PROTECTING PEOPLE AND PLACES HSE

Problem Description: Accelerated Dense Gas Dispersion (CO_2)

European Study Group with Industry: Processing and Safety in Fluids

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Health and Safety Executive

Outline

- Introduction to HSE
- CO_2 properties
- Satartia CO_2 release incident (2020)
- Previous and current CO_2 release studies/experiments
- Overview of dispersion models
- Computational cost
- Conclusions

Presentation Supplement/Document

A collection of notes relating to dense gas dispersion, in particular dispersion modelling of CO_2, will be provided to supplement this presentation:

LIFD industry problem solving group: processing and safety in fluids ESGI 191

HSE introduction to dense gas dispersion modelling

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Introduction to HSE

- The Health and Safety Executive (HSE) is Britain’s national regulator for workplace health and safety.
  - Includes onshore/offshore pipelines, chemical/oil/gas infrastructure, offshore platforms etc.
  - Activities: evidence gathering, policy development, consultation, regulation, incident investigation, enforcement
  - HSE acts as an enabling regulator, supporting the introduction of new technologies
  - 2,400 total staff (800 scientists and engineers)
  - £230M ($280M) budget: 60% from Government, 40% from external income

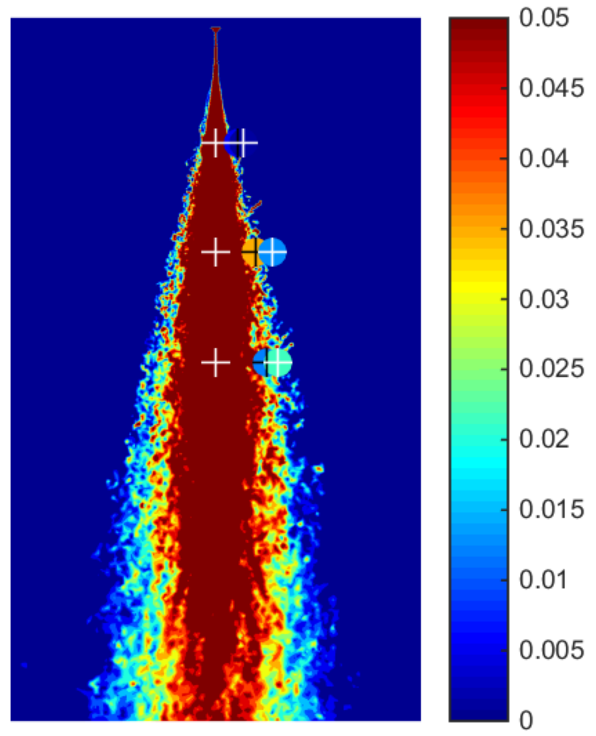
- HSE Science and Research Centre, Buxton, UK
  - 400 staff, 550-acre test site
  - Scientific support to HSE and other Government departments
  - “Shared research” or joint-industry projects co-funded by HSE
  - Bespoke consultancy on a commercial basis
  - Annual Science Review 2025

