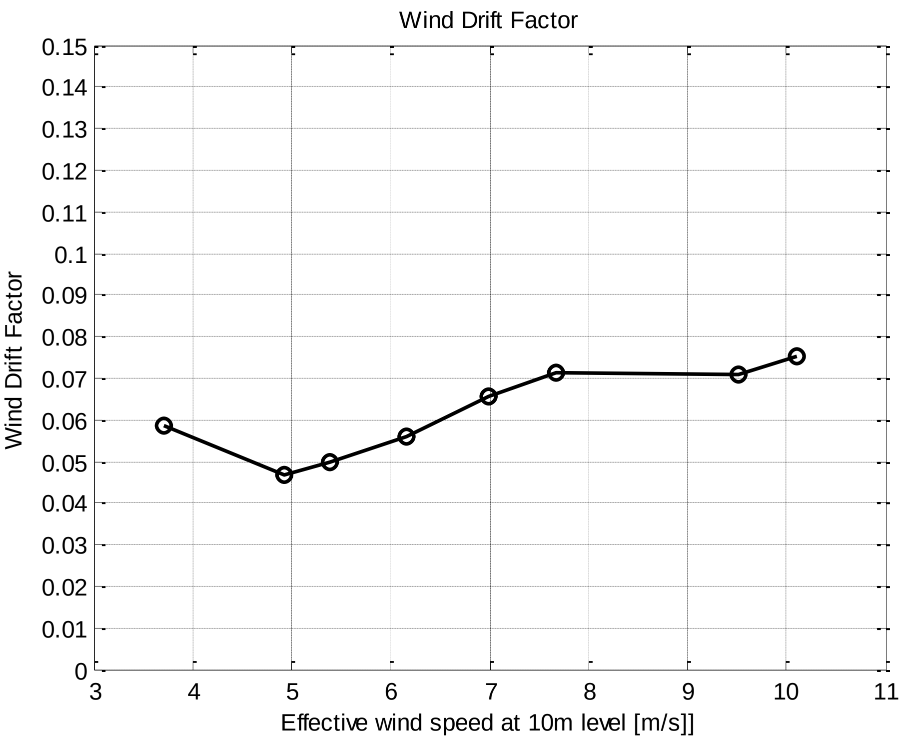

Fig.8 - Estimated wind drift factor.

Concerning the uncertainty analysis of the wind drift factor, the percentage results are the same results shown in table 2, as the wind drift factor is obtained from the ratio between the free surface velocity and the effective wind speed. The wind drift factors for the variation on the grid size and for the variation on the time step of the simulations are shown in figures 9 and 10 respectively.

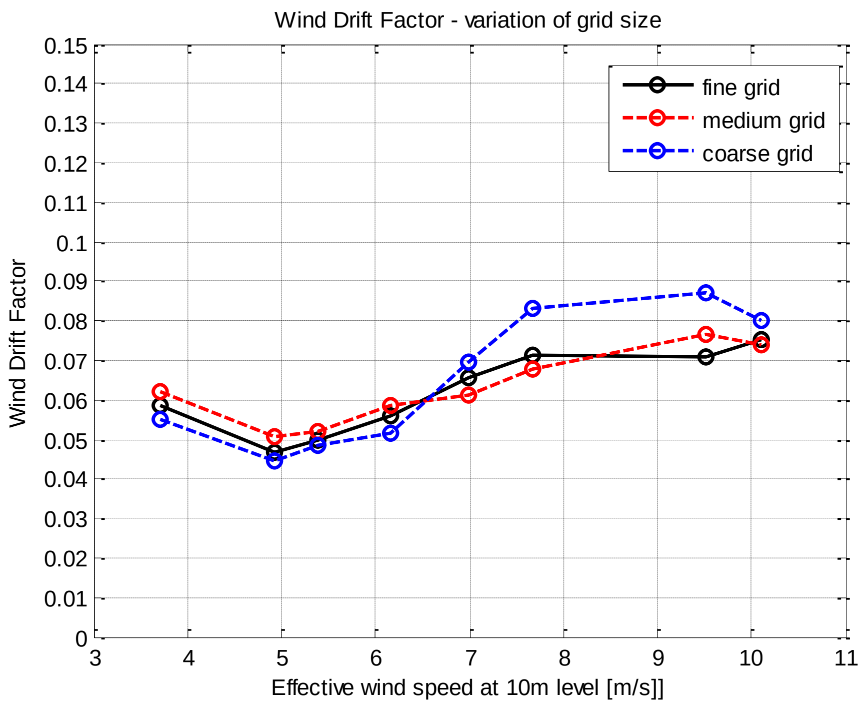

Fig.9 – Results of the wind drift factor due to the variation of the grid size.

