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Downwind Dispersion of CO_2 from a Major Subsea Blowout in Shallow Offshore Waters

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Keywords: CO_2 well blowout, offshore well blowout, atmospheric dispersion, dense gas dispersion, CO_2 leakage risk assessment, reduced order models

Abstract

Growing interest in offshore geologic carbon sequestration (GCS) motivates risk assessment of large-scale subsea CO_2 well blowouts or pipeline ruptures. For major leaks of CO_2 from wells or pipelines, significant fluxes of CO_2 may occur from the sea surface depending on water depth. In the context of risk assessment of human health and safety, we have used previously simulated coupled well-reservoir and water column model results as a source term for dense gas dispersion of CO_2 above the sea surface. The models are linked together by one-way coupling, i.e., output of one model is used as input to the next model. These first-of-their-kind coupled flow results are applicable to assessing the hazard of CO_2 to people at and downwind of the sea surface location of emission. Hazard is quantified by plotting the downwind dispersion length (DDL), which we define in the study as the distances from the emission source to the point at which the emitted CO_2 has been diluted to 5% and 1.5% in air by volume. Results suggest that large-scale blowouts in shallow water (10 m) may cause hazardous CO_2 plumes extending on the order of several hundred meters downwind. Details of the modeling show DDL has a maximum for windspeed (at an elevation of 10 m) of approximately 5 m/s, with smaller DDL for both weaker and stronger winds. This is explained by the fact that wind favors transport but also causes dispersion; therefore there is a certain wind speed that maximizes DDL.

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Introduction

Offshore geologic carbon sequestration (GCS) largely avoids a variety of concerns related to onshore GCS in the U.S., e.g., potential for impacting groundwater quality in the case of leakage of CO_2 into underground sources of drinking water [1. 2], inducing seismicity that is felt and/or damaging to houses and buildings [3, 4], and securing subsurface storage rights from a potential multitude of property owners [5, 6]. In addition, a great deal of capacity for GCS has been identified in the offshore waters of the U.S., e.g., in the near offshore waters of the Texas Gulf Coast where there are numerous existing industrial CO_2 sources and networks of transportation infrastructure [7, 8].

In addition to the decrease in concerns as mentioned above, health, safety, and environmental (HSE) risks of offshore GCS are generally lower than for onshore GCS if for no other reason than there are fewer people offshore. Nevertheless, there are people present periodically and typically clustered in small areas in the offshore environment, e.g., workers on offshore platforms, fishermen and other people on ships and boats, and these populations will be vulnerable to potential impacts arising from leakage of CO_2 from wells (injection wells along with other wells that may leak unexpectedly), and from leakage from pipelines or ships that are transporting CO_2. As such, it is important to assess health and safety risk in the offshore environment arising from large-scale CO_2 leakage incidents, e.g., those arising from sub-sea well blowouts or pipeline ruptures.

Carbon dioxide is a physiologically active chemical when inhaled by humans, and causes increasingly dangerous effects to humans as its concentration increases in inhaled air [9]. The hazard considered in this paper is the size of the region/extent of elevated CO_2 concentrations in air due to CO_2 emissions out of the sea surface related to a subsea well blowout. We do not consider the likelihood of occurrence of the blowout, or the likelihood of given wind speeds and directions, that would be a part of a complete risk assessment. Instead we focus only on the hazard of high concentrations of CO_2 in air and related potential impact (people breathing air with elevated CO_2 concentrations). We further do not consider the hydrodynamic hazards associated with large-scale upwellings of gas from the sea surface such as turbulence, fountaining, or radial outflow of seawater, all of which can destabilize ships and boats in the vicinity of large gas emissions [10].

With a focus on scoping-type HSE risk assessment that uses modeling-based information on the concentration of CO_2 in air above the sea surface that could arise from a large-scale offshore CO_2 blowout, we present here modeling results of the CO_2 sea-surface leakage flux and resulting dense gas dispersion in the air above the sea surface. The approach used for the atmospheric dispersion modeling was described previously [11]. The purpose of this paper is to summarize the results of modeling the flow, absorption, dilution, and dispersion of CO_2 originating from a major CO_2 blowout in shallow offshore waters of the Texas Gulf Coast. This present study, along with a recently published study of the coupled reservoir-well-water column modeling of the CO_2 blowout [12], combine to form a first-of-its-kind reservoir-to-atmosphere study of CO_2

transport and dispersion following a large-scale offshore CO_2 incident. The context is HSE risk assessment, and the approach of the atmospheric dispersion part of the study is aimed at generating fast approximate estimates of the extent of hazardous CO_2 plumes that could develop on the sea surface from major leakage incidents in shallow water. More detailed and site-specific studies will be required for quantitative risk assessments of specific scenarios at actual offshore GCS project sites.

Background and Prior work

Dense Gas Dispersion Modeling

The modeling of atmospheric dispersion of leaking CO_2 from hypothetical CO_2 pipelines, wells, and surface seeps has been the subject of numerous papers in the area of HSE risk assessment related to GCS. Because dense gas dispersion experiments and modeling pre-date research on GCS, we can call the early work on the subject the zeroth generation of research related to CO_2 atmospheric dispersion. In fact, this early work was not for CO_2 at all but rather was motivated by the need to understand risks associated with cryogenic gas transport such as liquefied natural , gas (LNG) [13, 14]. A particularly good review of the field of dense gas dispersion in terms of its context, physics, and modeling is given by Britter [15]. We mention this early work first because the method that we will apply in the current study was built from the observations and synthesis of results of these early experiments as explained previously[11]. But before describing our methods, it is important to mention the considerable advances in dense gas dispersion modeling applicable to GCS risk assessment that have been made in the last 30-plus years.

