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

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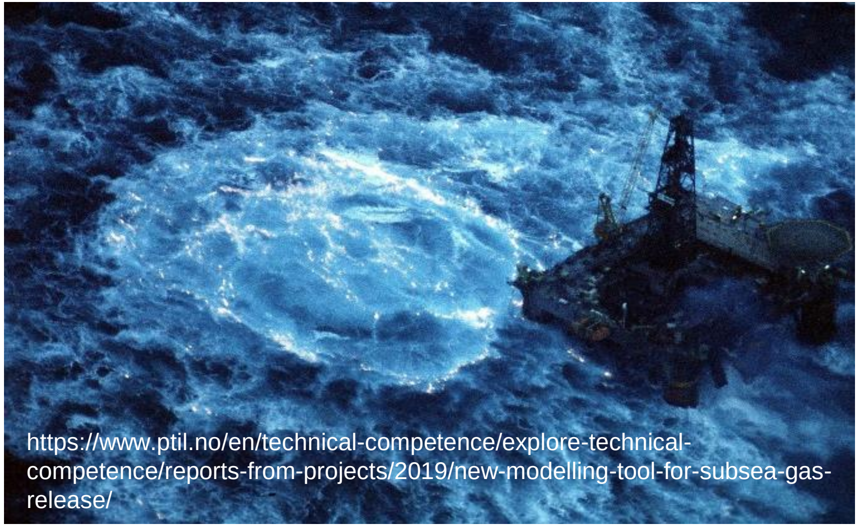
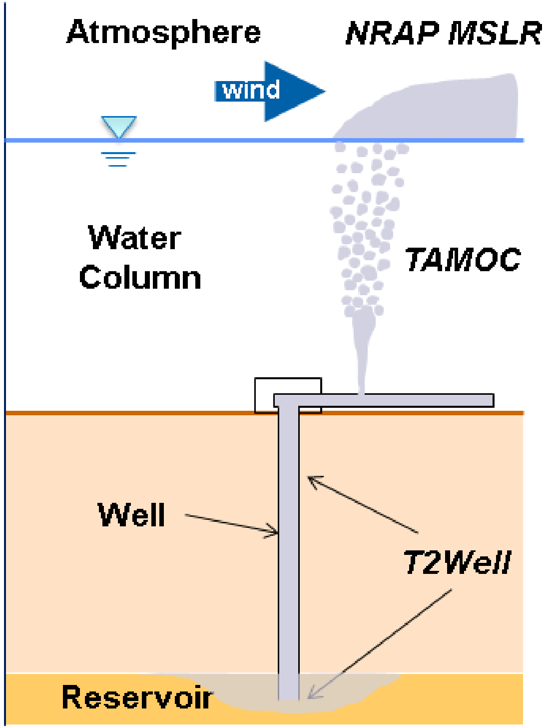
Offshore natural gas blowouts are useful analogues—but CH_4 is lighter than air



Large-scale offshore CO_2 blowouts may lead to a dense gas plume blowing along the sea surface

- 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 modeling of CO_2 above the sea surface.
  - The models are linked together by one-way coupling, that is, output of one model is used as input to the next model.
  - The main results can be used to estimate of size of CO_2 exposure safety exclusion zones.



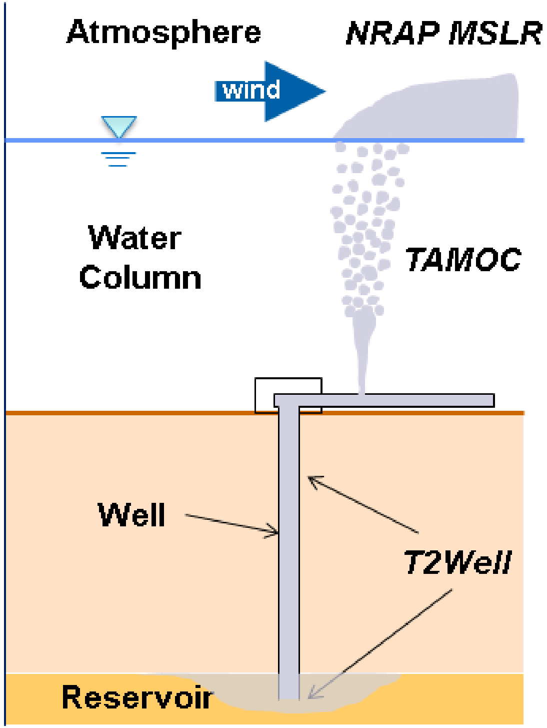
Offshore CO_2 well blowouts are strongly controlled by transport processes in the water column

