Modelling of leakage scenarios to determine impact and anomaly criteria for detection

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Introduction

- A fully coupled physicochemical hydrodynamic modelling system is developed for CO_2 leakage analysis in shelf waters, including:
  - A coastal ocean hydrodynamic model (FVCOM)
  - Using a new multi-scale multi-phase model for bubble plume dynamics (PLUME)
  - Both linked to the carbonate system from the ecosystem model (FABM-ERSEM)

- Aims to quantify impact potential for a range of scenarios
  - deriving highly sensitive indicators of anomalies which might arise from leakage in order to facilitate detection and assurance.

- Model outcomes feed into further studies
  - Development of systems to optimize detection criteria and monitoring strategies

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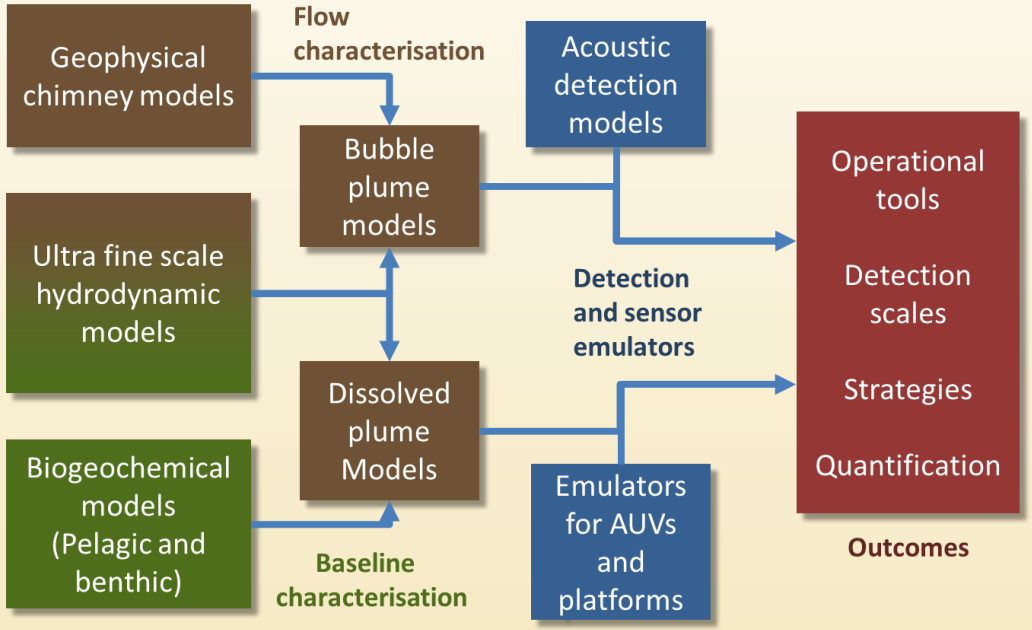
Modelling System

- Aims within the project and experiment
  - Develop a numerical model to show the CO_2 leakage experiment in the North Sea
    - Gas bubble plume physics
      - Initial leakage distribution
      - Bubble rise heights
      - Bubble rise velocities
      - Gas dissolution
    - Localised and coastal chemistry
      - Distribution of the dissolved solution
      - Increases in pCO2
      - Increases in DIC
      - Reductions in pH