Some of the work on dense-gas dispersion modeling in the GCS context has considered fixed source terms specified in terms of flow rate of single-phase (gaseous) CO_2 , e.g., from ruptured pipelines [16] or from the ground surface [17]. The effects of topography are profound for risk assessment of dense gases for well blowouts or pipeline leaks [18]. For surface seeps/emissions, considerable modeling work has been carried out to understand topographic effects with much of the work motivated by the Lake Nyos event [19, 20, 21] and other natural volcanic sources [22]. Other modeling work considered coupling of the source of CO_2 to the flux at the ground surface or out of the pipe rupture [23, 24]. Advances in the level of detail of the physics occurring upon leakage from high-pressure pipelines or tanks have been made by the consideration of multiphase aspects of leaking CO_2 that arise when CO_2 decompresses, e.g., causing formation of solid (dry ice) particles [25, 26, 27]. An industry-led collaborative project with both experimental and modeling components demonstrated that complex phase-change-related processes in CO_2 leakage can be evaluated and modeled [28, 29]. The determination and modeling of the nature of the source terms for atmospheric dispersion following pipeline leakage are improving up to the present through combined experimental and model development work that includes phase change [30, 31].

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Offshore Atmospheric Dispersion

In the specific area of dispersion of leaking gas in the offshore environment, i.e., gas being emitted from the sea surface, there is an enormous literature from the worldwide offshore oil and gas industry. One limitation to this knowledge base provided by the long experience of spill and leakage incidents, along with preventive risk assessment work on offshore oil and gas production and transport, is that the gas of interest is mostly natural gas (nominally methane) which is a light gas relative to air rather than a dense gas like CO_2. In short, natural gas emanating from the sea surface tends to rise and disperse, whereas CO_2 will generally be a dense gas and tend to spread out on the sea surface. Nevertheless, in the area of risk assessment of offshore GCS well and pipeline blowouts, there is an extensive knowledge base and established technical expertise that the GCS community can build upon. For example, the physical controls, basic physics, and simple mathematical models of subsea well blowouts and pipeline leaks were developed and tested experimentally several decades ago[32, 33, 34]. Jumping ahead to more recent times with powerful computers and software available, computational fluid dynamic (CFD) models have been demonstrated capable of simulating the dynamics of gas flow and dispersion at the meter-scale and smaller representing every desired detail of an offshore platform or ship [35, 36, 37, 38, 39]. As for the differences between light and dense gases with differing solubility in seawater, even the coupled subsea-atmosphere systems during blowout scenarios of natural gas and CO_2 have been simulated using CFD and other approaches [40].

Fast Modeling for Risk Assessment

Fast modeling is important in the context of uncertainty analysis when carrying out risk assessment for systems with unknown or variable properties typical of GCS projects. The U.S. National Risk Assessment Partnership (NRAP) has been putting the collective understanding and knowledge of GCS into the development of a set of reduced-order models (ROMs) and an associated integrated assessment model (IAM) [41]. The purpose of using ROMs rather than full-physics models is that many model runs can be carried out quickly for many different parameter values and scenarios to capture ranges of uncertainty inherent in scoping-type risk assessments. One of the ROMs developed in the NRAP project, the Multi-Source Leakage ROM (MSLR), is a simple model for atmospheric dispersion of the CO_2 [11]. In this paper, we will apply the MSLR to the offshore blowout scenario reported in a prior paper [12], the results of which are summarized below.

The reader will wonder why, with all of the advanced modeling capabilities in existence as described in the prior subsection, we use the very simple MSLR. Aside from the need for fast simulations for uncertainty analysis, in the context of GCS where work to date is mostly on hypothetical or yet-to-be-built GCS projects, there is a need for scoping-type risk assessments in which the goal is a general idea of risk rather than tightly constrained quantitative risk assessment. Simply put, for scoping studies there is no single site to characterize in detail so use of a detailed and highly sophisticated model does not match the level of detail of the input data. This is the case for the Gulf of Mexico Partnership for Offshore Carbon Storage (GoMCarb) where multiple sites are being evaluated generally for safe, long-term, and economically-viable offshore CO_2 storage.

As to the applicability of the MSLR, the offshore environment and the relatively long-term (> 10 days) and steady-state blowout scenario we model matches the assumptions made in the simple nomograph approach, e.g., no topography, steady-state winds, constant source strength, and uniform pressure and temperature. Finally, as described in our previous paper [11], the MSLR estimates of downwind concentration match closely with an established CFD code [42] for an applicable test problem, so the use of a simple model like the MSLR is sufficient for the system of interest and for our present purposes.

Modeling to Generate the Source Term

Coupled Reservoir-Well and Water Column Subsea CO_2 Blowout Model

Full details of previous modeling of a scenario of an offshore CO_2 well blowout into shallow seawater are given in the prior paper [12]. To summarize this prior work briefly, the scenario involved a well blowout at the seafloor as shown in Figure 1. The objective of the work was to understand roughly the potential for such an incident to cause hazardous CO_2 emissions (high flow rates of CO_2) at the sea surface. The system comprises a reservoir under injection of CO_2, a long well (3 km), the water column, and the atmosphere (Figure 1). Each of these flow domains is important in the transport and/or dispersion/absorption of CO_2 that could lead to high CO_2 concentrations in air at the sea surface. The three different models used in the four domains are shown in Figure 1, specifically T2Well for the coupled reservoir and well, TAMOC for the water column, and MSLR for the atmosphere, each of which will be described below.