Relative to ambient air, the water column provides

- **More resistance to flow**
- **Positive buoyancy for CO_2**
- **Vast source of heat to counter cooling caused by decompression**
- **Vast sink for CO_2 dissolution**

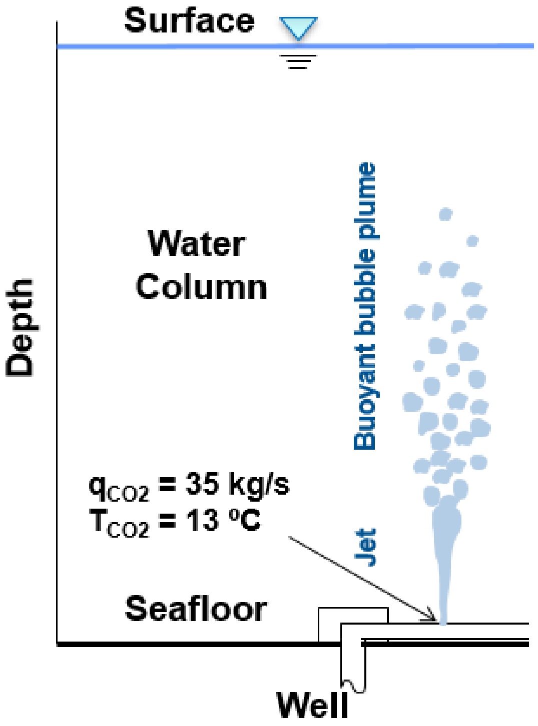
We coupled three existing models to understand consequences of sub-sea CO_2 leaks and blowouts

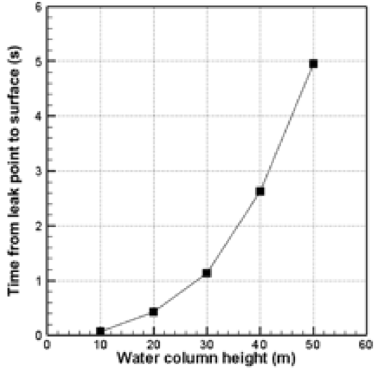
- **Reservoir-well flow (T2Well)**
- **Jet and buoyant flow in the water column (TAMOC)**
- **Atmospheric dispersion (NRAP MSLR)**

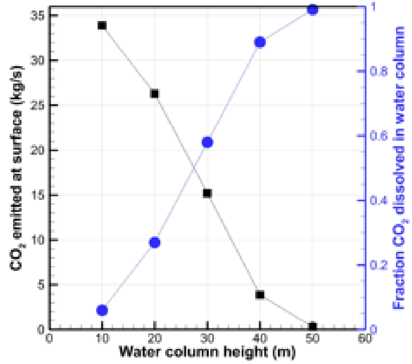


Source term for this work is from prior modeling of reservoir, well, and water column (T2Well + TAMOC)

- Results showed that for water depths of 50 m or more, a large CO_2 blowout was almost entirely absorbed by seawater during upward flow, i.e., almost no CO_2 emitted at sea surface.
- In contrast, for water depths of 10 m, the blowout was barely affected by the water column, i.e., a large CO_2 flux occurs at sea surface.
- Question to address: How far downwind does the surface CO_2 plume extend?







Background on Modeling Atmospheric Dispersion of Dense CO_2

Field experiments in the 1980's of dense gas dispersion provided data for empirical correlations

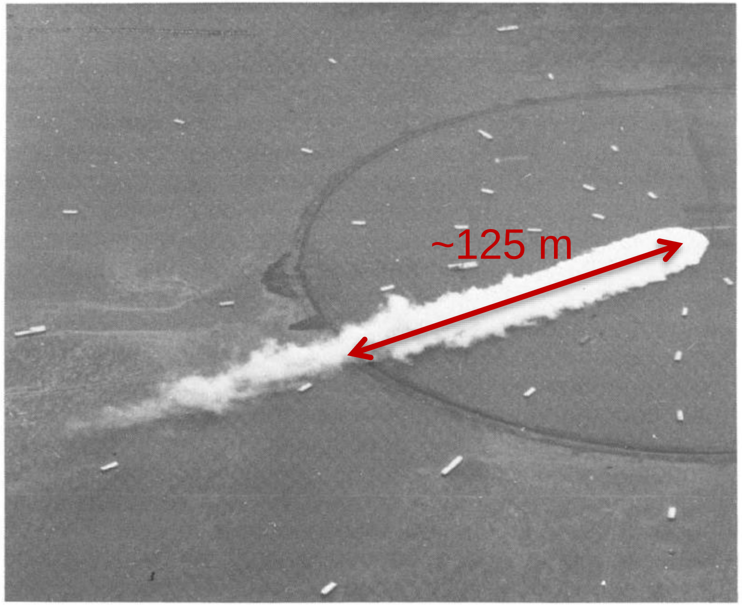


Fig. 3. Spill 56 — continuous LNG spill at 2.5 m^3/min in a 4.8 m/s wind.