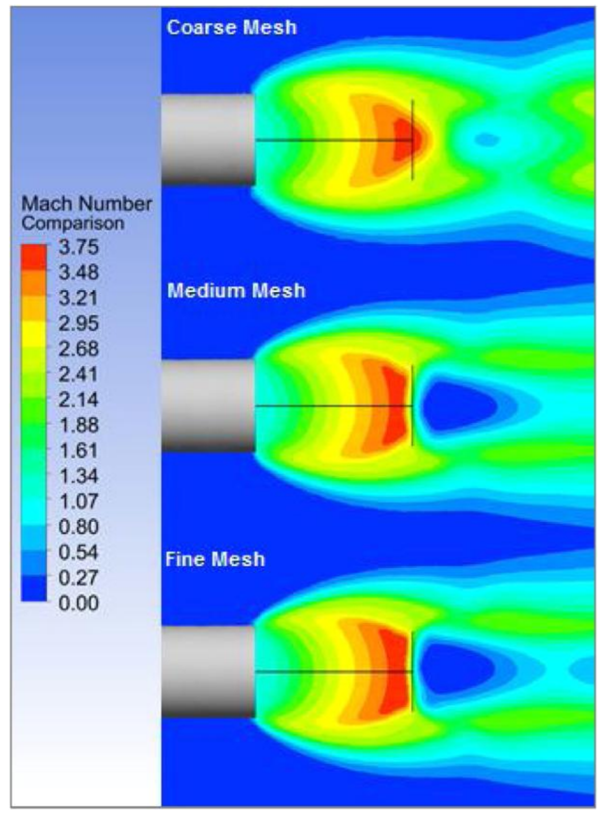


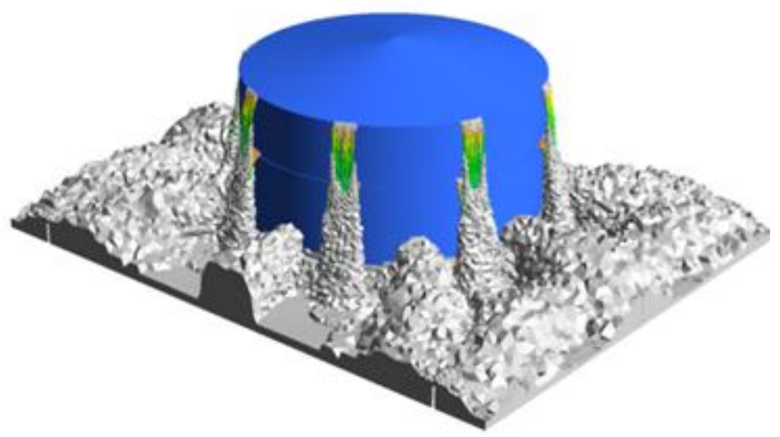
HSE Fluid Dynamics Team

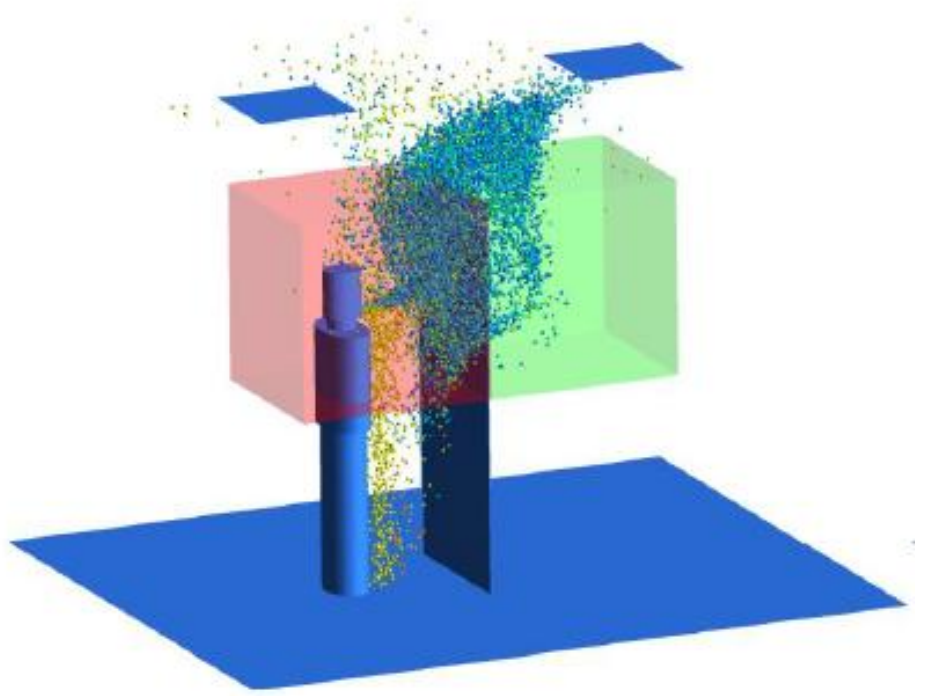
Fluid Dynamics Team:

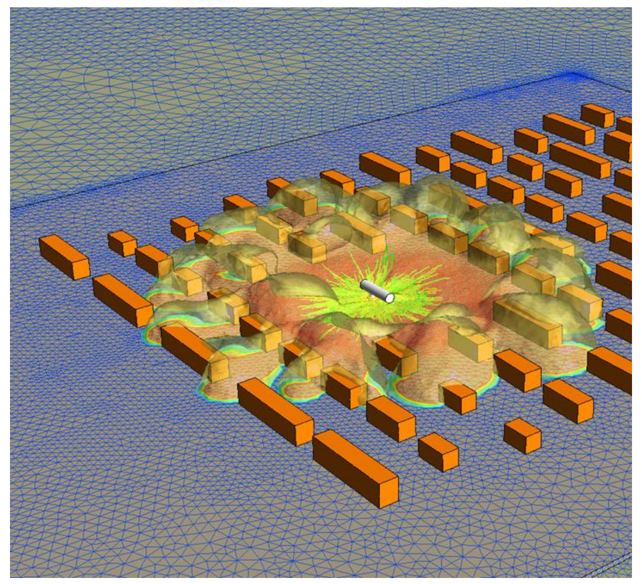
- 6 members
- Backgrounds: engineering, maths, physics, fluid dynamics

