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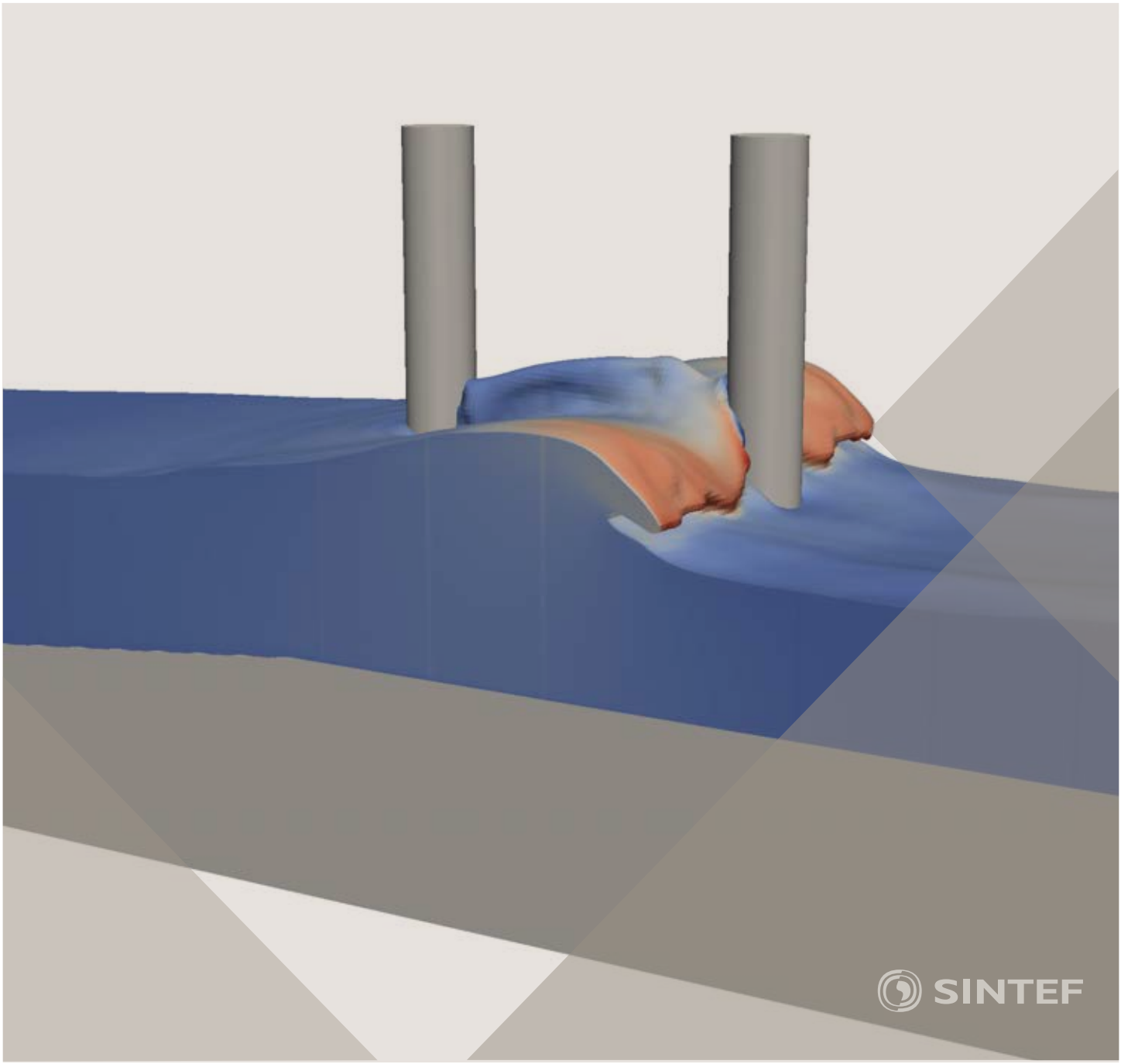
Progress in Applied CFD – CFD2017



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Editors:
Jan Erik Olsen and Stein Tore Johansen