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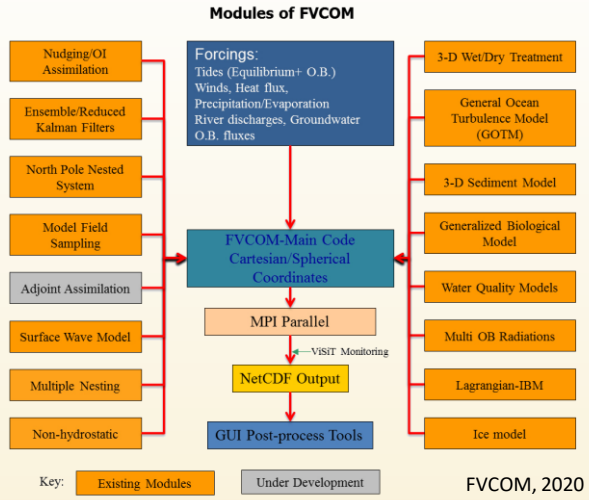
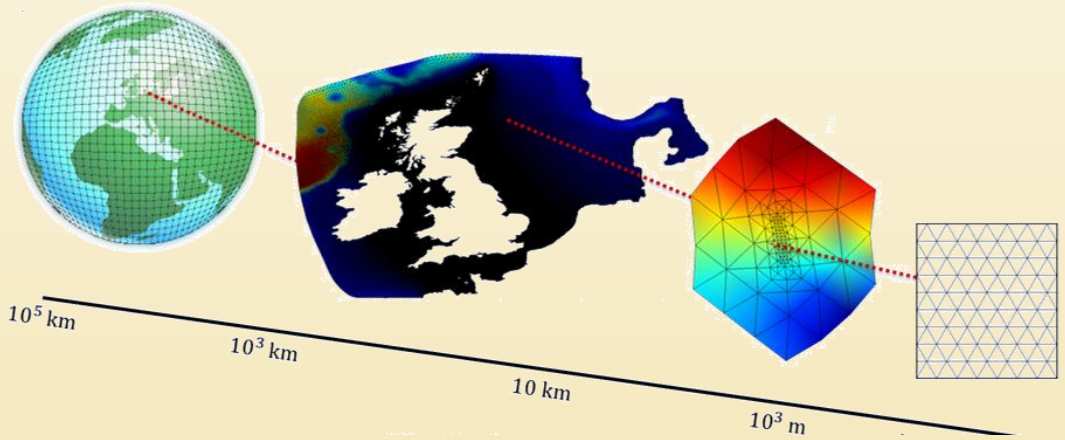
The Unstructured Grid Finite Volume Community Ocean Model (FVCOM)

- Unstructured and non-uniform grid
  - Allows use of topography, coastal waters and multiple-scales
- Modular system
  - Built using various modules, for different physics, parameters and coupled models
- Nesting
  - Allows nesting to run connected models at various scales from global, down to less than 1 meter
  - The Scottish Shelf Model (SSM) is a grid system and data developed to use with FVCOM to simulate the North Sea
  - A meter scale grid system is developed as a nested model within the SSM, using FVCOM to simulate the hydrodynamics and FABM-ERSEM to simulate the carbonate system.



FVCOM, 2020



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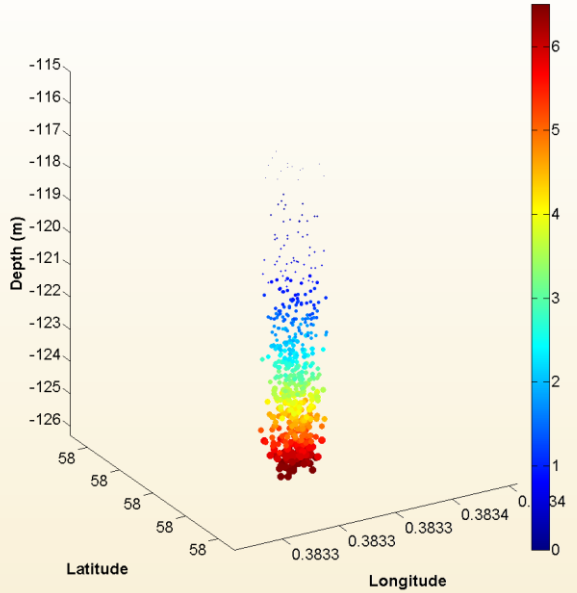
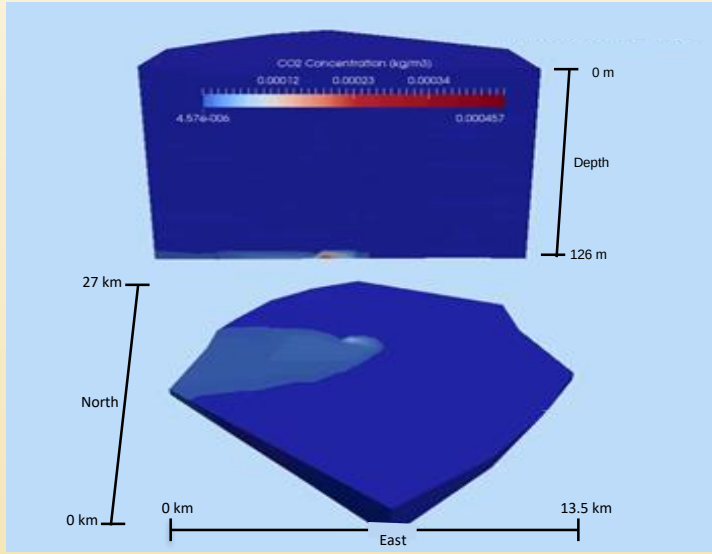
Predicting Leakage Using Multi-phase Equations (PLUME) Model