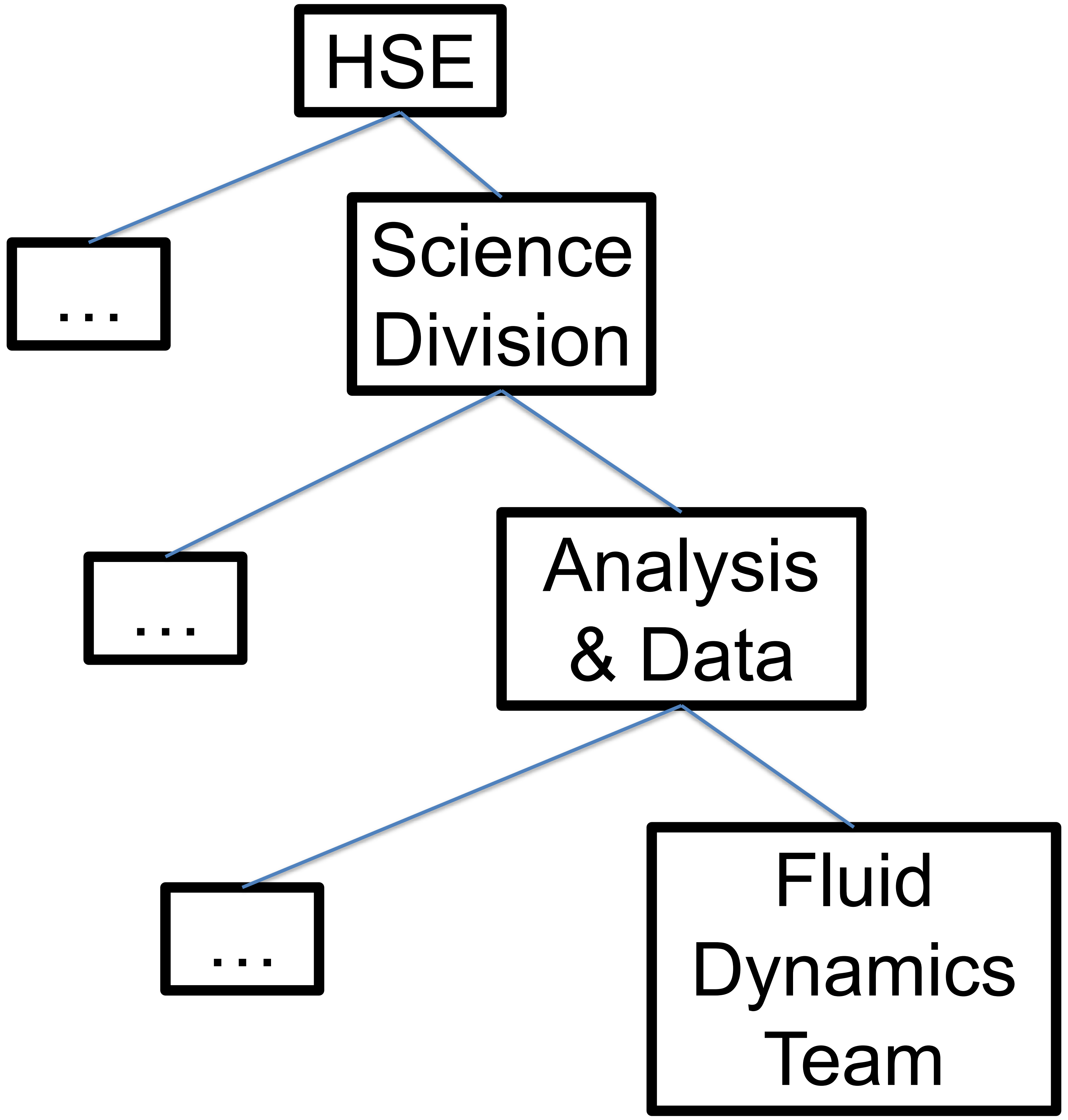












Introduction to CO_2

Carbon Capture Utilisation and Storage (CCUS):

- CO_2 captured from large industrial emitters (power stations, steel mills, cement industry.
  - Cement contributes about 8% to global CO_2 emissions[1]
- Transported to CO_2 storage options
- CO_2 transported in pipelines as a liquid
  - Density comparable to water, viscosity more akin to a gas.
- CO_2 is not currently defined as a dangerous substance under the Control of Major Accident Hazards Regulations 1999 (COMAH) or as a dangerous fluid under the Pipelines Safety Regulations 1996 (PSR)[3]
- At atmospheric pressure it is either gas or solid
- Significant cooling upon release

UK government net-zero policy documents:

- The Climate Change Act 2008
- The Ten Point Plan for a Green Industrial Revolution, Nov. 2020
- Net Zero Strategy: Build Back Greener, Oct. 2021
- Spring Budget 2023 (£20 billions towards CCUS[2]

[1]https://www.newscientist.com/article/2428967-carbon-negative-cement-can-be-made-with-a-mineral-that-helps-catch-co2/
[2]https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1144442/Print_Budget_2023.pdf
[3]https://www.hse.gov.uk/carboncapture/major-hazard.htm

Incident- Satartia CO_2 pipeline (2020)

- Failure of Denbury 24-inch CO_2 pipeline near Satartia, Mississippi due to landslide
- ~200 people evacuated, 45 hospitalised
- Dense CO_2 cloud rolled downhill and engulfed Satartia village (a mile away)
- Denbury's risk assessment did not identify that a release could affect the nearby village of Satartia

The Gassing Of Satartia

A CO2 pipeline in Mississippi ruptured last year, sickening dozens of people. What does it forecast for the massive proposed buildout of pipelines across the U.S.?

