Bayes' theorem as the fundament to design monitoring programs.

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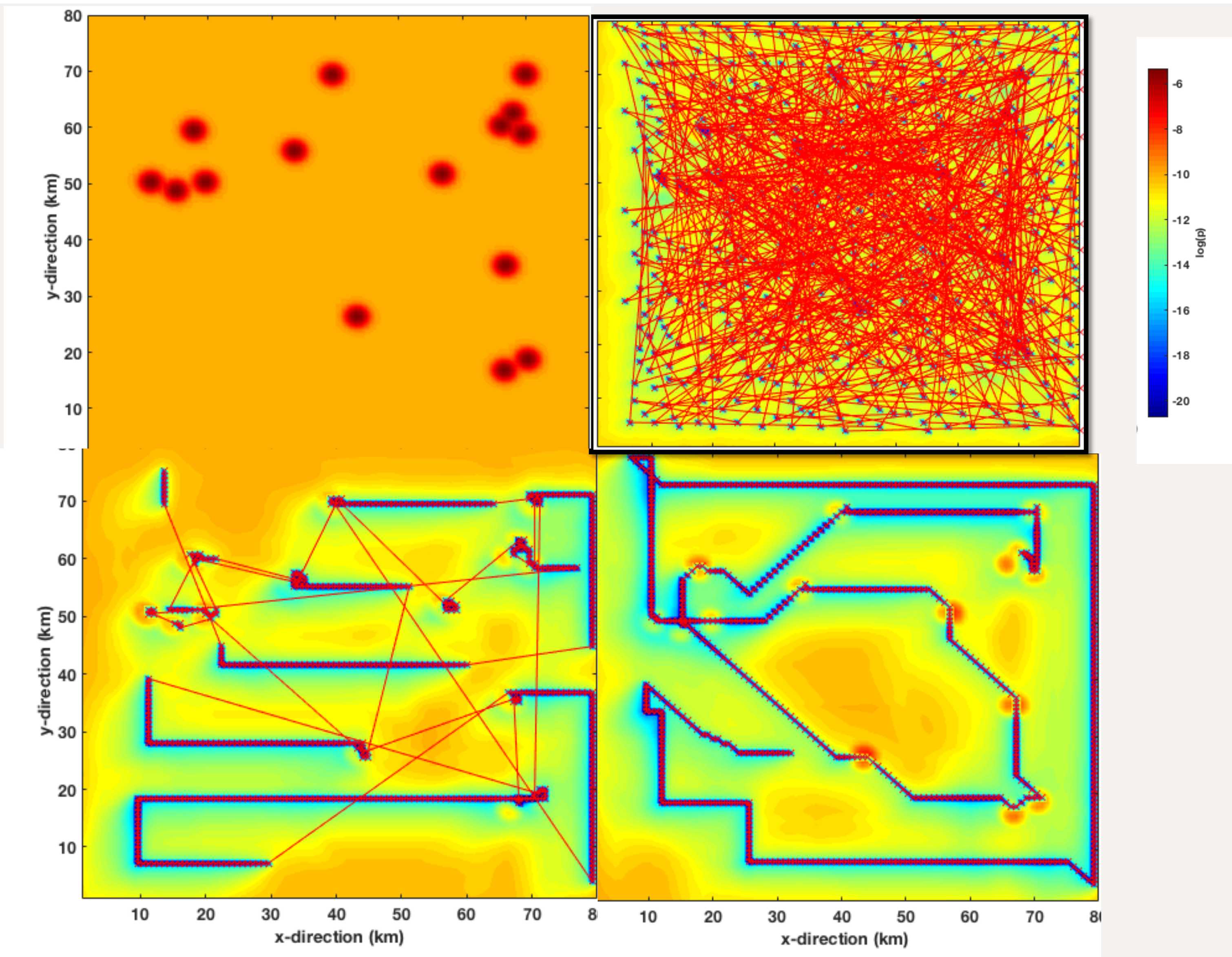


Upper left: Random prior probability for location of a leak. Highest probabilities are at well locations, gradually decreasing away from them. A general background probability is enforced. The total probability sums to 1. ***Upper right****: (Highest)The resulting probability field and corresponding paths when the next measurement is chosen to be taken at the point with highest probability of being the location of a leak.* ***Lower left:*** *(Distance) Similar to the previous but the probability is weighted with the inverse distance to the point.* ***Lower right:*** *(Continuous) As the previous but measurements are takenat each cell while moving toward the target location.*

Introduction

Designing marine monitoring programs capable of detecting CO_2 leaks from subsea geological storage projects in highly variable marine is challenging. Marine operations are costly constraining the availability of measurements.

Based on site characteristics , environmental baseline, and reliable footprint predictions it is demonstrated that Bayes theorem offers to design efficient monitoring programs. Here demonstrating by defining paths taken by an AUV traversing an area to detect a seep. The STEMM-CCS baseline and experiment planned for 2019 is important in this aspect, providing environmental and experimental data.