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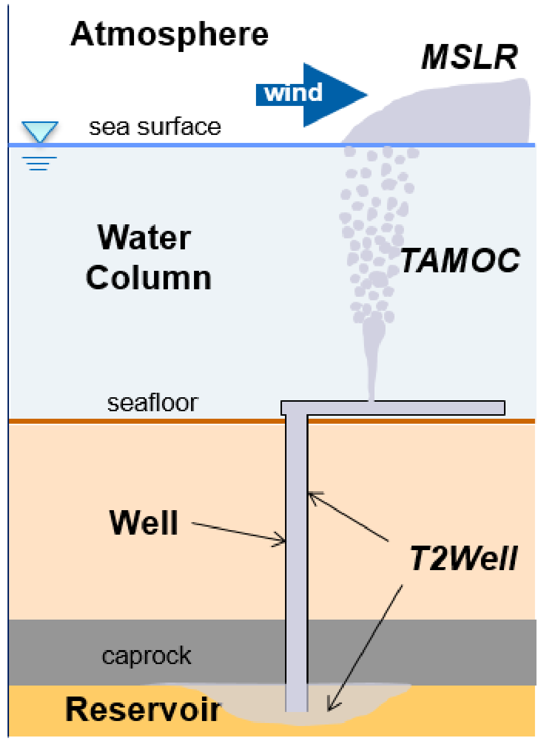

Figure 1. Schematic of offshore CO_2 well blowout with four different domains (reservoir, well, water column, and atmosphere) shown along with the three one-way coupled models (T2Well, TAMOC, and MSLR) used to model CO_2 transport and attenuation/dispersion in each domain. While not to scale, the scenario sketched is for a case with small water column height (shallow depth) where there is sufficient CO_2 flux to migrate through the entire water column without significant absorption of CO_2 before being emitted at the sea surface where the CO_2 undergoes dense gas dispersion.

Referred to here as a well blowout, the incident scenario considered was actually the breaching of the supply line near (10 m away from) the wellhead in the form of a small hole 5 cm (2 inches) in diameter. The scenario definition included the assumption that the supply pipeline would be automatically shutdown quickly after pressure-drop detection, but that the blowout preventer on the injection well somehow fails with the result that CO_2 flows up the well unrestricted and leaks into the water column. Because this was an injection well, the CO_2 around the perforations in the well in the injection interval would be highly mobile. The fully coupled reservoir-well system was modeled using T2Well [43] which captured the physics of two-phase non-isothermal CO_2-water flow in the reservoir and well system up to the discharge point at the seafloor. Briefly, T2Well models two-phase flow in a well by the drift-flux model, and is fully coupled to flow in the porous media reservoir through perforations in the well [43].

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To summarize the results, the CO_2 was emitted into the water column from the hole in the pipe at the seafloor as a jet rapidly entraining seawater and breaking up into small bubbles [12]. All of the water-column bubble plume flow and transport processes were modeling using TAMOC [44, 45, 46] with the T2Well leakage flow output as the source term. Briefly, TAMOC estimates a distribution of bubble sizes based on the source term strength (here a jet of CO_2 emanating from the hole in the pipe) and models the rise of the bubble-plume through the water column in an integral model sense including a variety of processes such as seawater entrainment and absorption (dissolution) of CO_2 into seawater. The height of the water column (depth of seafloor and source of back-pressure on CO_2 blowout into water column) was varied in the simulations from 10 m to 50 m representing a range of shallow near-offshore Texas Gulf Coast sites being examined by the GoMCarb project. The TAMOC results showed strong absorption (dissolution) of CO_2 from the small bubbles (mean size approximately 0.5 mm) generated by the vigorous outflow at the hole in the pipe.

The main results of the Oldenburg and Pan (2020) study [12] are compactly shown in Figure 2 by the sketch on the left-hand side showing a cartoon of one variation, and the two insets on the right-hand side showing quantitative results. Specifically, the upper frame on the right-hand side of Figure 2 shows the travel time of CO_2 from the breach in the pipe to the sea surface as a function of water depth. Travel time for the 10 m-depth case was less than one second, while it took approximately 5 s for CO_2 exiting the pipe at the seafloor to reach the sea surface for the 50 m-depth system. In the lower inset on the right-hand side is shown the amount of CO_2 that leaves the sea surface and enters the atmosphere both as a mass flow rate and fraction of the amount emitted from the pipe breach. As shown, the modeling determined that nearly all of the CO_2 in the deepest system (50 m) was absorbed by seawater, while very little CO_2 was absorbed in the shallowest system (10 m), and there were intermediate results for water column heights in between. For reference, one million tonnes per year of CO_2 is 31.7 kg/s; the shallow depth system is predicted to emit CO_2 at more than this rate for this scenario). These results suggests that from the point of view of human health risk assessment related to sea-surface CO_2 emissions from sea floor blowouts, deeper sites are preferred. In the case where shallow-water sites are chosen for CO_2 injection wells and/or CO_2 pipelines exist, and if a large-scale containment failure scenario occurs, CO_2 can be expected to be emitted out of the sea surface and therefore it is important to understand CO_2 plume dispersion in air above the sea surface. Full details of the reservoir-well-water-column modeling study are presented in [12].