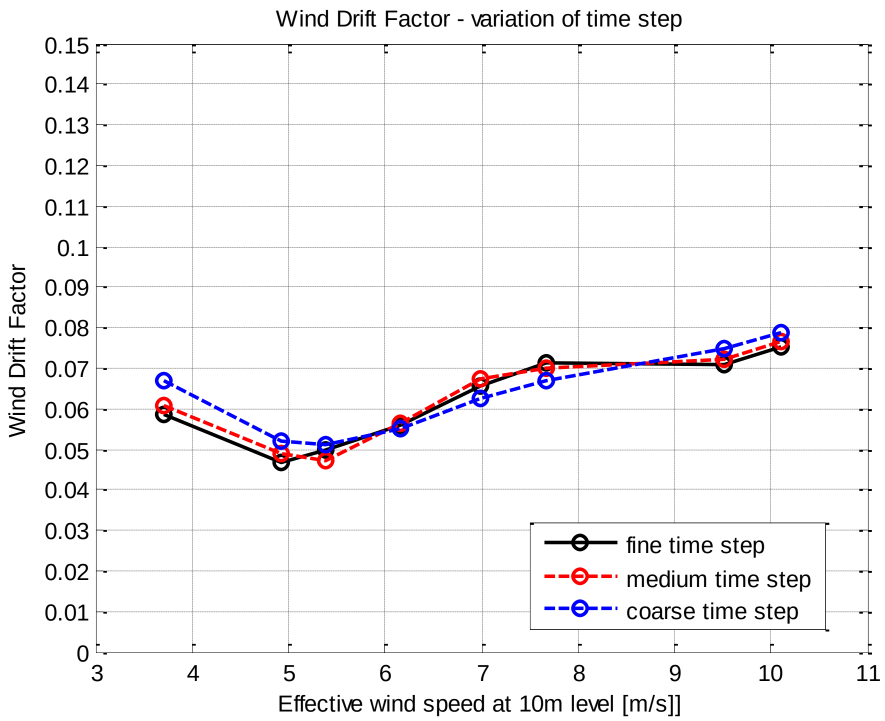

Fig.10 – Results of the wind drift factor due to the variation of the time step.

The average wind drift factor for the range of the wind speed of the simulations is 0.0617 and varied from 0.0468 to 0.0751. The average values of the wind drift factor for the medium grid simulation and for the coarse grid simulations are 0.0627 and 0.0649, respectively, corresponding to a grid uncertainty (U_G) of 1.98%. For the variation of time step, the average values are 0.0624 for the medium time step and 0.0635 for the coarse time step leading to a time step uncertainty (U_T) of 2.40%. The simulation numerical uncertainty (U_{SN}) for the average wind drift factor is 3.11%.

4. DISCUSSION

The usual values of the wind drift factors used in previous literature works are in the range between 0.01 and 0.06. The results obtained in the CFD simulations are close to the top limit of the ones from literature and extends from 0.0468 to 0.0751, with an average value of $0.0617 \pm 3.11\%$. The results obtained for the wind drift factor are specifically for the case of fetch limited waves using a fetch of 40km length. This length is used as part of a risk analysis of an oil spill that occurred in the region of Point Wells [1,2], Related to this case, ref. [2] used a value of 0.06 for the wind drift factor in the simulation of the oil spill, which is very close to the average value obtained in this research.

An important issue that is necessary in CFD simulations is to estimate the range of the uncertainty in the simulation numerical results. The procedure used in this research considers three simulations (fine, medium and coarse simulation) for each parameter under analysis, with a refinement ratio of $\sqrt{2}$, as stated in [28-30], to test its convergence. The procedure allows obtaining the uncertainty, although it requires an extensive number of simulations. The application of this procedure for a case that involves wave simulation turns to be more complicated as the wave requires a good discretization and using a coarse grid or a coarse time step can degenerate the wave and unbalance a good compromise between computational time and accuracy which is essential for the fine grid. Also, wave simulation convergence takes more computational time, leading to a high computational cost.

The simulation numerical procedure is considered verified for the level of uncertainty obtained, under the boundary conditions and setup used in the simulation, concerning the grid size and the time step. No validation procedure of this methodology was conducted as there is no available experimental data for comparison. However, the results are in good agreement with the data usually adopted in literature.

Although it is time consuming, the CFD simulations are essential to reduce the subjectivity in the value of the wind drift factor that is used in the estimation of the free surface velocities induced by the wind. From the obtained results, the use of a value close to 0.06 seems to be very adequate for the oil spill case under analysis.