By Dan Zegart
August 26, 2021

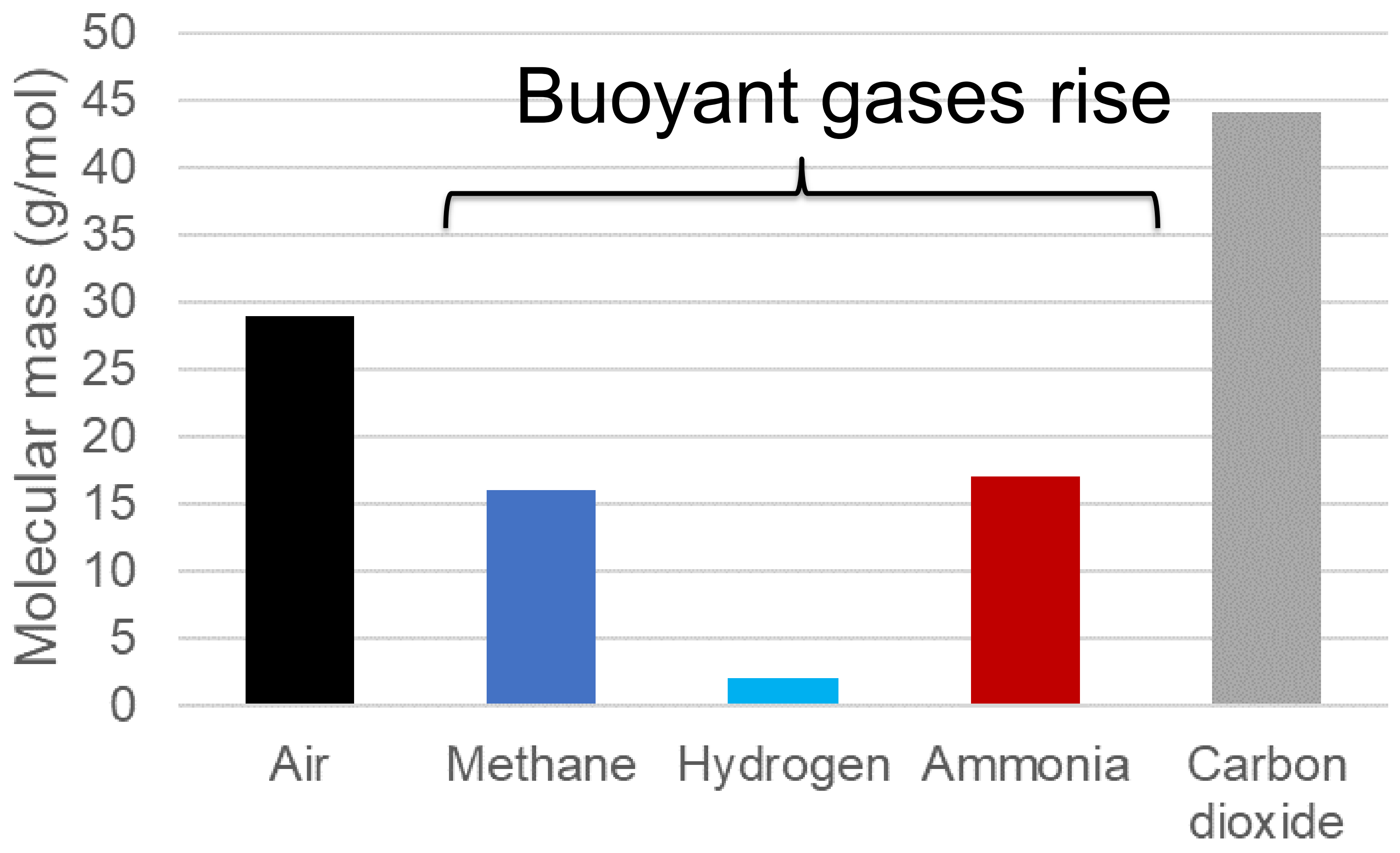
https://www.huffingtonpost.co.uk/entry/gassing-satartia-mississippi-co2-pipeline_n_60ddea9fe4b0ddef8b0ddc8f

Yazoo County Emergency Management Agency/Rory Doyle for HuffPost and PHMSA

- https://www.huffingtonpost.co.uk/entry/gassing-satartia-mississippi-co2-pipeline_n_60ddea9fe4b0ddef8b0ddc8f
- https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2022-05/Failure%20Investigation%20Report%20-%20Denbury%20Gulf%20Coast%20Pipeline.pdf