Progress in Applied CFD – CFD2017

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PREFACE

This book contains all manuscripts approved by the reviewers and the organizing committee of the 12th International Conference on Computational Fluid Dynamics in the Oil & Gas, Metallurgical and Process Industries. The conference was hosted by SINTEF in Trondheim in May/June 2017 and is also known as CFD2017 for short. The conference series was initiated by CSIRO and Phil Schwarz in 1997. So far the conference has been alternating between CSIRO in Melbourne and SINTEF in Trondheim. The conferences focuses on the application of CFD in the oil and gas industries, metal production, mineral processing, power generation, chemicals and other process industries. In addition pragmatic modelling concepts and bio-mechanical applications have become an important part of the conference. The papers in this book demonstrate the current progress in applied CFD.

The conference papers undergo a review process involving two experts. Only papers accepted by the reviewers are included in the proceedings. 108 contributions were presented at the conference together with six keynote presentations. A majority of these contributions are presented by their manuscript in this collection (a few were granted to present without an accompanying manuscript).

The organizing committee would like to thank everyone who has helped with review of manuscripts, all those who helped to promote the conference and all authors who have submitted scientific contributions. We are also grateful for the support from the conference sponsors: ANSYS, SFI Metal Production and NanoSim.

Stein Tore Johansen & Jan Erik Olsen

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CONTENTS

ON THE SURFACING MECHANISM OF BUBBLE PLUMES FROM SUBSEA GAS RELEASE

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ABSTRACT

A subsea release of gas poses a risk to humans and assets at the surface. Assessing this risk requires knowledge on how much gas reaches the surface and how it is distributed at the surface. This can be estimated by various modelling techniques, e.g. CFD. Reported surfacing flux can then be fed into a CFD model for atmospheric dispersion calculations. This paper briefly discusses how the surface flux can be calculated by CFD, but primarily focuses on the surfacing characteristics and discusses how the surface flux can be reported and issues related to this.

Keywords: CFD, bubbly flows, subsea gas release

NOMENCLATURE

Greek Symbols

ρ	Mass density, [kg/m^3].
σ	Standard deviation, [m].

Latin Symbols

a	Characteristic length, [m].
$\mathbf{F}$	Force, [N/m].
$\mathbf{g}$	Gravitational acceleration, [m/s^2].
J	Gas flux, [kg/m^{2}s].
$\dot{m}$	mass rate, [kg/s].
r	radius, [m].
t	Time, [s].
$\mathbf{u}$	Velocity, [m/s].

Sub/superscripts

0	Centre
b	Bubble.
D	Drag.
VM	Virtual mass.
tot	Total

INTRODUCTION

A subsea gas release of hydrocarbons such as methane presents a risk of fire and explosions when the gas emerges into the atmosphere. Risk assessments are normally based on modelling of atmospheric dispersion of hazardous gases. Modelling of atmospheric dispersion relies on a boundary condition which prescribes the flux of gas escaping from the ocean into the atmosphere. This flux will vary in time and position, although many assume it to be constant. In this work we try to characterize a surfacing profile and provide guidelines on how this can be represented as a boundary condition in atmospheric dispersion models.

The ocean surface boundary condition for atmospheric simulations can be provided by a subsea model of the bubble plume. Different modelling concepts are available for this. Traditionally, classical plume integral models, which are computationally fast, have been applied for this (Johansen, 2000; Morton *et al.*, 1956; Zheng & Yapa, 2002). These are based on a series of assumptions and calibration coefficients, but still have proven to reproduce experimental results at least at smaller scales. Transient 3-dimensional CFD modelling of these plumes are computationally expensive due to the large length scales involved, but they rely on fewer assumptions – especially in the surfacing region. The authors of this work have contributed to the development of a CFD model for bubble plumes from subsea gas releases (Cloete *et al.*, 2009; Olsen *et al.*, 2017).