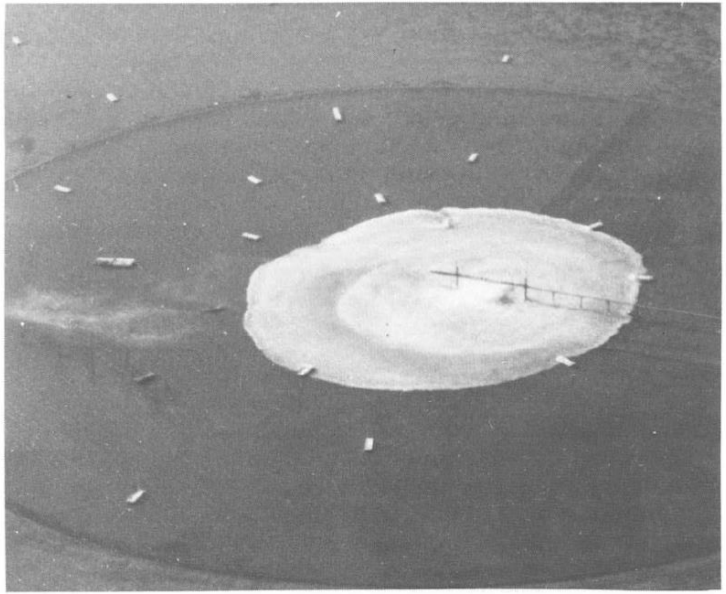


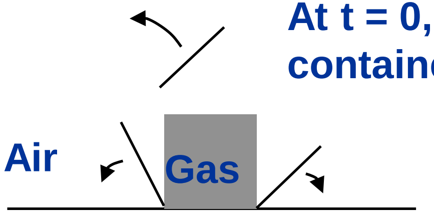
Fig. 4. Spill 60 — instantaneous propane spill of 27 m^3 in 1.2 m/s wind.

Source: Puttock et al., 1982.

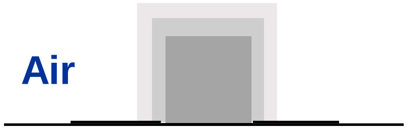
Density contrast does not always inhibit mixing

Consider a container of gas on a flat surface at ambient P, T

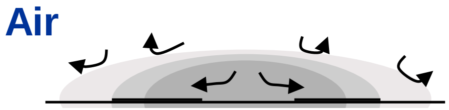
At t = 0, the walls of the container are removed



If no wind, a passive gas will mix only by diffusion

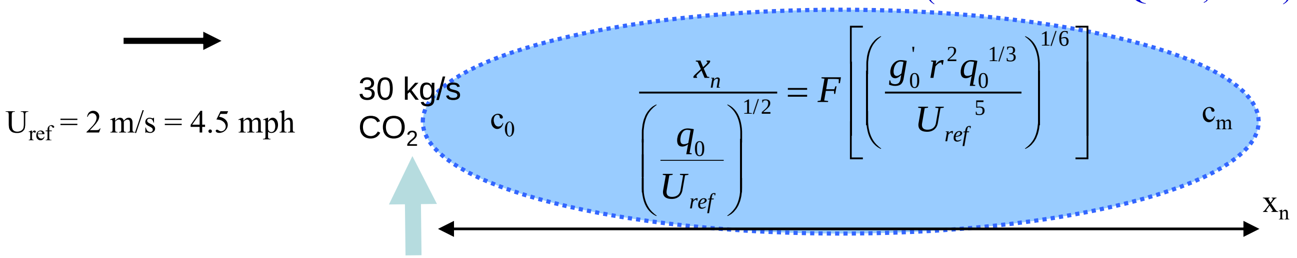


A dense gas will flow on its own and mix by dispersion



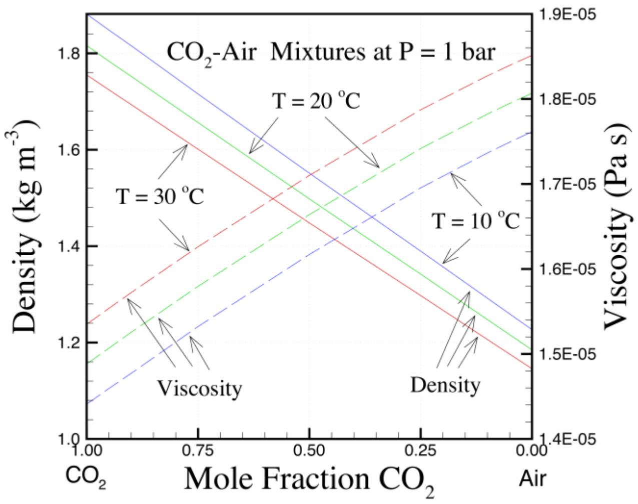
Empirical Correlations of Atmospheric Dispersion of CO_2