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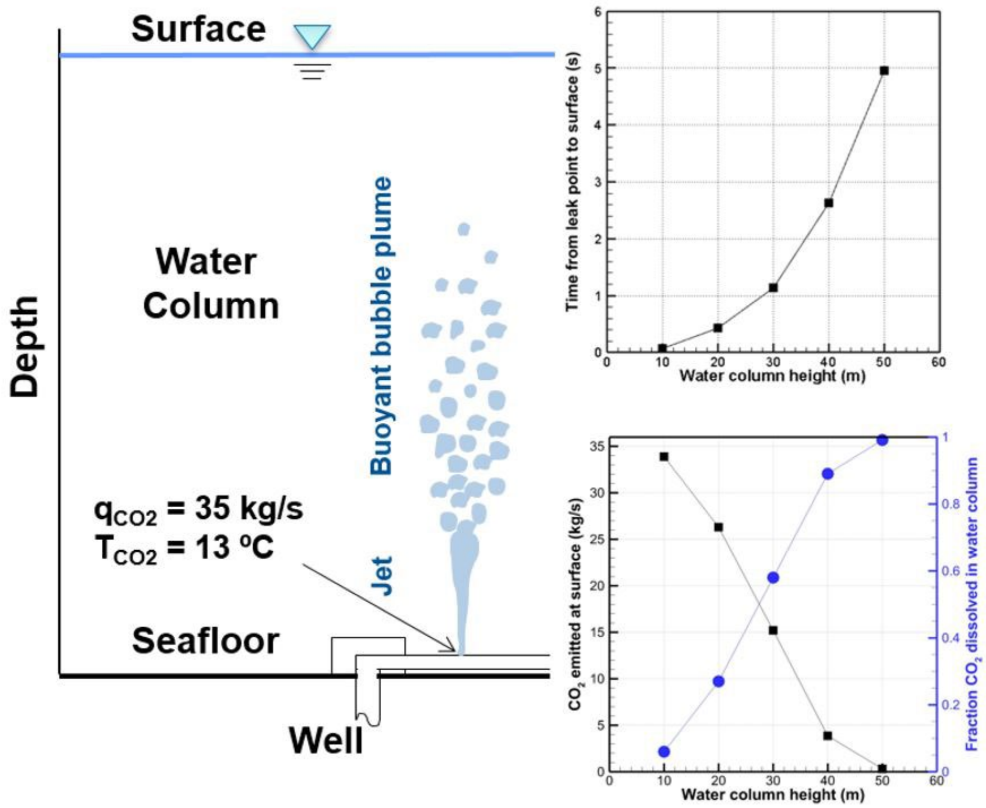

Figure 2. Offshore leakage scenario and summary of CO_2 well blowout simulations of [12] showing travel time in the water column (upper right-hand figure) and amount of CO_2 emitted and dissolved during transit through the water column (lower right-hand figure) as a function of water column height (water depth).

Atmospheric Dispersion Modeling Method

The method for estimating atmospheric dispersion of CO_2 (a dense gas) above the sea surface used here was described fully in a prior paper [11]. To briefly summarize, the approach is based on a nomograph that was developed from empirical data on dense gas dispersion [47]. In this earlier work [47], correlations were determined between measured downstream concentrations of various dense gases and wind speed and source strengths in terms of release rate and concentration. The multiple variables of the flow and dispersion field experiments were condensed into dimensionless quantities and correlated using two-dimensional nomographs. The nomographs allow one to estimate the distance (downstream of the source) to the locations of arbitrary fractions of initial concentration [47]. Zhang et al. (2016) [11] extended the nomograph approach to include multiple leakage source locations, where CO_2 leakage is quantified in the GCS context by leakage mass flow rate (kg CO_2/s). This enhanced model was converted by into a computational tool and named the Multi-Source Leakage ROM, or MSLR [11]. The National Risk Assessment Partnership (NRAP) project sponsored by the U.S. Department of Energy developed a graphical user interface for the MSLR with ability to take user input on leakage locations, emission source strengths (kg/s), windspeed (m/s) at a height of 10 m (approximate thickness of the (atmospheric) surface boundary layer), and critical concentration. The main output of the MSLR is the downwind dispersion length (DDL), i.e., the downwind distance at which the dispersing CO_2 reaches the critical concentration (i.e., a given level of dilution relative to the concentration at the source). The MSLR is one-dimensional and provides DDL for user-specified wind speed. Downwind transport makes the DDL larger than a corresponding transverse dispersion length and therefore considering downwind extent is a conservative approach for hazard analysis. Because the wind direction could be random and variable, a conservative method is to define the DDL as a circular exclusion zone within which CO_2 concentration can be expected to be unhealthy to breathe for any wind direction.

Although the original work [47] to develop the nomograph underlying the MSLR pre-dates interest in GCS and was focused not on CO_2 risk assessment but rather on accidents that could happen during transport of cryogenic liquid hydrocarbons (e.g., liquefied natural gas, propane, etc.), the ranges of leakage rates and density contrasts used to develop the original nomographs overlap those relevant to CO_2. For example, we note the molecular weight of propane and CO_2 are the same at 44 g mole^{-1} making CO_2 and propane densities in ambient air roughly the same. In addition, incidents involving leakage of liquefied gas or propane may result in similar flow rates and processes because high-pressure pipeline and ship transport and related infrastructure are common to both liquefied gas and CO_2 transport.

For the offshore CO_2 blowout case considered here, the resulting plume of interest is a direct emission of CO_2 from a source area on the sea surface as opposed to evaporation from a puddle, high-energy pipe or tank emission, or smoke-stack or other elevated source. The characteristic length scale of the emission area on the sea surface modeled by TAMOC was between 3.2-16 m [12]. This length scale is used by the MSLR to determine if dense gas dispersion is applicable for the given mass flow rate of the source. We further assume the transport above the sea is isothermal at 25 °C and 1 atm (0.101325 MPa) and that CO_2 does not absorb (dissolve) into seawater as it flows over the sea surface (i.e., the sea surface is a closed boundary). By neglecting absorption of CO_2 into the seawater as the CO_2 flows over the sea surface, and by using the single-temperature results of the prior study [12] as the emission source term, the present study does not address the sensitivity of DDL to seawater temperature. Knowing that colder water absorbs more CO_2, we can safely speculate that colder seawater would result in a smaller emission source term and shorter DDL, but we leave quantification of this effect for future study. Although vigorous boil areas with fountain heights up to 70 m have been observed for offshore blowouts of natural gas and these can create significant marine hazards to boats and ships [48], here we assume the sea surface is horizontal and model only the downwind dispersion and CO_2 concentration in air as the hazard of interest. Atmospheric stability was reported to play a minor role in the empirical data upon which the nomograph was constructed [47], and therefore atmospheric stability is not a factor in the MSLR.