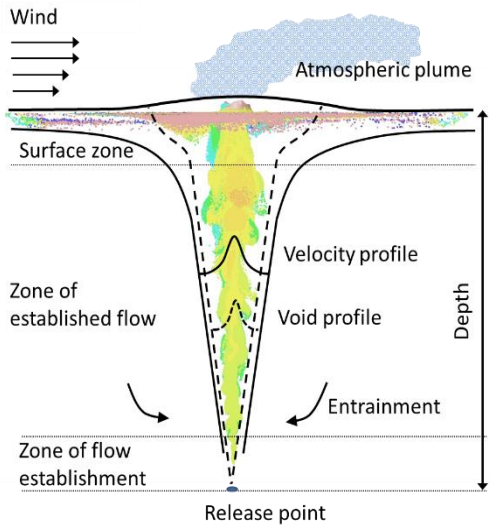


Figure 1: Illustration of subsea gas release.

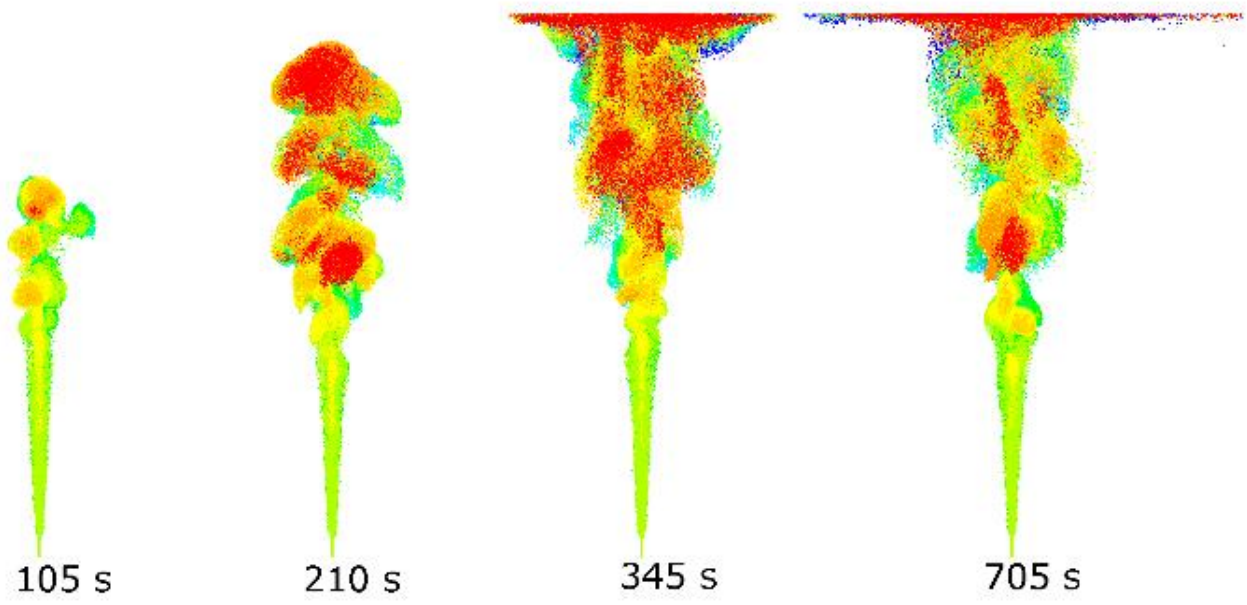


Figure 2: Development of the starting plume from 300 m at a constant rate of 30 kg/s.

Gas released from the ocean floor rises as bubbles towards the surface. If the release rate is sufficient, the buoyancy of the bubbles will cause the water to accelerate and travel upwards with bubbles. At the surface the bubbles enters the atmosphere whereas the water is forced outwards in a radial flow. The CFD model quantifies where and when bubbles penetrate the surface and the strength of the radial outflow.

Here we apply the CFD model for a selected release scenario and analyse the surfacing characteristics. The resulting surfacing fluxes and radial outflow velocity are compared to mathematical profiles to verify if some of these are representative for the *true* surfacing profiles.

MODEL DESCRIPTION

The CFD model developed to study large scale bubble plumes from subsea gas release is based on an Eulerian-Lagrangian modelling concept. The bubbles are treated as Lagrangian particles which move according to Newton's second law. The background fluid, i.e. the ocean, is governed by the Navier-Stokes equation in an Eulerian frame of reference. The interface between the ocean and the atmosphere is tracked by the *geo-reconstruct* algorithm. The details are provided in earlier publications (Olsen & Skjetne, 2016; Olsen *et al.*, 2017).