(Britter and McQuaid, 1988)



$$\frac{x_n}{\left(\frac{q_0}{U_{ref}}\right)^{1/2}} = F\left[\left(\frac{g_0^{'}\, r^2 q_0^{1/3}}{U_{ref}^{5}}\right)^{1/6}\right]$$

x_n	c_m/c_0
300 m	0.02

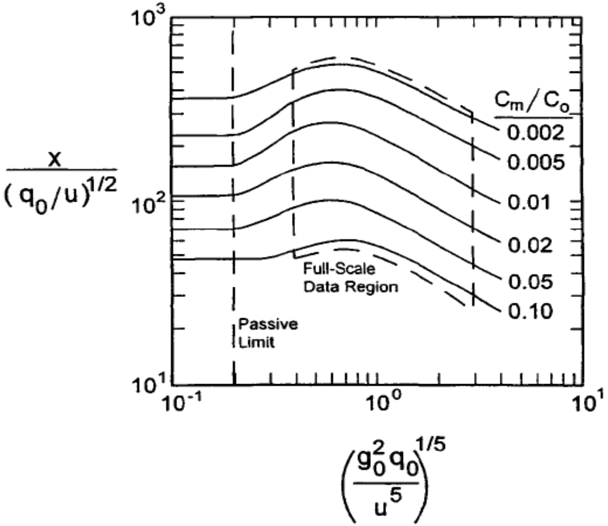


Empirical results suggest atmospheric dispersion is effective in diluting dense gases over relatively short time and length scales.

However, calm conditions and topographic effects may alter these predictions and require numerical modeling approaches to assess.

Single Point Release

- **Continuous (vs. instantaneous) release:** $\frac{uR_d}{x} \geq 2.5$
- **Dense gas release:** $\left(\frac{g_0 q_0}{D_c u^3}\right)^{1/3} \geq 0.15$
- **Critical radius**



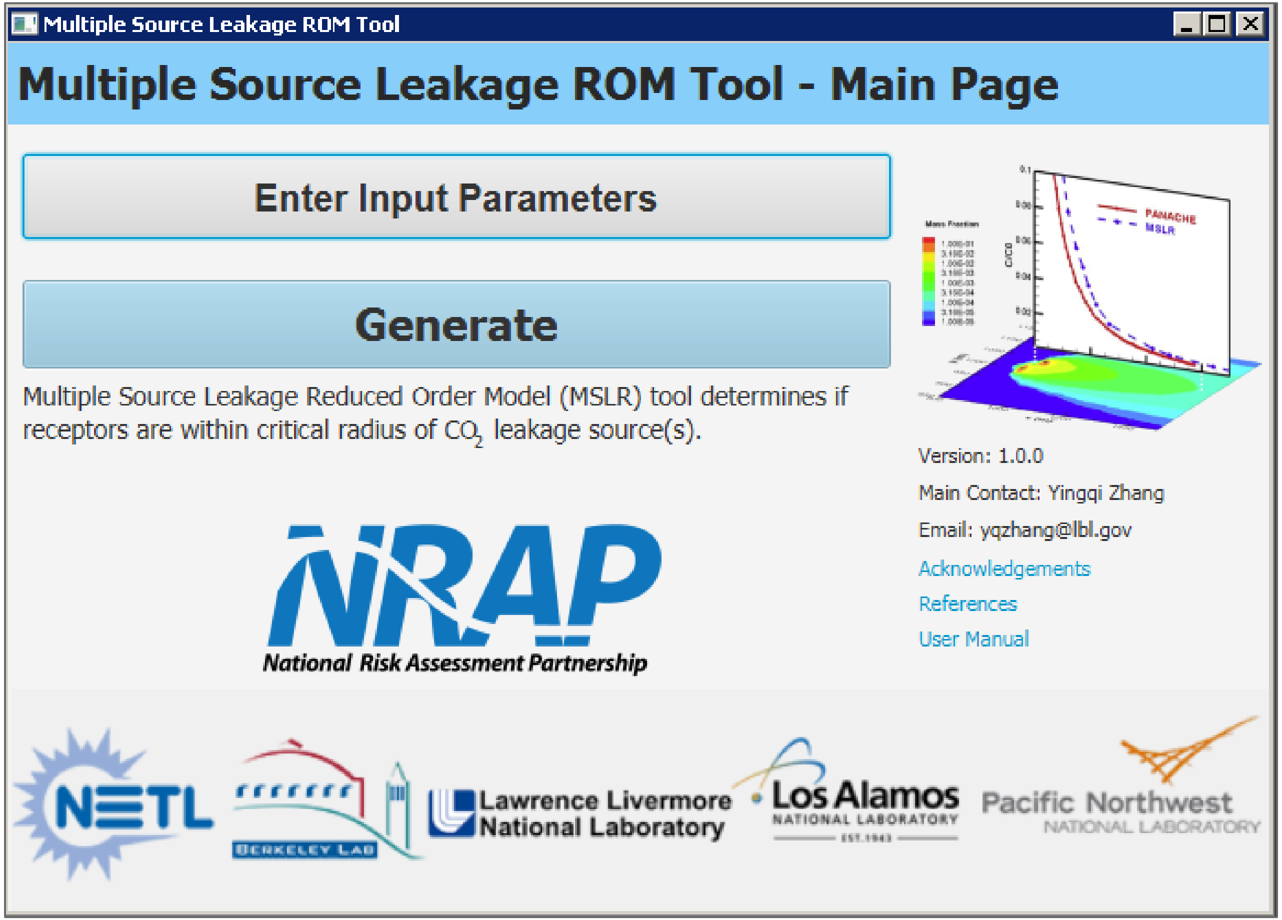
R_d: release duration (s)
x : downwind distance (m)
u : wind speed (m/s) at 10 m height