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Results

The output of T2Well for five different water-column heights was fed to TAMOC, and the output of TAMOC for the five different water column heights in terms of flow rate (kg/s) out of the sea surface were used as inputs to the MSLR. Seven different windspeeds (at a height of 10 m) above the sea surface were modeled for three different water-column heights (10, 30, and 50 m--the intervening 20 m- and 40 m-depth cases being intermediate results not shown here for brevity) for a single leakage source. The three different water column heights produce different source strengths for many reasons, e.g., the longer time and distance traveled upward through the water column increases absorption of CO_2 into the seawater, the spreading of the bubble plume, and the amount of entrained water. In addition, there is a small effect of the hydrostatic back pressure on the hole in the pipe that slightly affects leakage flow at the sea floor. Inputs to the MSLR are shown in Table 1. The MSLR also needs input on release duration which was chosen to be 1×10^6 s (~11 days) to represent a long period relative to the travel time to reach the DDL (i.e., represents a steady-state condition for the leak relative to wind transport times) even for the lowest wind speed. Specifically, consider that the wind speeds vary from 0.5 m/s (~1.1 mph) to 40 m/s (~88 mph) which corresponds to downwind travel times for 500 m radius from the source varying from 1000 s (17 mins) and 12.5 s, respectively. In this sense, winds that persist for 10 mins or more are easily able to advect leaking CO_2 to the farthest extent of the DDL, and this time is short relative to the duration of the leakage (~11 days).

The results of the MSLR model are shown in Figure 3 as the downwind dispersion length (DDL) at which the concentration of CO_2 in the air has been diluted from pure CO_2 to a mixture of air with CO_2 at 5% (dilution factor of 20) and 1.5% (dilution factor of 67) by volume, respectively. Note that these distances are referred to as downwind dispersion lengths (DDL) rather than a downwind safety lengths because inhalation of air with 5% CO_2 by volume may present a health and safety hazard; 4% CO_2 by volume is the U.S. national standard concentration considered immediately dangerous to life or health [49]. The lower concentration value, 1.5% CO_2 by volume, is a concentration at which some people will experience mild respiratory stimulation [50], i.e., a concentration with non-zero but low impact to human health over short exposure periods.

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Table 1. Properties of the system assumed in the MSLR.

Pressure (atm)	Air, seawater, and source temperature (°C)	Wind speed at 10 m elevation (m/s)	Source strength for 10 m-high water column (kg/s)	Source strength for 30 m-high water column (kg/s)	Source strength for 50 m-high water column (kg/s)	Critical concentrations (fraction by volume)
1.0	25.	0.5	33.4	15.1	0.31	0.05, 0.015
1.0	25.	1.	33.4	15.1	0.31	0.05, 0.015
1.0	25.	2.	33.4	15.1	0.31	0.05, 0.015
1.0	25.	5.	33.4	15.1	0.31	0.05, 0.015
1.0	25.	10.	33.4	15.1	0.31	0.05, 0.015
1.0	25.	20.	33.4	15.1	0.31	0.05, 0.015
1.0	25.	40.	33.4	15.1	0.31	0.05, 0.015

Note first in Figure 3 that smaller critical concentrations imply larger DDL (note the different y-axis scales). In other words, the smaller the critical concentration chosen to ensure health and safety, the larger will be the exclusion zone. The second conclusion from Figure 3 is that higher wind speeds cause smaller DDL generally because there is more turbulent mixing and air entrainment to dilute and spread the leaking CO_2 when windspeed is higher. Recall from Figure 2 that surface emissions vary for the different water column heights (depths), and in the deepest case (50 m water column) the surface leakage flow rate is very low so that for all wind speeds, the resulting DDL never exceeds approximately 35 m (115 ft) for the 5% critical concentration, and 65 m (213 ft) for the 1.5% critical concentration. In contrast, for the 10-m water-column height, the DDL for a CO_2 critical concentration of 1.5% by volume can reach over 400 m.

Considering again the shallowest case (10 m water column), an interesting reversal in DDL trend is observed. First, recall in the 10 m-depth case, nearly all of the CO_2 leaking from the well/pipe is emitted at the sea surface (i.e., very little absorption of CO_2 occurs in the water column as shown in Figure 2). For this case of a large CO_2 emission at the sea surface, the maximum DDL for both critical concentrations (5% and 1.5%) occurs for windspeeds of approximately 5 m/s (~11 mph), with slightly smaller DDL for weaker winds and much smaller DDL for much higher winds (10, 20, 40 m/s).

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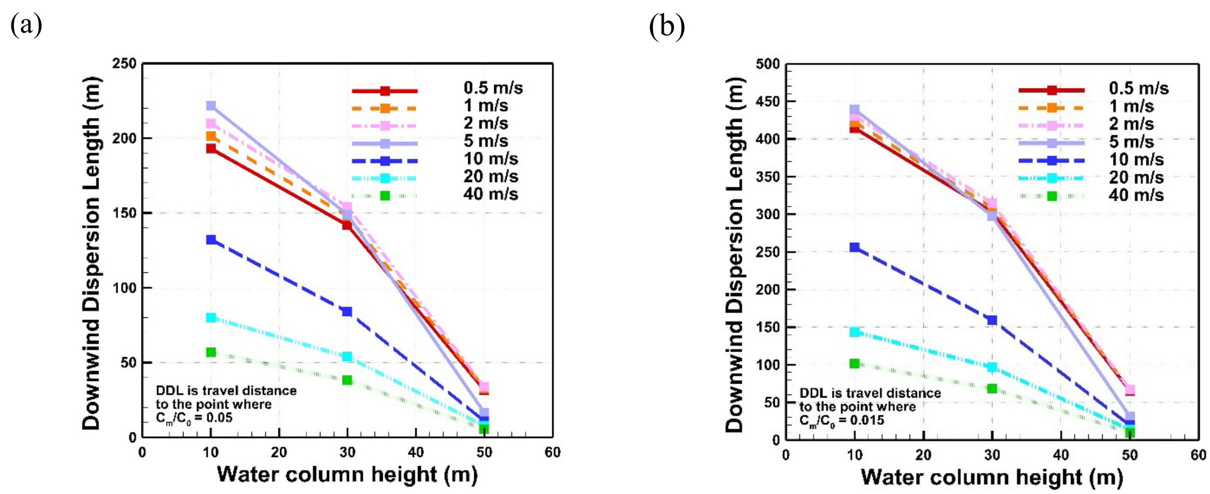

Figure 3. Downwind dispersion length (DDL) for the subsea CO_2 blowout scenarios for different water column heights (different surface leakage rates) and wind speeds for two different critical concentrations: (a) $C_m/C_0 = 0.05$; (b) $C_m/C_0 = 0.015$ (note the different y-axis scales).