- A number of CO_2 bubbles is released at a set location at each numerical time step
- The initial state is based on leakage data predicted through
  - Experimental measurements
  - Geological models
  - Natural seepage
  - Potential scenarios
- The bubbles rise and dissolve based on buoyancy, drag and mass transfer
- The bubbles don't follow a grid, but determine location based on numerically predicted velocities and previous known positions
- As we know the position, we can find the grid to add the dissolved solution within FABM-ERSEM and FVCOM





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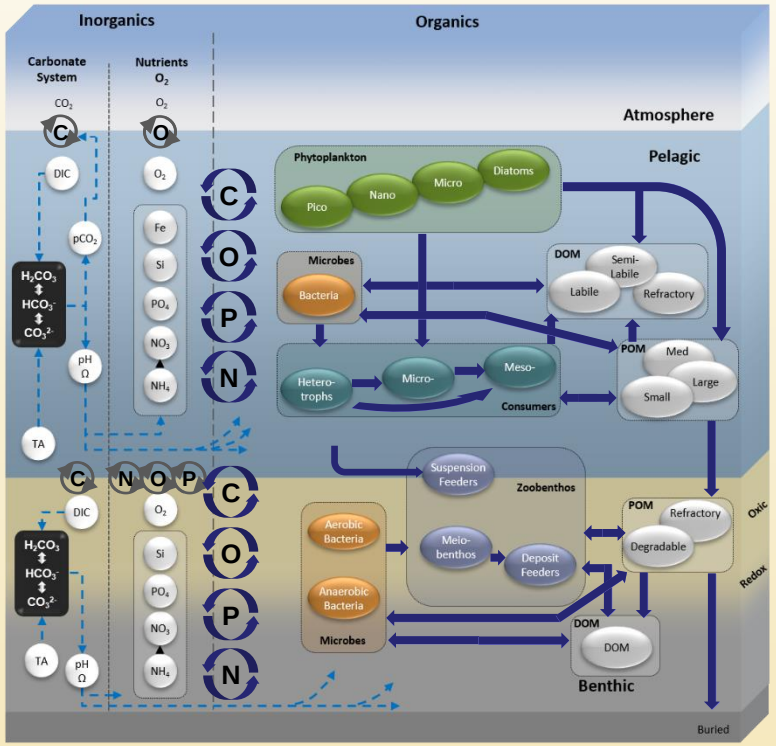
European Regional Seas Ecosystem Model (ERSEM) through the Framework for Aquatic Biogeochemical Models (FABM)

- ERSEM is a comprehensive biogeochemical and ecological model
  - Used in this case to calculate the pelagic carbonate system
    - DIC, pH, pCO2 etc.

- FABM collects the hydrodynamic data from FVCOM and ports to ERSEM
  - 3D grid system
  - Currents
  - Salinity
  - Temperature
  - Pressure

- The PLUME model provides a source term of DIC
  - The corresponding chemical changes in the carbonate system predicted through FABM-ERSEM.

- ERSEM then calculates the biogeochemical parameters
  - FABM then takes the output and calculates the advection and diffusion before outputting with FVCOM.



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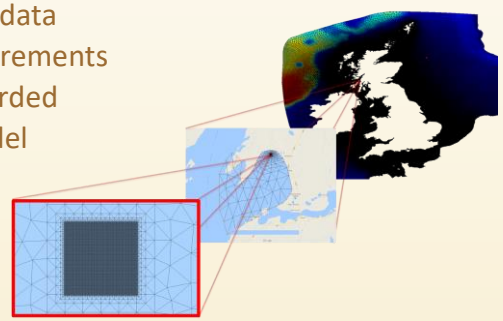
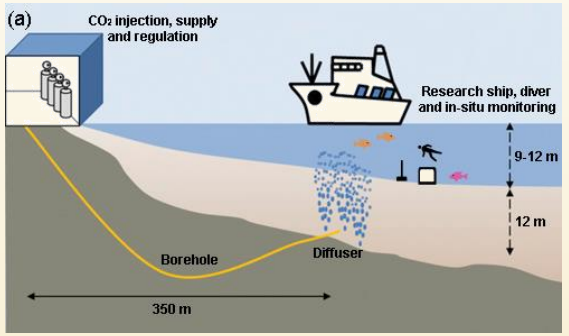
Leakage Scenarios