$$g_0 = \frac{g(\rho_0 - \rho_a)}{\rho_a}$$

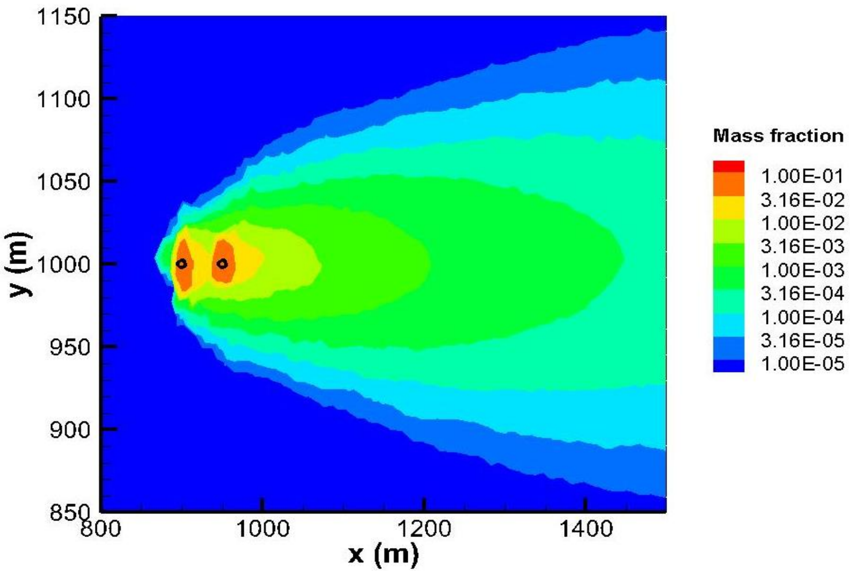
$$D_c = \left(\frac{q_0}{u}\right)^{0.5}$$

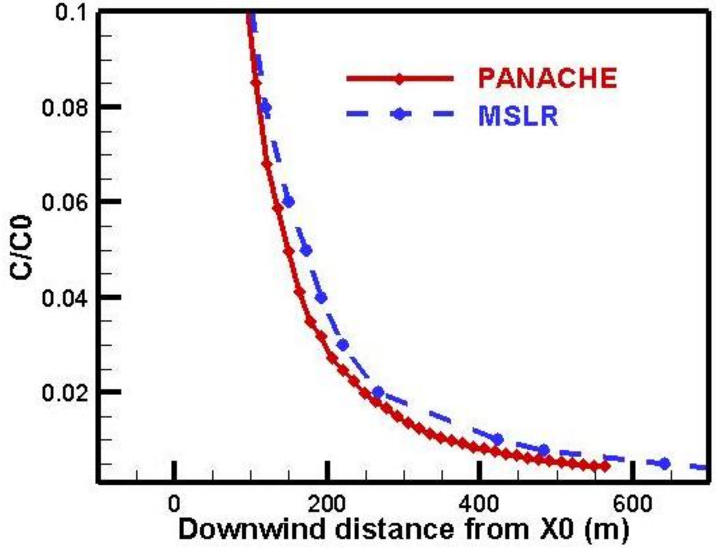
q_0: initial plume volume flux (m^3/s)
g : gravity factor (m/s^2)
ρ_0: initial density of released gas (kg/m^3)
ρ_a: density of ambient air (kg/m^3)