The DDL maxima as a function of windspeed are shown explicitly in Figure 4 where DDL is plotted as a function of windspeed for the three water-column-height cases. The reason for a local maximum in DDL is that very slow winds do not transport the gas very effectively leaving advective spreading to occur only by self-generated density-dependent flow effects [15]. On the other hand, faster winds transport the CO_2 downwind effectively but also have more dispersive capacity. So there is a competition between fast-moving air and the dispersive capacity of that air in how far high-CO_2 concentrations can persist downwind. For the scenario modeled here, and depending on the particular case, windspeeds of 2-5 m/s (~4.4-11 mph) are effective at transporting CO_2 without diluting it as much as when the windspeeds are higher and thereby generate a larger DDL, all other things being equal. We emphasize that the MSLR used to generate these results is based on actual field studies of dense gas dispersion, and the nomograph upon which the MSLR is based represents a multitude of lumped physical dispersion processes.

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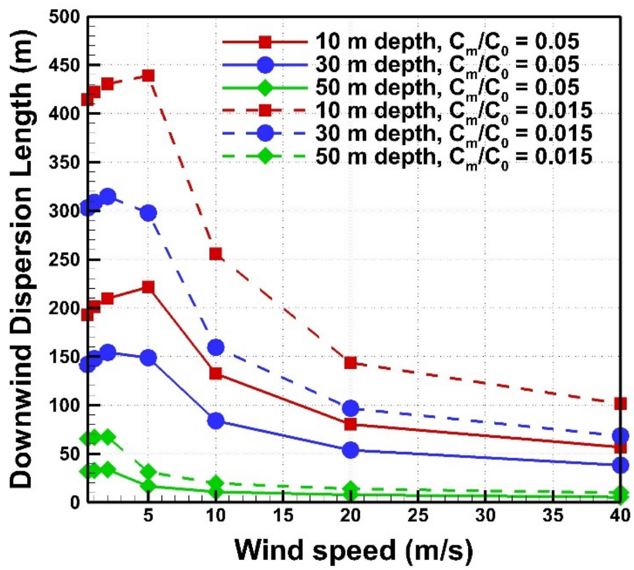

Figure 4. DDL as a function of windspeed for three different water column depths and two different critical concentrations. The plot shows that a maximum DDL occurs for windspeeds of 2-5 m/s depending on the case.

Conclusions

We have applied a fast model (NRAP MSLR) for atmospheric dispersion of a dense gas (CO_2) to estimate downwind dispersion of CO_2 emitted from the sea surface following a generalized large-scale subsea well blowout. The source term for the fast dispersion model is the mass flow rate out of the sea surface which was simulated previously [12] using TAMOC, which modeled the transport and absorption of CO_2 in a bubble plume rising upward through the water column. The source term for TAMOC was the mass flow rate into the water column from the well which was also simulated previously using the fully coupled T2Well code to couple reservoir and well flow with water depth providing the upper pressure boundary condition on the hole in the pipe [12]. To our knowledge, the work described in the present paper together with that in [12] comprise the first study that has coupled three models of CO_2 flow in these four key domains to estimate CO_2 concentrations downwind of a sea-surface emission from a large-scale blowout. The results show that for very shallow offshore GCS sites (e.g., 10 m water depth) with a large-scale blowout underway, one can expect hazardous CO_2 concentrations to extend a few hundred to several hundred meters from the emissions source, depending of course on CO_2 emission source strength, windspeed, choice of critical concentration, etc. For deeper sites (e.g., 50 m) the large amount of CO_2 absorption in the water column makes a much weaker emission at the sea surface resulting in hazardous CO_2 concentration extending shorter distances from the emissions site, all other things being equal.

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The results presented here are in the context of providing estimates of DDL for scoping-type risk assessments. For any individual site and for a quantitative risk assessment, a more detailed and advanced CFD-based atmospheric dispersion model should be considered along with site-specific information to characterize the wind speed, direction, and frequency (e.g., a wind rose). Nevertheless, as shown here, even the simple nomograph-based MSLR model captures an interesting effect of the playoff between windspeed in transporting CO_2 downwind while also causing its dispersion. For the well-reservoir system and water column properties considered here, T2Well and TAMOC are appropriate models to capture the details of the physics of CO_2 flow and transport. For deeper and/or colder systems for which hydrates (not modeled by T2Well currently) could form at the hole in the pipe due to severe decompression cooling, simulators capable of modeling CO_2 hydrate should be used.

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References

1. Qafoku, N.P., Lawter, A.R., Bacon, D.H., Zheng, L., Kyle, J. and Brown, C.F., 2017. Review of the impacts of leaking CO_2 gas and brine on groundwater quality. Earth-Science Reviews, 169, pp. 69-84.
2. Zheng, L., Nico, P., Spycher, N., Domen, J. and Credoz, A., 2021. Potential impacts of CO_2 leakage on groundwater quality of overlying aquifer at geological carbon sequestration sites: A review and a proposed assessment procedure. Greenhouse Gases: Science and Technology, 11(5), pp.1134-1166.
3. Rutqvist, J., Cappa, F., Rinaldi, A.P. and Godano, M., 2014. Modeling of induced seismicity and ground vibrations associated with geologic CO_2 storage, and assessing

their effects on surface structures and human perception. International Journal of Greenhouse Gas Control, 24, pp.64-77.