In a short summary it is worth mentioning that the model moves bubbles according to Newton's second law

$$\frac{d\boldsymbol{u}_b}{dt} = \frac{\boldsymbol{g}(\rho_b - \rho)}{\rho_b} + \boldsymbol{F}_D + \boldsymbol{F}_{VM} \qquad (1)$$

where the forces on the right hand side are buoyancy, drag and virtual mass. The background fluids (ocean and atmosphere) are mathematically described by the principles of conservation of mass, momentum and energy through the continuity-, momentum- and heat-equation. The bubble motion and the flow of the background fluids are coupled through the drag term. Turbulence is modelled with a VLES model where turbulent structures larger than the grid size are captured by the momentum equations and the subgrid turbulence is modelled by the k-ε model.

A model for the local mean bubble diameter is implemented accounting for break-up, coalescence, gas expansion and gas dissolution. Gas expansion is caused by the decrease in pressure and gas density as the bubbles rises upwards. Gas dissolution is driven by the difference in gas solubility and ocean saturation.

The model has been validated against meso scale experiments at 7, 30 and 50 meters depth and large scale data from 140 meters depth. The model is consistent with observations.

RESULTS

The modelling concept mentioned above was applied to a release of 30 kg/s of methane from a depth of 300 meters with an ocean temperature at 10°C and ocean salinity of 35 psu. The simulation results have been analysed to shed light on the surfacing mechanism and to discuss how these results can be reported as a boundary condition to atmospheric dispersion modelling.

The resulting plume from the release is illustrated in Figure 2 as predicted by the CFD simulation. Turbulent eddies with gas bubbles surface after roughly 4 minutes. The eddies cause a fluctuating surface rate and flux which would not have been captured by a RANS turbulence model. Observations of ocean bubble plumes confirms the fluctuating behaviour qualitatively. The surfacing rate is plotted in Figure 3. The surfacing rate (kg/s) is the area integral of the surface flux (kg/m^{2}s). It averages at 1.6 kg/s indicating that gas dissolution is significant since only 5% of the released gas reaches the surface. The fluctuations are also significant.

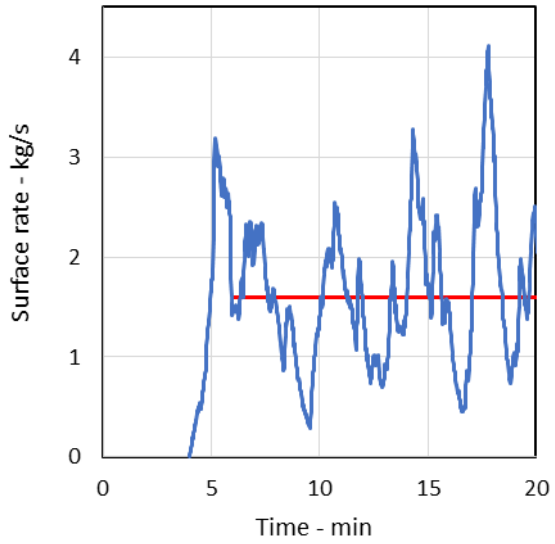


Figure 3: Surfacing rate as function of time, red line indicates average surfacing rate.

If we focus on the surfacing flux which varies in both time and space, we see that the fluctuations are even more significant. The resulting averaged surface flux using different averaging intervals are depicted in Figure 5 (next page). The two top plots are both with an averaging interval of 1 second, but from two different times (650 and 750 secs after release). There is a big difference in the peak flux and total surface rate between these two periods.

The flux is quite noisy. As the averaging interval increases, the flux distribution becomes more smooth and starts looking like a Gaussian distribution. Note that with an averaging period of 800 seconds the peak is less than ¼ of the maximum peaks in the fastest fluctuations. It is the long-averaged surface flux fitted to a Gaussian profile which is normally applied as a boundary condition in atmospheric dispersion modelling. This practice stems from modelling experiences with integral models and CFD models with RANS turbulence models. These models do not capture the fluctuations seen in Figures 3 and 5. Thus it can be questioned whether the conveniently long-averaged Gaussian profile is a proper boundary condition.