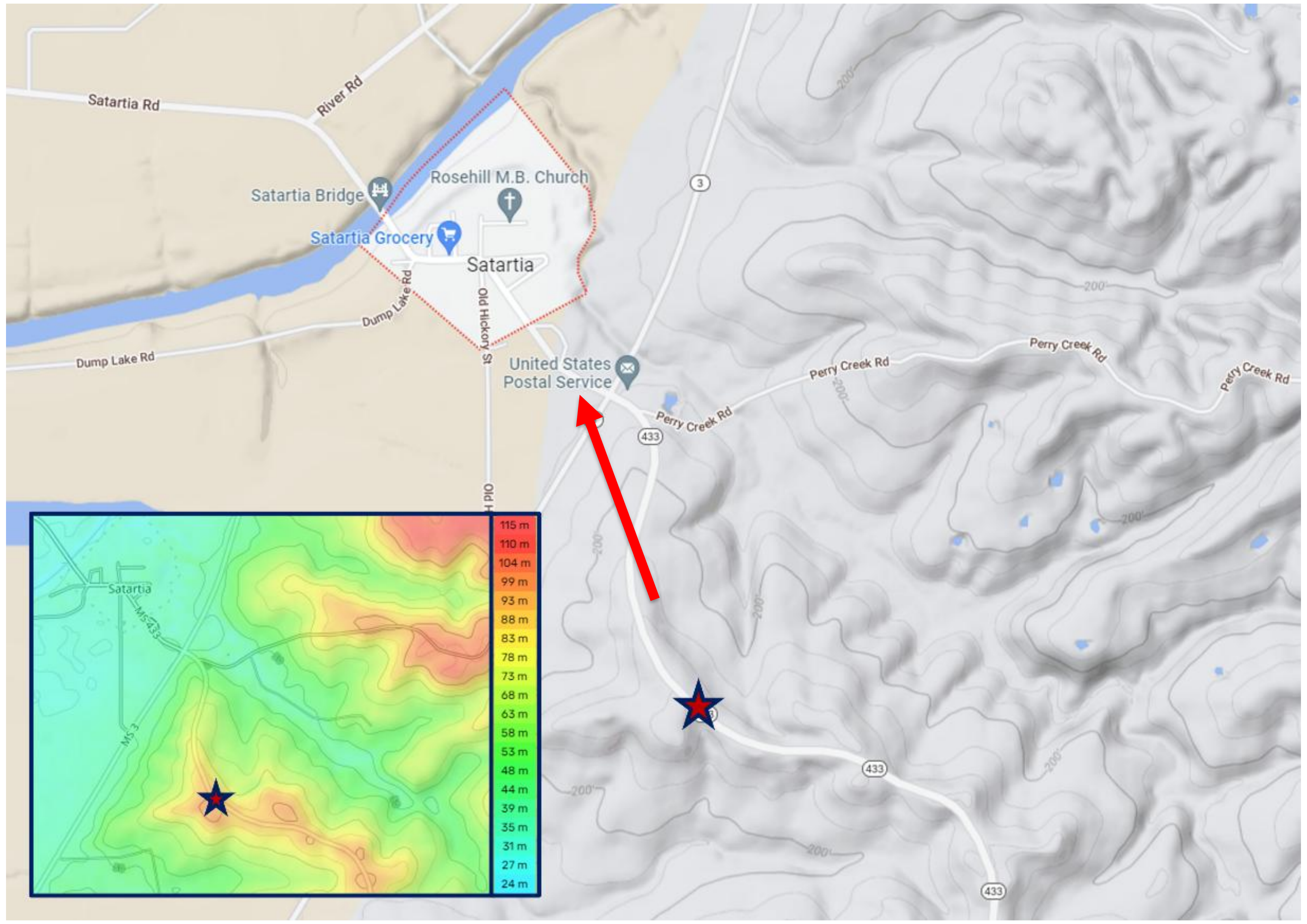
Dense Gas Effects and CO_2

- What causes dense gas effects?
  1. Molecular mass
  2. Temperature and aerosol formation



Dense/slumping cloud- terrain could be influential on cloud behaviour.

Satartia topography



Terrain map taken from Google Maps and contour map taken from topographic-map.com. Approximate location of release marked by a star.

HSE Research Activities (CO_2)

Skylark JIP

- Large scale releases of CO_2
- Funding from government (DESNZ), and industry
- These are the largest set of dispersion trials in the UK since the 1980’s. The JIP, led by DNV with collaboration from HSE and other partners, aims to address knowledge gaps in the behaviour of CO_2 clouds, such as in complex terrain.
- Any model developed can therefore be validated against the latest large-scale CO_2 release experiments.

[Skylark: Pioneering excellence in CO2 pipeline safety (dnv.com)](dnv.com)

Aspects of Skylark:

- Pipeline craters and source terms
- Wind tunnel experiments (University of Arkansas)
- Simple/**complex** terrain experiments
- Model validation
- Emergency response
- Venting

DNV HSE GT Science & Software
RAND CORPORATION UNIVERSITY OF ARKANSAS COLLEGE OF ENGINEERING NCEC RICARDO HANNA Consultants

Previous CO_2 Release Experiments at DNV Spadeadam

- **COOLTRANS**: the COOLTRANS (CO_2Liquid pipeline TRANSportation) research programme was initiated by National Grid to address and resolve key issues relating to pipelines carrying dense phase CO_2 (Allason *et al*., 2012; Cooper 2012).
- **CO2PIPETRANS**: large-scale CO_2 release experiments were undertaken by DNV GL at the DNV Spadeadam site in 2013. Experiments were part of the CO2PIPETRANS joint industry project (JIP) alongside 15 partner organisations. Liquid phase CO_2 at pressures of around 100 barg was released through holes ranging in diameters from 25 to150 mm.
- **COSHER**: the COSHER (CO_2 Safety, Health, Environment, and Risk) JIP focused on conducting realistic-scale pipeline rupture tests on a high-pressure underground pipeline at the DNV-GL Site in Spadeadam (Ahmad *et al*., 2015).

Dense Gas Blanket

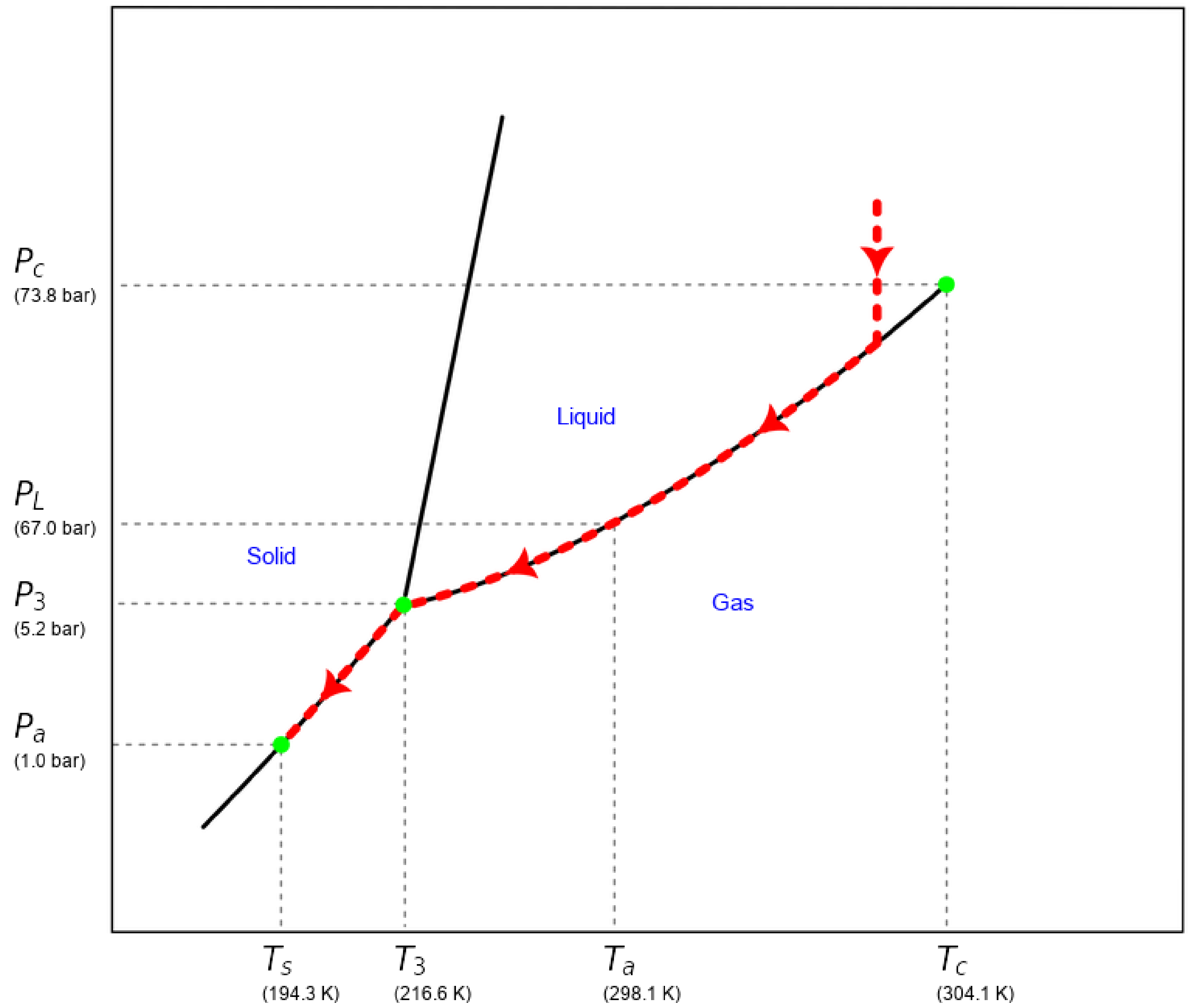
- The COSHER project observed CO_2 pooling into the low-lying areas of the test section. Ahmad *et al*. (2015) described this behaviour as follows:

“After termination of the test, the central region of the visible cloud around the rupture location began to disappear but the remainder of the cloud took a considerable time (6–8 min) to disperse, particularly in the regions of the cloud to the north and south which occupied the low level areas around the streams which run parallel to the site boundary.”

Aerial view of the CO_2 cloud in the COSHER project, from Ahmed et al. (2015). Left: snapshot at 10 s, right: snapshot at 120 s.

Properties of CO2

- When pressurised dense-phase liquid CO_2 is released into the atmosphere it expands as the pressure of the CO_2 falls to atmospheric pressure.
- As the temperature drops below the sublimation temperature (-78.8 ºC), solid particles (dry ice) form
- As the cloud of CO_2 gas and dry ice disperses it entrains ambient air and the solid dry-ice particles sublime into CO_2 gas

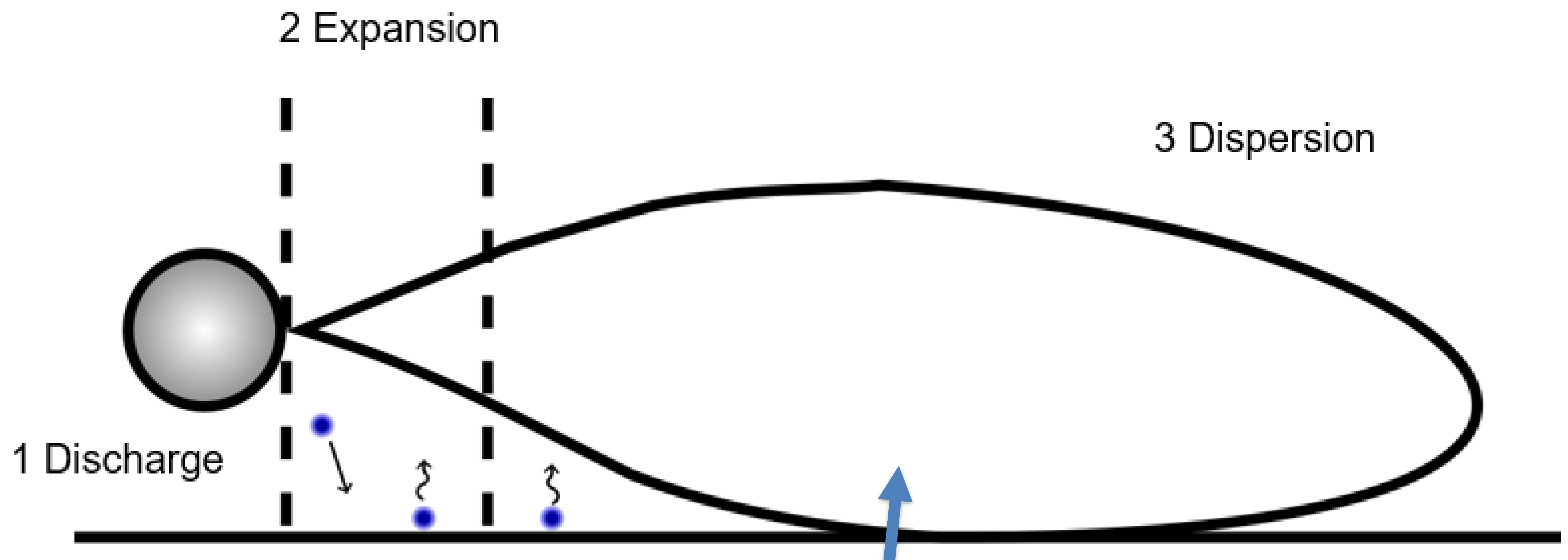


CO_2 phase diagram, adapted from Webber (2011). Not to scale. Triple point and critical point pressure and temperatures extracted from the Coolprop Python library (Bell et al., 2014).