5. CONCLUSION

This work showed the procedures and the results obtained in the estimation of the wind drift factor by a series of two dimensional transient CFD simulations. A wind flow velocity and a linear Airy wave are applied at the inlet of the domain. The average values of the free surface velocity and the 10m wind velocity along the domain are used to determine the wind drift factor. The waves are fetch limited and calculated using the SMB procedure for a 40km length fetch. The obtained average wind drift factor of $0.0617 \pm 3.11\%$. shows consistency with the values from literature. The simulation numerical uncertainty is estimated by varying the grid size and the time step size, using three levels of refinement for each parameter.

6. ACKNOWLEDGEMENTS

This work was supported by ‘Agência Nacional do Petróleo, Gás Natural e Biocombustíveis – ANP’, by ‘Financiadora de Estudos e Projetos – FINEP’, and by ‘Ministério da Ciência, Tecnologia e Inovação – MCTI’, through the ‘Programa de Recursos Humanos da ANP para o Setor Petróleo e Gás – PRH-ANP/MCTI’.

The authors would like to acknowledge and thank the Pacific Northwest National Laboratory (PNLL) for providing the Salish Model Application Solution Files used in this research in the determination of the seawater property data.

Prof. Marcelo Martins also wishes to acknowledge his support from the Brazilian National Council for Scientific and Technological Development (CNPq) through grant 308712/2019-6.

7. REFERENCES

[1] The Foss-Pt.Wells Natural Resource Trustees, Restoration Plan and Environmental Assessment for the Foss 248-P2 Oil Spill on December 30, 2003; Foss-Pt. Wells Natural Resources Trustees: USA, (2009).

[2] DURAN R.; ROMEO L.; WHITING J.; VIELMA J.; ROSE, K., BUNN A; BAUER J., Simulation of the 2003 Foss Barge – Point Wells oil spill: a comparison between BLOSOM and GNOME oil spill models. Journal of Marine Science and Engineering, v. 6, 104, (2018). doi:10.3390/jmse6030104.

[3] STOKES G.G., On the theory of oscillatory waves. Transactions of the Cambridge Philosophical Society. Vol. VIII (1847) 441–455. Reprinted in: Mathematical and Physical Papers, Volume I. Cambridge University Press (1880) 197–229.

[4] ZELENKE B., O'CONNOR C., BARKER C., BEEGLE-KRAUSE C. J., ECLIPSE L., General NOAA Operational Modeling Environment (GNOME) Technical Documentation. NOAA Technical Memorandum NOS OR&R 40. Seattle, WA: Emergency Response Division, NOAA. 105 pp. http://response.restoration.noaa.gov/gnome_manual, (2012).

[5] STOLZENBACH K.D., MADSEN O.S., ADAMS E.E., POLLACK A.M., COOPER C.K., A Review and Evaluation of Basic Techniques Predicting the Behavior of Surface Oil Slicks. Report No. 222 of the Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics. Massachusetts Institute of Technology, Cambridge, Massachusetts (1977).

[6] GALT J.A., Trajectory analysis for oil spills. J. Adv. Mar. Tech. Conf., 11 (1994) 91-126.

[7] CSANADY G.T., The “slip law” of the free surface, J. Oceanogr. 53 (1997) 67–80. https://doi.org/10.1007/BF02700750.

[8] ALLSHOUSE M.R., IVEY G.N., LOWE R.J., JONES N.L., BEEGLE-KRAUSE C.J., XU J., PEACOCK T., Impact of windage on ocean surface Lagrangian coherent structures, Environ. Fluid Mech. 17 (2017) 473–483. https://doi.org/10.1007/s10652-016-9499-3.

[9] SAMUELS W.B., HUANG N.E., AMSTUTZ D.E., An oilspill trajectory analysis model with a variable wind deflection angle, Ocean Eng. 9 (1982) 347–360. https://doi.org/10.1016/0029-8018(82)90028-2.

[10] ANSYS, ANSYS Fluent Theory Guide Release 15.0, ANSYS Inc., USA. (2013).

[11] ANSYS, ANSYS Fluent User's Guide Release 15.0, ANSYS Inc., USA. (2013).

[12] CERC (Coastal Engineering Research Center). Shore Protection Manual, Vol. 1, 4th ed. U.S. Army Corps of Engineers, Washington, D.C. (1984).

[13] BRETSCHNEIDER C.L., Revised wave forecasting relationships. Coastal Engineering Proceedings 1 (2) (1951) 1-5. https://doi.org/10.9753/icce.v2.1.