- QICS Experiment – 2012
  - Enclosed Bay off the west coast of Scotland
  - Data measurements
    - Bubble size from acoustic and imaged data
    - Leakage rate based on acoustic measurements
    - Background and changes to pCO_2 recorded
    - A lot of data available to calibrate model





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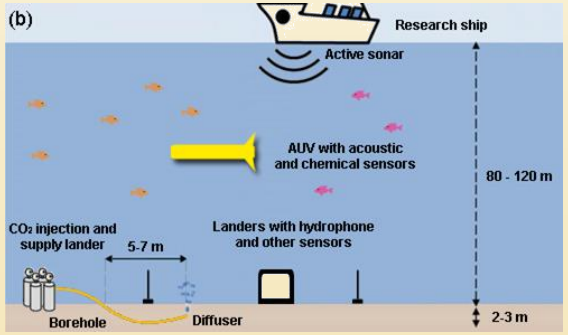
- STEMM-CCS Experiment – 2019
  - Open waters near the Goldeneye complex
  - Data measurements
    - Bubble size from imaged data
    - Leakage rate based on physical measurements and injection rate
    - Background and changes to pH recorded
    - Full data is not yet readily available due to the experiment being conducted last summer
  - Model is a preliminary run
    - Will be re-run once more data is available.



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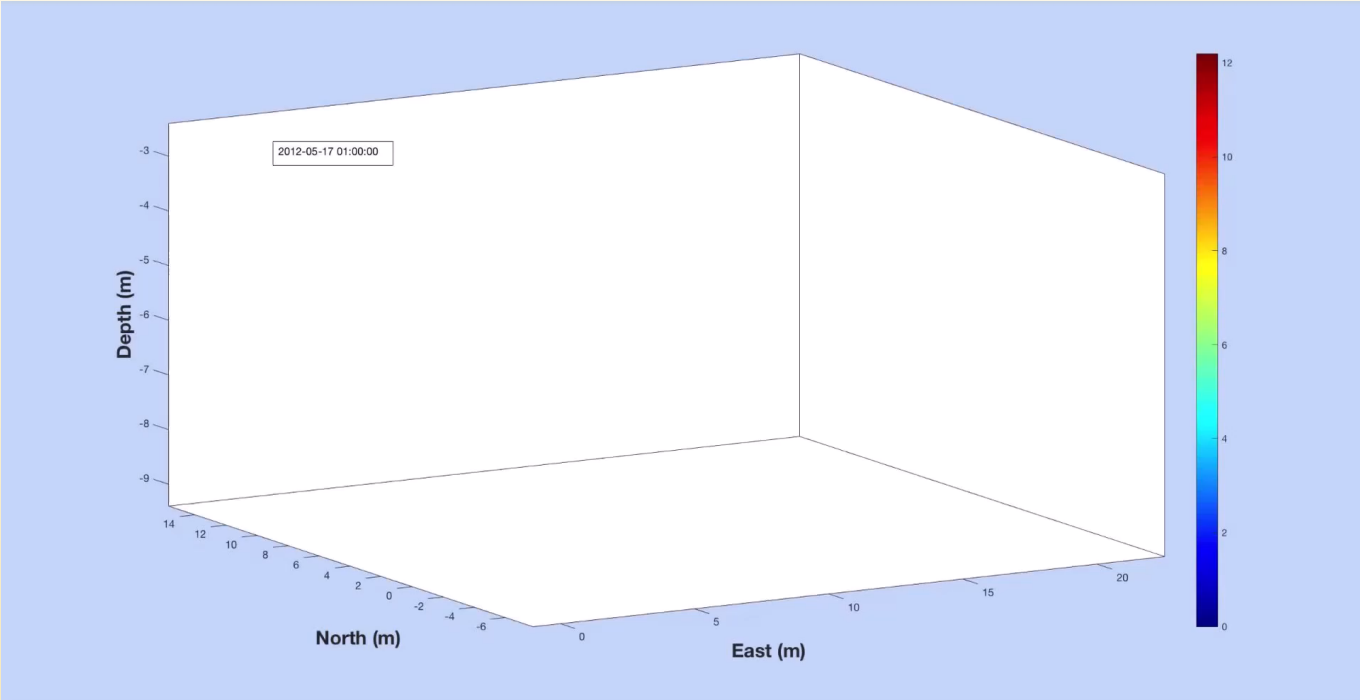
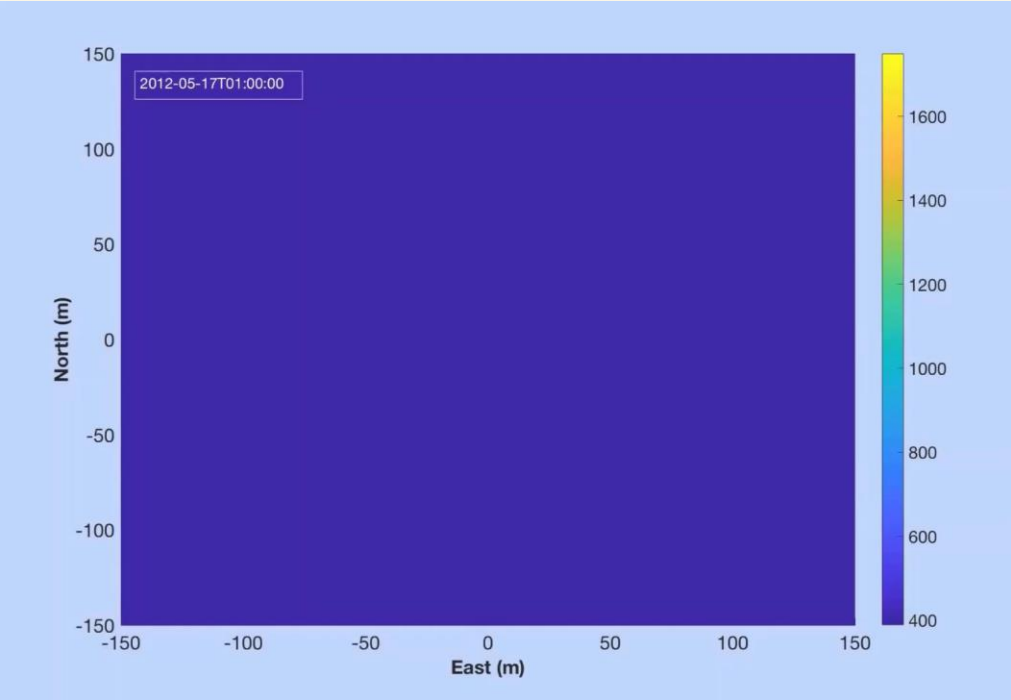
QICS Experiment – Model Development (no FABM-ERSEM)