Dispersion schematic

Region 2 (near-field, expansion). Liquid CO_2 expands to atmospheric pressure. Vapour is formed, and if the temperature is low enough, solid particles form.

Region 1 (discharge). CO_2 is at storage conditions. Most likely pressurised and in a dense, liquid phase.



Region 3 (far-field, dispersion). Vapour cloud, often colder and more dense than the surrounding air, disperses and interacts with the atmosphere (wind, humidity, etc.), and terrain.

Dispersion Model Methods

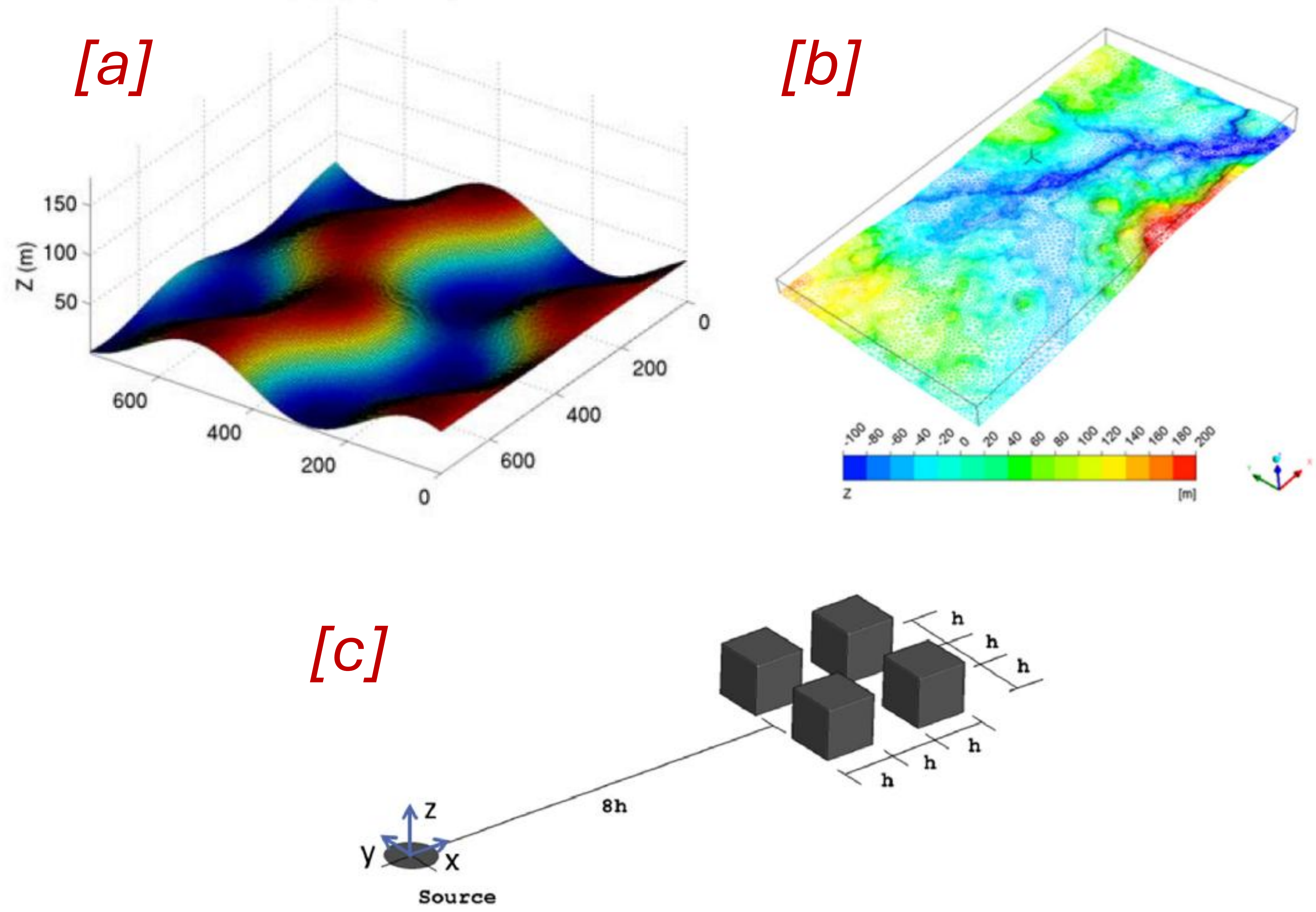
Method	Description	Reference*
Nomographs	Graphical representation of a mathematical relation	Britter and McQuaid (B&M) Workbook
Gaussian plume	Analytical Gaussian shaped-plume	Mazzoldi *et al*. (2011)
Integral and box	Mass, momentum, energy conservation ODEs	Witlox *et al*. (2014)
Shallow-layer	Solve conservation eqns. for depth	Folch *et al*. (2009)
RANS/LES	Modelling some form of the NSE	Wang *et al*. (2020)
Lattice Boltzmann	Particle distributions on a lattice	Merlier et al. (2019)
Machine learning	Construct models using algorithms trained on data	Gant *et al*. (2013)