If we assume that a Gaussian profile is sufficiently representative of the surfacing flux, there are still some issues related on how to report the coefficients in the Gaussian expression. The Gaussian flux profile is given by

$$J = J_0 e^{-r^2/2\sigma^2} \qquad (2)$$

where J_0 is the centre flux (or peak flux) and σ is the standard deviation. If the long-averaged surface flux is truly Gaussian, a perfect fit between the surface flux from the CFD simulation and a Gaussian profile exists. This is unfortunately not true.

All gas surfacing within the radius defined by the standard deviation amount to 39% of all gas surfacing in total (see Appendix). By analysing the surface flux from the CFD simulation, the radius within which 39% of the gas surfaces can be extracted and reported as a standard deviation. Applying the principle that the Gaussian profile shall fulfil mass conservation, the centre flux is obtained from

$$\dot{m}_{tot} = 2\pi J_0 \sigma^2 \qquad (3)$$

From this procedure we get J_0=0.165 g/m^{2}s and σ=28 m. Alternatively we can quantify the coefficients by matching the Gaussian centre flux with the true peak flux and finding the standard deviation from mass conservation with Eq.(3). From this procedure we get J_0=0.39 g/m^{2}s and σ=18 m. The true long-averaged profile and the Gaussian curve fits are plotted below in Figure 4.

The two procedures for obtaining the Gaussian coefficients obviously produces two quite different sets of coefficients. From this we can conclude that the profile is not truly Gaussian. For a true Gaussian, both procedures would have resulted in the same set of coefficients. This gives rise to an important question; which procedure provides the most representative Gaussian profile for the long-averaged surface flux? Visually it is probably the procedure based on the centre flux which seems superior (see Figure 5). However, it is also fair to question whether a Gaussian profile is truly representative

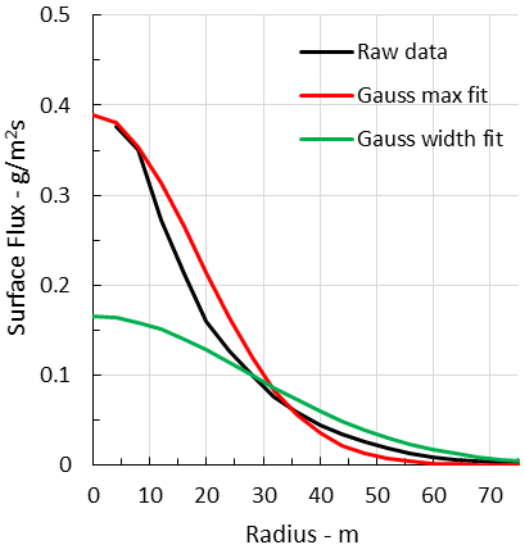
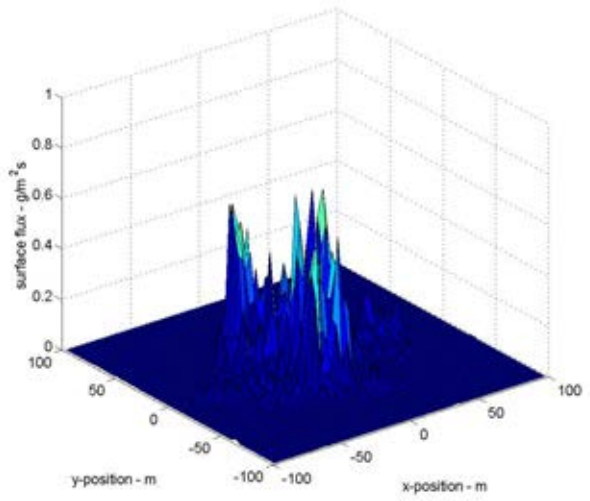
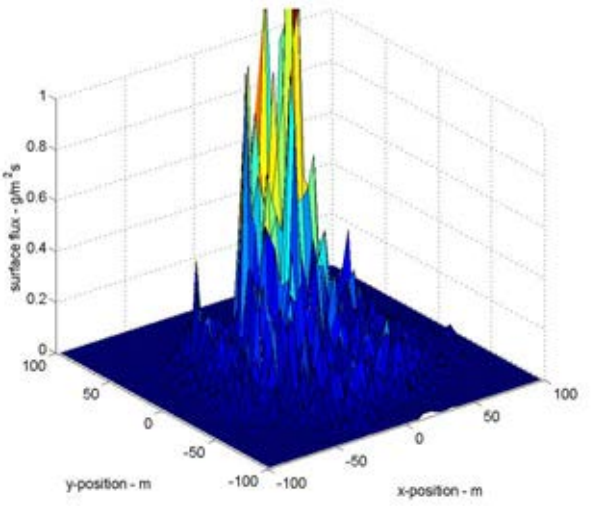