Bubble Plume



pCO_2 Measurements



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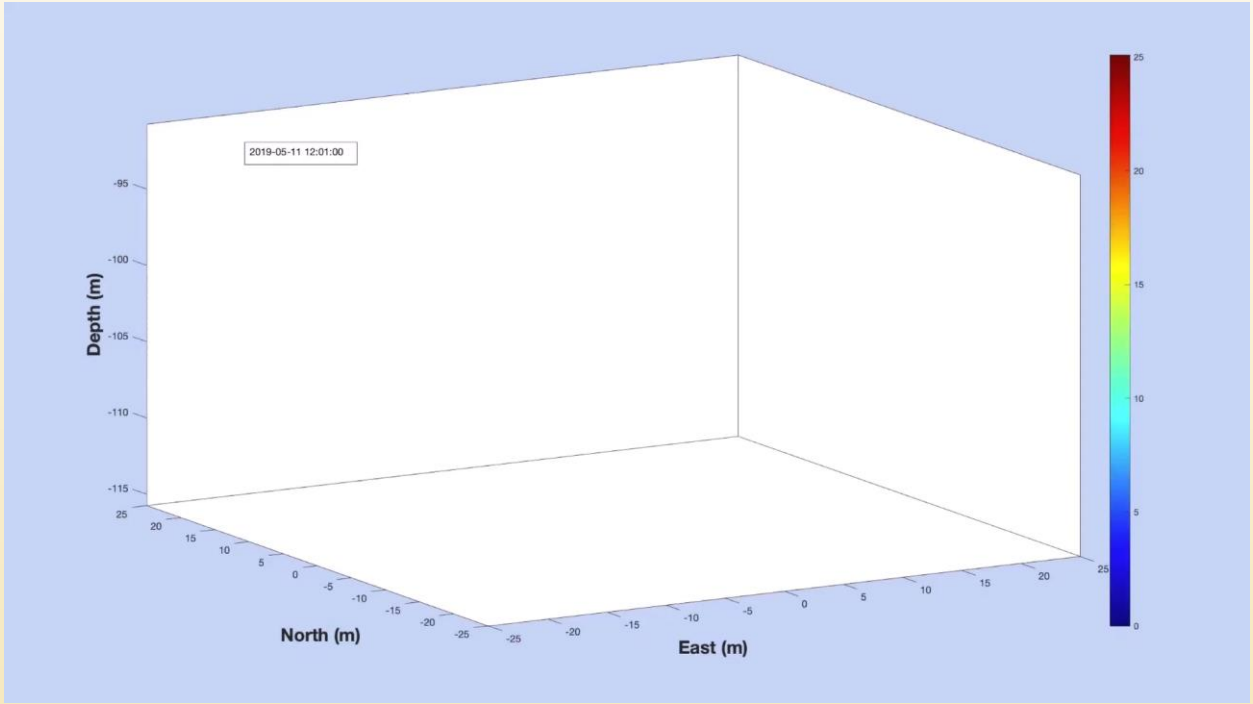
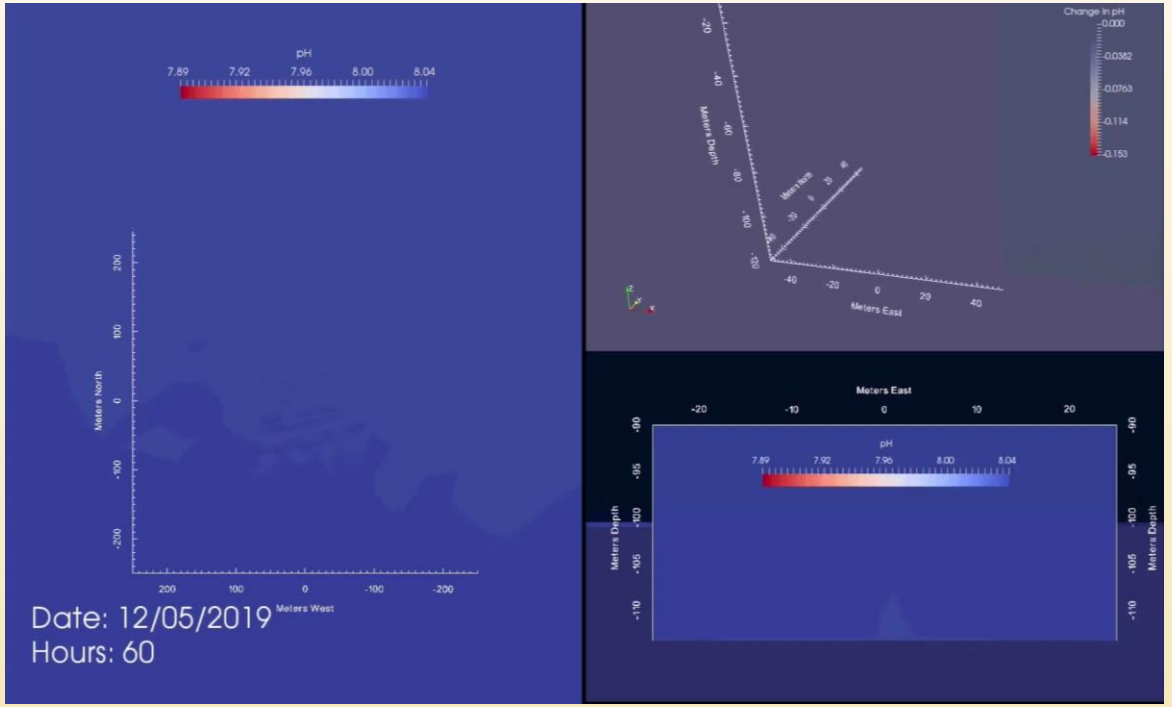
STEMM-CCS Experiment – Initial Model Results (Estimated leakage rates)