4. Rinaldi, A.P., Vilarrasa, V., Rutqvist, J. and Cappa, F., 2015. Fault reactivation during CO_2 sequestration: Effects of well orientation on seismicity and leakage. Greenhouse Gases: Science and Technology, 5(5), pp.645-656.
5. Wilson, E.J. and de Figueiredo, M.A., 2006. Geologic carbon dioxide sequestration: an analysis of subsurface property law. Envtl. L. Rep. News & Analysis, 36, p.10114
6. Gormally, A.M., Markusson, N.O. and Bentham, M., 2018. The pore space scramble; challenges and opportunities for subsurface governance. Geoforum, 95, pp.70-77.
7. Wallace, K.J., Meckel, T.A., Carr, D.L., Treviño, R.H. and Yang, C., 2014. Regional CO_2 sequestration capacity assessment for the coastal and offshore Texas Miocene interval. Greenhouse Gases: Science and Technology, 4(1), pp.53-65.
8. Meckel, T.A., Bump, A.P., Hovorka, S.D. and Trevino, R.H., 2021. Carbon capture, utilization, and storage hub development on the Gulf Coast. *Greenhouse Gases: Science and Technology, 11*(4), pp.619-632.
9. Rice, S.A., 2014. Human health risk assessment of CO_2: survivors of acute high-level exposure and populations sensitive to prolonged low-level exposure. environments, 3(5), pp.7-15.
10. Aprin, L., Lauret, P., Heymes, F., Lopez, C., Petrie, F. and Lefloch, S., 2020. Experimental Investigation of Blowouts, Characterization of Fountain Effect Consequences at the Sea Surface. CHEMICAL ENGINEERING, 82.
11. Zhang, Y., Oldenburg, C.M. and Pan, L., 2016. Fast estimation of dense gas dispersion from multiple continuous CO_2 surface leakage sources for risk assessment. International Journal of Greenhouse Gas Control, 49, pp.323-329.
12. Oldenburg, C.M. and Pan, L., 2020. Major CO_2 blowouts from offshore wells are strongly attenuated in water deeper than 50 m. Greenhouse Gases: Science and Technology, 10(1), pp.15-31.
13. Puttock, J.S., Blackmore, D.R. and Colenbrander, G.W., 1982. Field experiments on dense gas dispersion. Journal of Hazardous Materials, 6(1-2), pp.13-41.
14. McQuaid, J., 1985. Objectives and design of the phase I heavy gas dispersion trials. *Journal of Hazardous Materials*, *11*, pp.1-33.
15. Britter, R.E., Atmospheric dispersion of dense gases, Annual Reviews of Fluid Mechanics, 21 (1989), 317-344.
16. Mazzoldi, A., Hill, T. and Colls, J.J., 2011. Assessing the risk for CO_2 transportation within CCS projects, CFD modelling. International Journal of Greenhouse Gas Control, 5(4), pp.816-825.
17. Cortis, A., and C. M. Oldenburg. Short-range atmospheric dispersion of carbon dioxide. Boundary-layer meteorology 133, no. 1 (2009): 17-34.
18. Lisbona, D., McGillivray, A., Saw, J.L., Gant, S., Bilio, M. and Wardman, M., 2014. Risk assessment methodology for high-pressure pipelines incorporating topography. Process Safety and Environmental Protection, 92(1), pp.27-35.

19. Costa, A. and Chiodini, G., 2015. Modelling air dispersion of CO 2 from limnic eruptions. In *Volcanic Lakes* (pp. 451-465). Springer, Berlin, Heidelberg.
20. Folch, A., Costa, A. and Hankin, R.K., 2009. twodee-2: A shallow layer model for dense gas dispersion on complex topography. Computers & Geosciences, 35(3), pp.667-674.
21. Hsieh, K.J., Lien, F.S. and Yee, E., 2013. Dense gas dispersion modeling of CO_2 released from carbon capture and storage infrastructure into a complex environment. International Journal of Greenhouse Gas Control, 17, pp.127-139.
22. Costa, A., Chiodini, G., Granieri, D., Folch, A., Hankin, R.K.S., Caliro, S., Avino, R.,Cardellini, C.A., 2008. Shallow layer model for heavy gas dispersion fromnatural sources: application and hazard assessment at Caldara di Manziana,Italy. Geochem. Geophys. Geosyst. 9, Q03002.
23. Oldenburg, C.M., and Unger, A.J.A., 2004. Coupled vadose zone and atmospheric surface-layer transport of CO_2 from geologic carbon sequestration sites, Vadose Zone Journal, 3, 848–857.
24. Mazzoldi, A., Picard, D., Sriram, P.G. and Oldenburg, C.M., 2013. Simulation-based estimates of safety distances for pipeline transportation of carbon dioxide. Greenhouse Gases: Science and Technology, 3(1), pp.66-83.
25. Mazzoldi, A., Hill, T. and Colls, J.J., 2008. CO2 transportation for carbon capture and storage: Sublimation of carbon dioxide from a dry ice bank. *International Journal of Greenhouse Gas Control*, *2*(2), pp.210-218.
26. Hulsbosch-Dam, C.E.C., Spruijt, M.P.N., Necci, A. and Cozzani, V., 2012. Assessment of particle size distribution in CO_2 accidental releases. Journal of Loss Prevention in the Process Industries, 25(2), pp.254-262.
27. Gant, S.E., Narasimhamurthy, V.D., Skjold, T., Jamois, D. and Proust, C., 2014. Evaluation of multi-phase atmospheric dispersion models for application to Carbon Capture and Storage. Journal of Loss Prevention in the Process Industries, 32, pp.286-298.
28. Witlox, H.W., Harper, M. and Oke, A., 2009. Modelling of discharge and atmospheric dispersion for carbon dioxide releases. *Journal of Loss Prevention in the Process Industries*, *22*(6), pp.795-802.
29. Witlox, H.W., Stene, J., Harper, M. and Nilsen, S.H., 2011. Modelling of discharge and atmospheric dispersion for carbon dioxide releases including sensitivity analysis for wide range of scenarios. Energy Procedia, 4, pp.2253-2260.
30. Munkejord, S.T. and Hammer, M., 2015. Depressurization of CO_2-rich mixtures in pipes: Two-phase flow modelling and comparison with experiments. International Journal of Greenhouse Gas Control, 37, pp.398-411.
31. Munkejord, S.T., Austegard, A., Deng, H., Hammer, M., Stang, H.J. and Løvseth, S.W., 2020. Depressurization of CO_2 in a pipe: High-resolution pressure and temperature data and comparison with model predictions. Energy, 211, p.118560.