*For references, see the supplementary document

Examples of terrain

There is no standard definition of ‘terrain’ in the literature

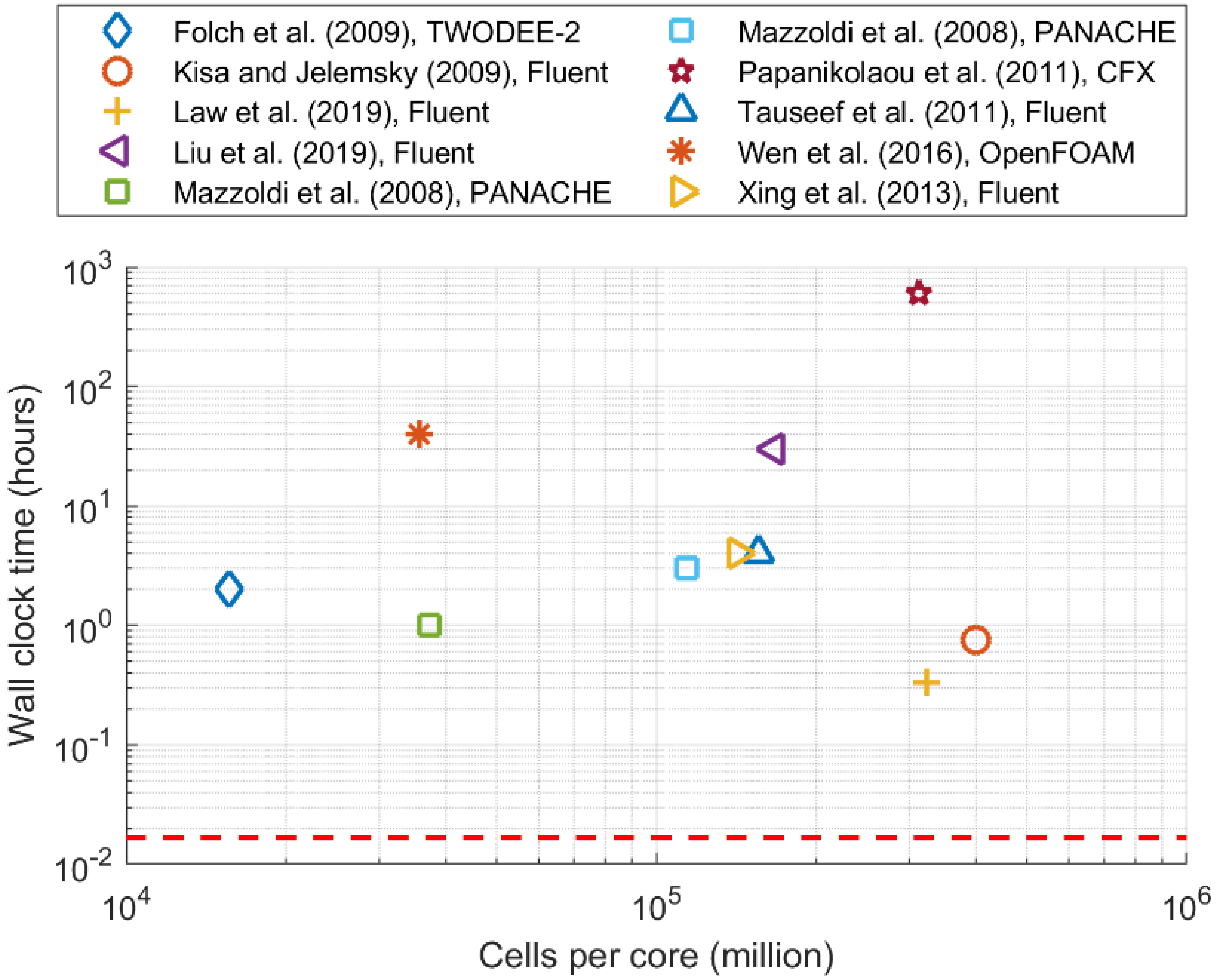
- Chow et al. (2009): idealised undulations
- Woolley et al. (2014): large and small scale structures within a topography
- Wingstead et al. (2017): the ground is flat, but there are obstacles present



Examples of terrain from the literature: [a] Chow et al. (2009); [b] Woolley et al. (2014); [c] Wingstead et al. (2017).

Computational Cost

- RHS figure presents computational cost (in wall clock time) against cells per core, for 10 studies where computational cost has been reported.
- Dashed line indicates simulation time of 1 min
- These models are not fast enough for our case



Computational cost for 10 studies identified during the current literature review. A horizontal dashed red line is plotted at a wall clock time of 1 minute.

Conclusions

- There is a clear need to develop new capabilities in this area of modelling atmospheric dispersion of CO_2 from pipeline releases
- The next decade is likely to see a rapid growth in CCS in the UK, with two CCS projects having already reached final investment decisions (HyNet and the East Coast Cluster) and the Government recently committing funds towards two further projects (Acorn and Viking).
- There is an opportunity to develop new modelling tools that could have significant impact in these new developing areas

PhD Project Proposal

- Leeds-HSE PhD project on this topic proposed for the 2025 Fluids CDT intake
- Very similar to the topic introduced here, but with development of an LBM/AI model
- No student uptake this year (2025)

Accelerated Fluid Dynamics of CO2 dense gas dispersion in complex terrain

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Industrial lead: Dr Simon Gant, Health and Safety Executive (HSE), simon.gant@hse.gov.uk
Co-supervisor(s):
Dr Andrew Ross, School of Earth and Environment, A.N.Ross@leeds.ac.uk, Dr Rory Hetherington, Health and Safety Executive (HSE), rory.hetherington@hse.gov.uk (External)
Project themes:
Clean Energy, Computational & Analytical Tools, Data-driven methods, Multiphysics & Complex Fluids

https://fluid-dynamics.leeds.ac.uk/projects/accelerated-fluid-dynamics-of-co2-dense-gas-dispersion-in-complex-terrain/

Thank You

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