[14] BRETSCHNEIDER C.L., Revisions in wave forecasting: deep and shallow water. Coastal Engineering Proceedings 1 (6) (1957) 3. https://doi.org/10.9753/icce.v6.3.

[15] SVERDRUP H.U., MUNK W.H., Wind, Sea, and Swell. Theory of Relations For Forecasting, US Hydrographic Office, Washington, DC, USA, technical report no. 601 (1947). DOI: https://doi.org/10.5962/bhl.title.38751.

[16] HIRT C.W, NICHOLS B.D., Volume of uid (VOF) method for the dynamics of free boundaries, Journal of Computational Physics 39 (1) (1981) 201-225, ISSN 0021-9991, https://doi.org/10.1016/0021-9991(81)90145-5.

[17] IAPWS, The International Association for the Properties of Water and Steam, Release on the IAPWS Formulation 2008 for the Thermodynamic Properties of Seawater, (2008) 1-12.

[18] McDOUGALL T.J., BARKER P.M., Getting started with TEOS-10 and the Gibbs Seawater (GSW) Oceanographic Toolbox (2011) 28pp., SCOR/IAPSO WG127, ISBN 978-0-646-55621-5.

[19] PNLL, Salish Sea Model, Pacific Northwest National Laboratory, https://www.pnnl.gov/projects/salish-sea-model.

[20] KHANGAONKAR T, NUGRAHA A., XU W., LONG W., BIANUCCI L., AHMED A., MOHAMEDALI T., PELLETIER G., Analysis of Hypoxia and Sensitivity to Nutrient Pollution in Salish Sea. Journal of Geophysical Research – Oceans, 123. doi: 10.1029/2017JC013650 (2018).

[21] KHANGAONKAR T, LONG W., XU W., Assessment of circulation and inter-basin transport in the Salish Sea including Johnstone Strait and Discovery Islands pathways, Ocean Modelling, 109:11-32.doi: 10.1016/j.ocemod.2016.11.004 (2017).

[22] KHANGAONKAR T, YANG Z., KIM T.Y., ROBERTS M., Tidally averaged circulation in Puget Sound sub-basins: Comparison of historical data, analytical model, and numerical model. Estuarine, Coastal and Shelf Science 93(4):305-319. doi.org/10.1016/j.ecss.2011.04.016 (2011).

[23] KHANGAONKAR T, SACKMANN B., LONG W., MOHAMEDALI T., ROBERTS M.. Simulation of annual biogeochemical cycles of nutrient balance, phytoplankton bloom(s), and DO in Puget Sound using an unstructured grid model. Ocean Dynamics, 62(9):1353-1379.doi: 10.1007/s10236-012-0562-4 (2012).

[24] SHARQAWY M.H., LIENHARD V J.H., ZUBAIR S.M., Thermophysical properties of seawater: A review of existing correlations and data, Desalin.Water Treat. 16 (2010) 354{380. https://doi.org/10.5004/dwt.2010.1079.

[25] IAPWS, The International Association for the Properties of Water and Steam, Guideline on the surface tension of seawater, (2019) 1-5.

[26] NOAA, National Oceanic and Atmospheric Administration, NOAA's National Data Buoy Center (NDBC). https://www.ndbc.noaa.gov/view_text_file.php?filename=wpow1h2003.txt.gz&dir=data/historical/stdmet/, access in 02/12/2021.

[27] FINLAYSON D., The geomorphology of Puget Sound beaches. Puget Sound Nearshore Partnership Report No. 2006-02. Published by Washington Sea Grant Program, University of Washington, Seattle, Washington. Available at http://pugetsoundnearshore.org (2006).

[28] ITTC, Resistance Committee of 23rd International Towing Tank Conference, ITTC - Recommended procedures and guidelines, uncertainty analysis in CFD , verification and validation methodology and procedures, 7.5-03-01–01 (2002).

[29] STERN F., WILSON R. V., COLEMAN H.W, PATERSON E.G., Comprehensive approach to verification and validation of CFD simulations—Part 1: Methodology and procedures, J. Fluids Eng. Trans. ASME. 123 (2001) 793–802. https://doi.org/10.1115/1.1412235.

[30] WILSON R.V., STERN F. COLEMAN H.W., PATERSON E.G., Comprehensive approach to verification and validation of CFD simulations—Part 2: Application for rans simulation of a cargo/container ship, J. Fluids Eng. Trans. ASME. 123 (2001) 803–810. https://doi.org/10.1115/1.1412236.

[31] ROACHE P.J., Verification and Validation in Computational Science and Engineering, Hermosa Publishers, Albuquerque, New Mexico (1998).