32. Fannelop, T. and Sjoen, K., 1980, January. Hydrodynamics of underwater blowouts. In 18th Aerospace Sciences Meeting (p. 219).
33. Topham, D.R. and Bishnoi, P.R., 1980. Deep water blowouts. Spill Technology Newsletter, 5(3).
34. Loes, M. and Fannelop, T.K., 1987, September. Fire hazard from an underwater release of natural gas. In SPE Offshore Europe. OnePetro.
35. Cloete, S., Olsen, J.E. and Skjetne, P., 2009. CFD modeling of plume and free surface behavior resulting from a sub-sea gas release. Applied Ocean Research, 31(3), pp.220-225.
36. Huser, A., Bengherbia, T., Skjetne, P., Olsen, J.E. and Postvoll, W., 2015. Subsea gas plumes and dispersion above sea. Safety, Reliability and Risk Analysis: Beyond the Horizon, 155-161, in Steenbergen et al., (Eds.), Taylor & Francis Group, London, ISBN 978-1-138-00123-7.
37. Lu, J., Filippov, A., Marcancola, F. and Rosales, V., 2015, July. Dispersion of Relief and Leaked Hazardous Gases on Offshore Facilities. In SPE Latin American and Caribbean Health, Safety, Environment and Sustainability Conference. OnePetro.
38. Xinhong, L., Guoming, C., Renren, Z., Hongwei, Z. and Jianmin, F., 2018. Simulation and assessment of underwater gas release and dispersion from subsea gas pipelines leak. Process Safety and Environmental Protection, 119, pp.46-57.
39. Franklin, G., Barros, W., Ceciliano, M., Cunha, J., da Rocha, A., Fagundes, D. and Margotto, R., 2020, November. Computational Fluid Dynamic Modeling For Hazardous Gas Dispersion Analysis In Deepwater, Brazil. In Abu Dhabi International Petroleum Exhibition & Conference. OnePetro.
40. Olsen, J.E. and Skjetne, P., 2020. Summarizing an Eulerian–Lagrangian model for subsea gas release and comparing release of CO_2 with CH4. Applied Mathematical Modelling, 79, pp.672-684.
41. Pawar, R.J., Bromhal, G.S., Chu, S., Dilmore, R.M., Oldenburg, C.M., Stauffer, P.H., Zhang, Y. and Guthrie, G.D., 2016. The National Risk Assessment Partnership's integrated assessment model for carbon storage: A tool to support decision making amidst uncertainty. International Journal of Greenhouse Gas Control, 52, pp.175-189.
42. Fluidyn PANACHE, 2010. Fluidyn-PANCHE User Manual. FLUIDYN France/TRANSOFT International. Version 4.0.7 Edition.
43. Pan, L., and Oldenburg, C.M., 2014. T2Well—an integrated wellbore–reservoir simulator. Computers & Geosciences, 65, 46-55.
44. Socolofsky, S.A., Dissanayake, A.L., Jun, I., Gros, J., Arey, J.S. and Reddy, C.M., 2015. Texas A&M Oilspill Calculator (TAMOC): Modeling Suite for Subsea Spills. In Proceedings of the Thirty-Eighth AMOP Technical Seminar (Environment Canada, Ottawa) (pp. 153-168).
45. Gros, J., Socolofsky, S.A., Dissanayake, A.L., Jun, I., Zhao, L., Boufadel, M.C., Reddy, C.M. and Arey, J.S., 2017. Petroleum dynamics in the sea and influence of subsea

dispersant injection during Deepwater Horizon. Proceedings of the National Academy of Sciences, 114(38), pp.10065-10070.

46. Dissanayake, A.L., Gros, J. and Socolofsky, S.A., 2018. Integral models for bubble, droplet, and multiphase plume dynamics in stratification and crossflow. Environmental Fluid Mechanics, 18(5), pp.1167-1202.
47. Britter, R.E., and J. D. McQuaid. Workbook on the dispersion of dense gases. Contract Research Report 17, Health and Safety Executive, Sheffield, UK (1988).
48. Engebretsen, T., Northug, T., Sjøen, K. and Fanneløp, T.K., 1997, January. Surface flow and gas dispersion from a subsea release of natural gas. In The Seventh International Offshore and Polar Engineering Conference. International Society of Offshore and Polar Engineers.
49. NIOSH, The National Institute of Occupational Safety and Health, May 1994. NIOSH Publications & Products, Immediately Dangerous To Life or Health (IDLH) Values, Table of IDLH Values. https://www.cdc.gov/niosh/idlh/124389.html.
50. U.S. Department of Agriculture, Food Safety and Inspection Service, Hazard Information Sheet, 2020. https://www.fsis.usda.gov/sites/default/files/media_file/2020-08/Carbon-Dioxide.pdf