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)

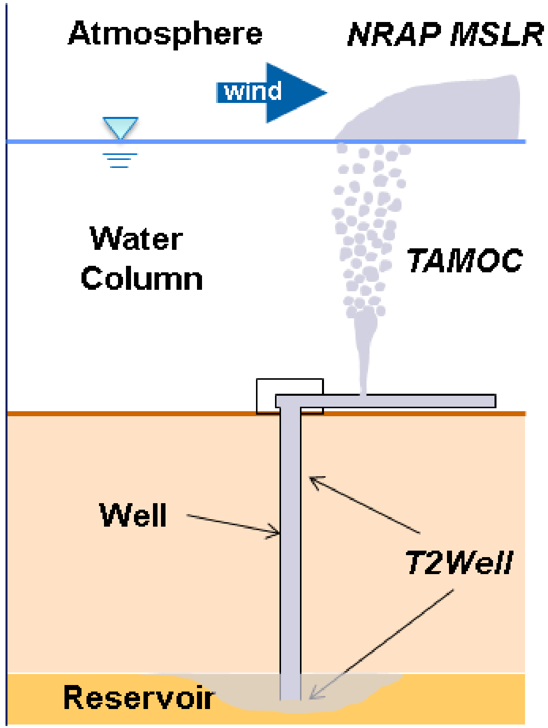

Multiple Source Leakage ROM Tool
Multiple Source Leakage ROM Tool - Main Page
Enter Input Parameters
Generate
Multiple Source Leakage Reduced Order Model (MSLR) tool determines if receptors are within critical radius of CO_2 leakage source(s).
PANACHE
MSLR
Version: 1.0.0
Main Contact: Yingqi Zhang
Email: yqzhang@lbl.gov
Acknowledgements
References
User Manual
NRAP
National Risk Assessment Partnership
NETL
BERKELEY LAB
Lawrence Livermore National Laboratory
Los Alamos NATIONAL LABORATORY
Pacific Northwest NATIONAL LABORATORY

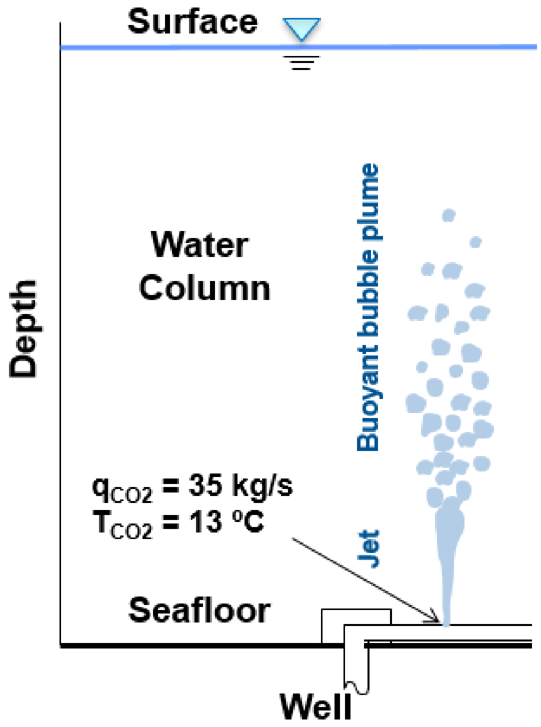
MSLR Verification Case 1:
Wind Direction Aligned With Two Sources