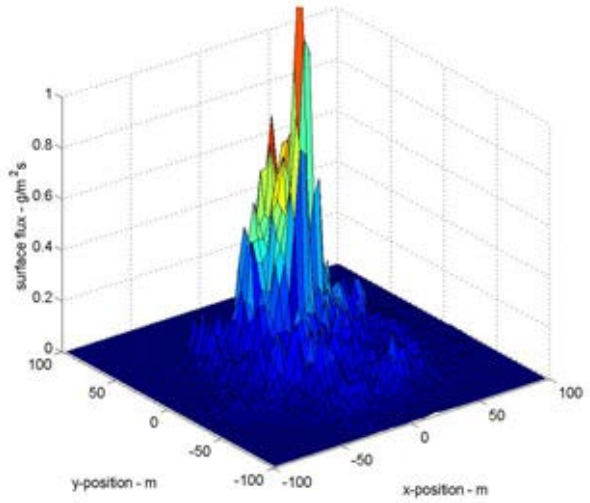
Figure 4: Surface flux



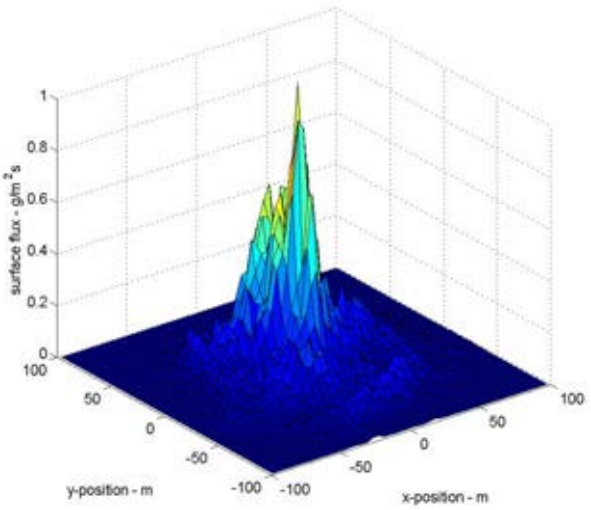
1 second averaging (at 750 secs)



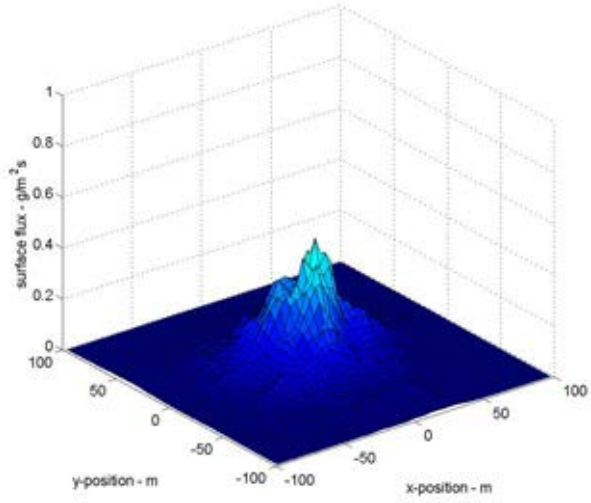
1 second averaging (at 650 secs)