Bubble Plume



pH Measurements



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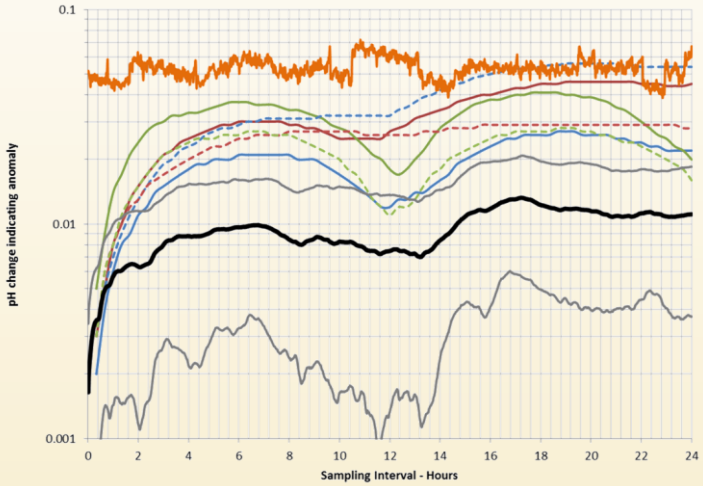
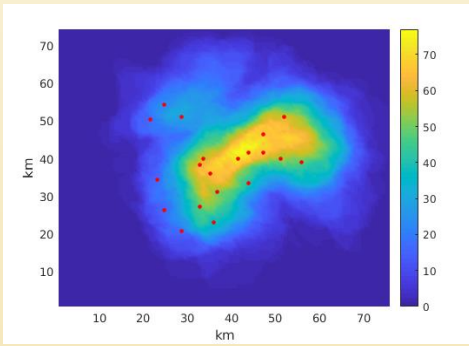
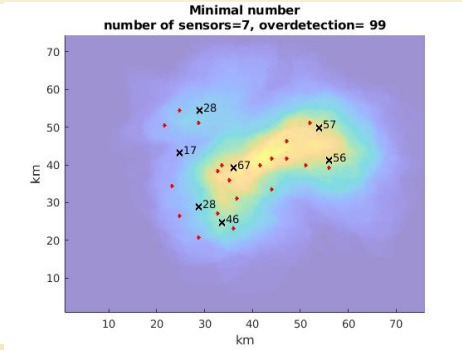
Development of systems to optimize detection criteria and monitoring strategies

- CO_2 leakage may be hidden within natural variability
  - photosynthesis, respiration, biosynthesis and dissolution of calcium carbonate
- The Rate of Change (RoC) Anomaly Criteria
  - A small change in pH in short timeframe is likely to be unnatural
    - A larger change over a longer timeframe how ever, can be natural background fluctuations
  - Aim to identify a uni-variate anomaly criteria for potential leak
    - a change of ≥ -0.01 pH unit in less than 20 minutes for much of the North Sea
- Machine / Deep Learning
  - Distinguishing a CO_2 leak signal from a signal of varying environment
  - Bayesian Convolutional Neural Network*
    - Trained to output the probability of a leak and uncertainty from a large time series data set
- Deployment Strategy
  - Optimal sensor placement, maximize detection efficiency with limited numbers of sensors
  - Monte Carlo (MC) simulations of the underlying Cseep model
    - Aim of optimal sensor placement to minimize the number of sensors used
  - Weighted Greedy Set
    - Provides the best sensor locations to cover the maximum area of the water column







*See poster titled: *Applications of a Machine Learning Extrapolating Technique in CCS Monitoring*
Kristian Gundersen et al. University of Bergen

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Brief Summary

- A fully coupled physicochemical modelling system has been developed for CO_2 leakage analysis in shelf waters
  - A multi-scale multi-phase model for bubble plume dynamics (PLUME)
    - bubble plume dissolution, height, and distribution
    - concentrations of dissolved solution within the water column.
  - Coastal ocean modelling (FVCOM)
    - providing the local and regional hydrodynamics
    - dispersing both the gas and the dissolved solution
  - Ecosystem modelling (FABM-ERSEM)
    - Analysis of the carbonate system
    - Provide DIC, pCO2 and pH changes
- Can quantify impact potential for a range of scenarios
  - derive highly sensitive indicators of anomalies which might arise from leakage in order to facilitate detection and assurance
- Model outcomes feed into further studies
  - Development of systems to optimize detection criteria and monitoring strategies
    - Providing effective methodologies for quantification of CO_2 fluxes across the seabed and dispersion in the water column
    - Informs the temporal and spatial scales required for effective chemical monitoring

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