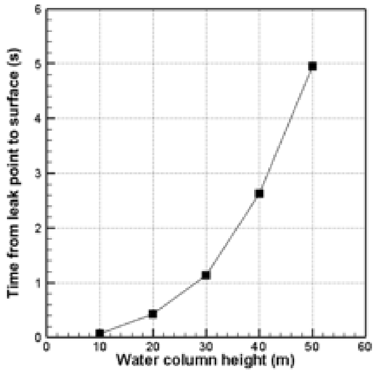


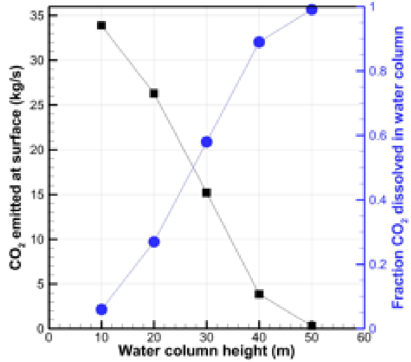


Approach: We take the output of TAMOC and use it as the source term for the MSLR



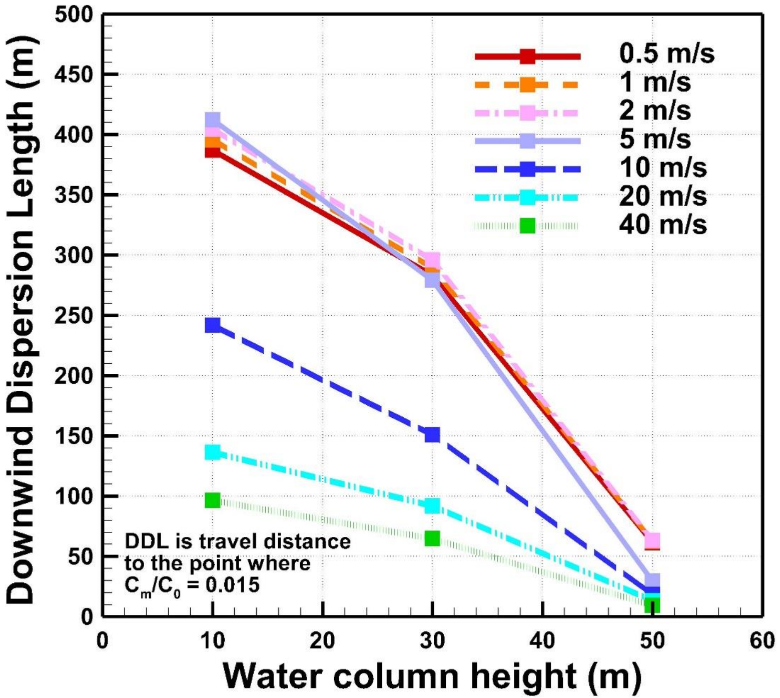






Results: Downwind Dispersion Length (DDL) varies with depth and windspeed

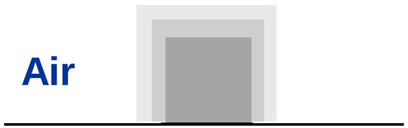
- **Source term for the MSLR is the output from TAMOC, i.e., flow rate of CO_2 out of the sea surface.**
- **We ran the MSLR for the different water depths and wind speeds.**
- **Results show the downwind dispersion length (DDL) is maximal at around 400 m for wind speed of 5 m/s for the 10 m water column (shallowest depth).**
- **For deeper systems, DDL is 100 m or less.**



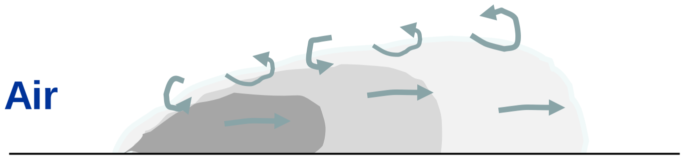
Why the reversal in trend at low windspeed?

There is a tradeoff between wind transporting CO_2 and wind dispersing and diluting the CO_2

If no wind, gas does not move much so the downwind safety distance is short



If wind, gas moves but also disperses so safety distance gets longer up to a point at which higher wind makes it shorter



Notes on Critical CO_2 Concentrations

- Note that dispersion distances are referred to as downwind dispersion lengths (DDLs) rather than downwind safety lengths
- Inhalation of air with
  - 4% CO_2 by volume is the U.S. national standard concentration considered immediately dangerous to life or health.[49]

- The lower concentration value used here, 1.5% CO_2 by volume, is a concentration at which some people will experience mild respiratory stimulation,[50] that is, a concentration with nonzero but low impact to human health over short exposure periods

[49] NIOSH, The National Institute of Occupational Safety and Health. NIOSH publications & products, immediately dangerous to life or health (IDLH) values, table of IDLH values. 1994. Available: https://www.cdc.gov/niosh/idlh/124389.html.
[50] U.S. Department of Agriculture, Food Safety and Inspection Service. Hazard information sheet. 2020. Available: https://www.fsis.usda.gov/sites/default/files/media_file/2020-08/Carbon-Dioxide.pdf

Conclusions

- **There is a need to understand potential health and safety impacts of large-scale CO_2 well blowouts/pipeline leaks at offshore sites.**
- **Offshore CO_2 blowouts are different from onshore blowouts because of the strong effects of the water column.**
- **We loosely coupled three models for simulations of this system:**
  - **T2Well (reservoir and well or pipeline)**
  - **TAMOC (water column)**
  - **MSLR (dense gas dispersion above the sea surface)**
- **Results show:**
  - **CO_2 leakage is strongly controlled by dissolution in the water column.**
  - **Above the sea surface, the CO_2 plume is dispersed by dense gas flow and wind.**
  - **Downwind Dispersion Length (~radius of safety exclusion zone) is on the order of several hundred meters for the shallow-water cases, and less for deep-water cases.**