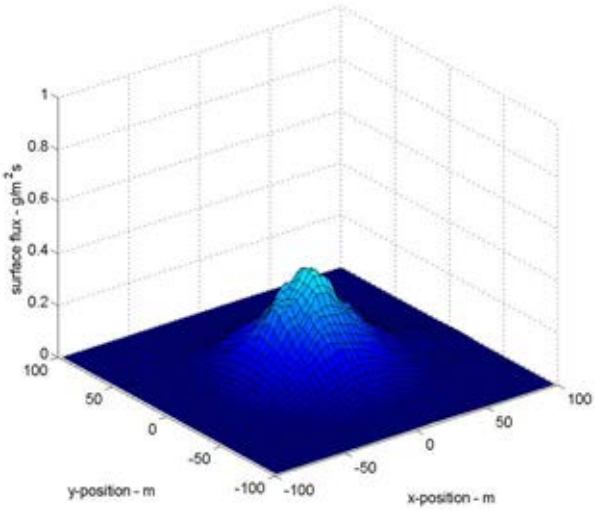
5 seconds averaging



10 seconds averaging



100 seconds averaging



800 seconds averaging

Figure 5: Surface flux for various averaging intervals. All averaging starts at 650 secs after start of release except top left example.

CONCLUSIONS

A CFD model with a transient VLES model representing turbulence has been applied to study the surfacing mechanism of an ocean plume caused by a subsea gas release. The resulting surface rate and surface flux is clearly fluctuating. A surface flux profile based on time-averaging over 800 seconds has a smooth shape which can be fitted to a Gaussian profile, although a perfect fit cannot be achieved. This indicates that the surface flux is not truly Gaussian even if similarities exist. Two different procedures for quantifying the Gaussian profile yields two different sets of Gaussian coefficients.

A consequence of these findings is to further study which profile best matches the true surface flux with respect to a risk assessment (e.g. conservatism). Sensitivity studies with atmospheric dispersion modelling could reveal the significance on how to report the surfacing profile. This includes assessments on both the fluctuating nature of the surfacing mechanism and the influence of how the time averaged profile is represented.

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APPENDIX A

A Gaussian flux profile is given by

$$J = J_0 e^{-r^2/2\sigma^2} \tag{4}$$

The total gas rate through the entire surface is given by

$$\begin{aligned} \dot{m}_{tot} &= 2\pi \int_0^\infty J_0 e^{-\frac{r^2}{2\sigma^2}} r\, dr \\ &= 2\pi J_0 \left[-\sigma^2 e^{-\frac{r^2}{2\sigma^2}} \right]_0^\infty = 2\pi J_0 \sigma^2 \end{aligned} \tag{5}$$

The total gas rate through a surface limited by an outer radius *R*, is

$$\begin{aligned} \dot{m} &= 2\pi \int_0^R J_0 e^{-\frac{r^2}{2\sigma^2}} r\, dr \\ &= 2\pi J_0 \sigma^2 \left(1 - e^{-\frac{R^2}{2\sigma^2}} \right) \end{aligned} \tag{6}$$

The ratio of mass surfacing inside a radius *R* and the total mass is thus

$$\frac{\dot{m}}{\dot{m}_{tot}} = 1 - e^{-\frac{R^2}{2\sigma^2}} \tag{7}$$

The relative amount of gas surfacing within the radius defined by the standard deviation, $R = \sigma$, is thus

$$\frac{\dot{m}_\sigma}{\dot{m}_{tot}} = 1 - e^{-\frac{1}{2}} = 0.39 \tag{8}$$

This means that 39% of all gas surfaces within a radius equal to the standard deviation, and subsequently 86% within 2 standard deviations and 99% within 3 standard deviations. Bear in mind that this is only true if the surfacing profile is perfectly described by a Gaussian profile.

This might come as a surprise since some might believe that the amount represented by the distribution within the extent of the standard deviation is 68%. This number comes from statistics where they perform a straight integration of the profile without multiplying with r.

$$\frac{\int_0^\sigma e^{-\frac{r^2}{2\sigma^2}}\, dr}{\int_0^\infty e^{-\frac{r^2}{2\sigma^2}}\, dr} = 0.68 \tag{9}$$

This is in principle a 1D version of the above derivation which holds for a 2D case.