For more details

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. https://doi.org/10.1002/ghg.1943

Oldenburg, C.M. and Zhang, Y., 2022. Downwind dispersion of CO_2 from a major subsea blowout in shallow offshore waters. *Greenhouse Gases: Science and Technology, 12(2), pp. 321–331*. https://doi.org/10.1002/ghg.2144

Acknowledgments

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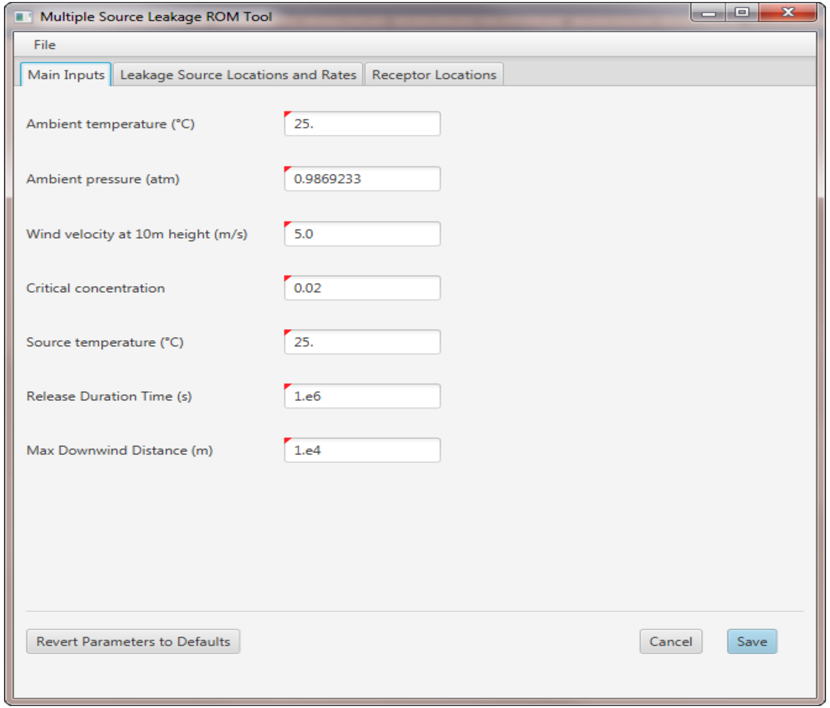
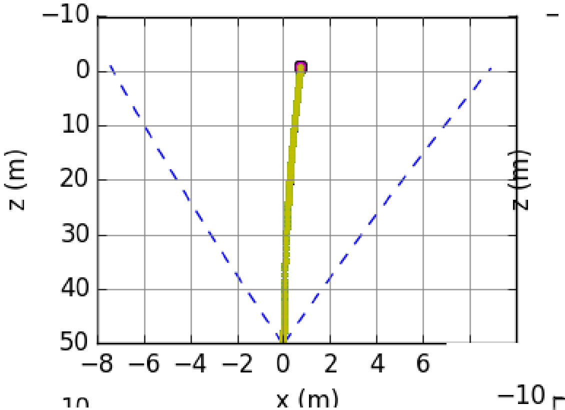
Three Types of Input

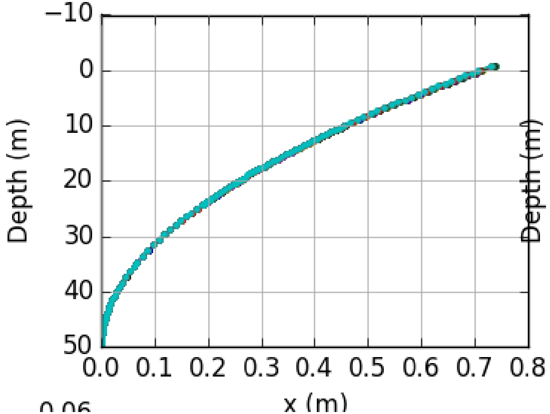
- **Main input:**
  - Ambient pressure
  - Ambient temperature
  - Wind velocity at 10 m height
  - Critical concentration
  - Source temperature
  - Release time (stand-alone only)
  - maximum downwind distance (stand-alone only)
- **Leakage source location and rates**
- **Receptor locations**



10 m plume spreads to diameter of 3 m even with high flux emission

50 m water column





10 m water column