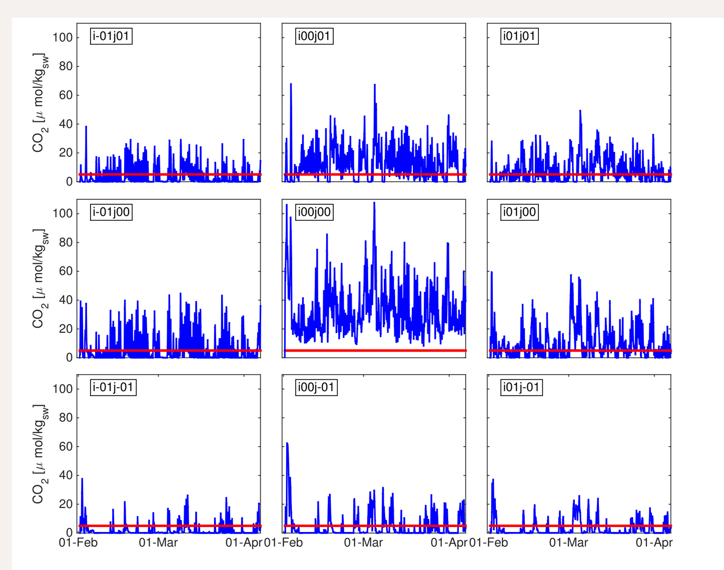
Bayes theorem

A variant of Bayes theorem is given below. The updated probability of a location to be the site of a leak after a measurement failing to detect a leak is based on the prior belief (p) and the probability of detecting the leak (q) with that particular measurement.

$$p' = \frac{p(1-q)}{1-pq}$$

Search algorithm

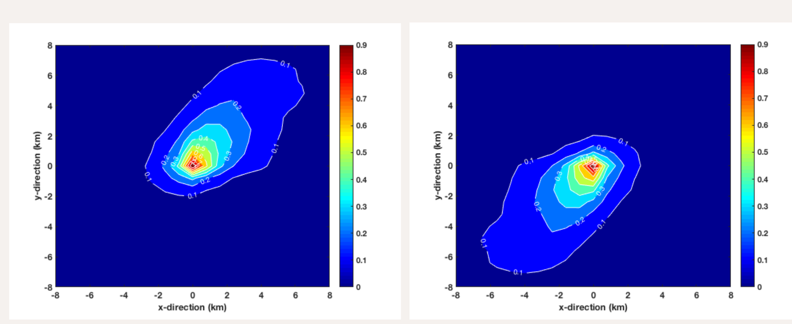
-Create a prior probability field $p(\mathbf{x})$.
-Create the monitored area; $m(\mathbf{r})$.
-while $\Sigma p(\mathbf{x})>p_t$
---Create field; largest likelihood for detection.
-- Choose measurement location.
---Update $p(\mathbf{x})$.
-end while



Time series of CO_2 at the seep location (center) and the eight adjacent grid cells. The red line indicates the detection threshold from Botnen et al. (2015).

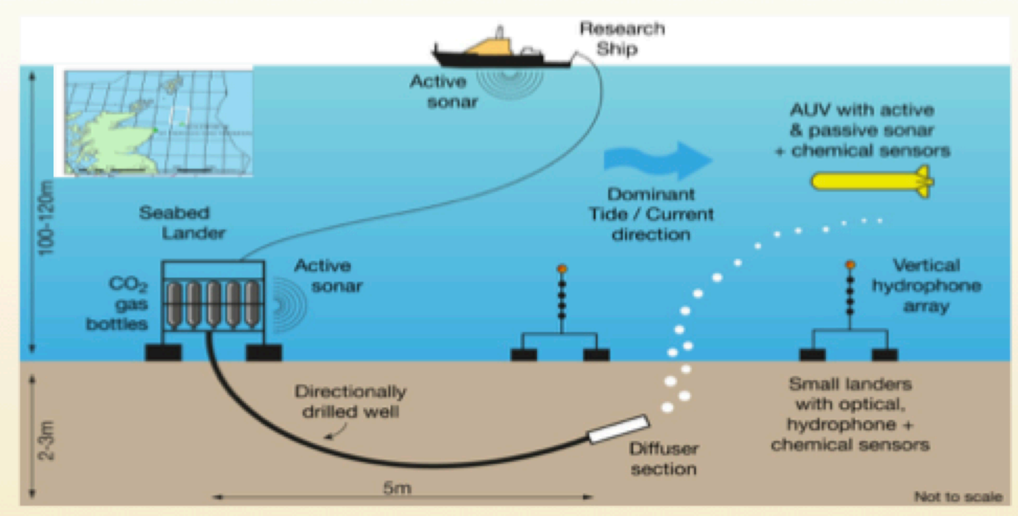
Area measured

Bergen Ocean Model is used to simulate dispersion of CO_2 leaking from locations, focusing on temporal and spatial variability of the CO_2 concentration, (Ali et al. 2015). Time series gives the relative time the CO_2 signal stays above the detection limit of 5 *μmol/kg* (*Botnen et al. 2015*). This gives a field of probabilities for individual measurements to detect a leak some distance away. Inverting this footprint gives rise to the likelihood of detecting a distance seep from a given location.



The predicted footprint (left), i.e. the relative time the CO_2 is above threshold and the resulting monitoring area (right), representing a 180 degree rotation..

Main Experiment - 2019



Schematic of the shallow sub-surface release of CO_2 gas in sediments (< 5 m depth) near Peterhead (Goldeneye) CCS demonstration project. Note that this small-scale release in near-surface sediment does not affect the integrity of the CCS Storage Site.

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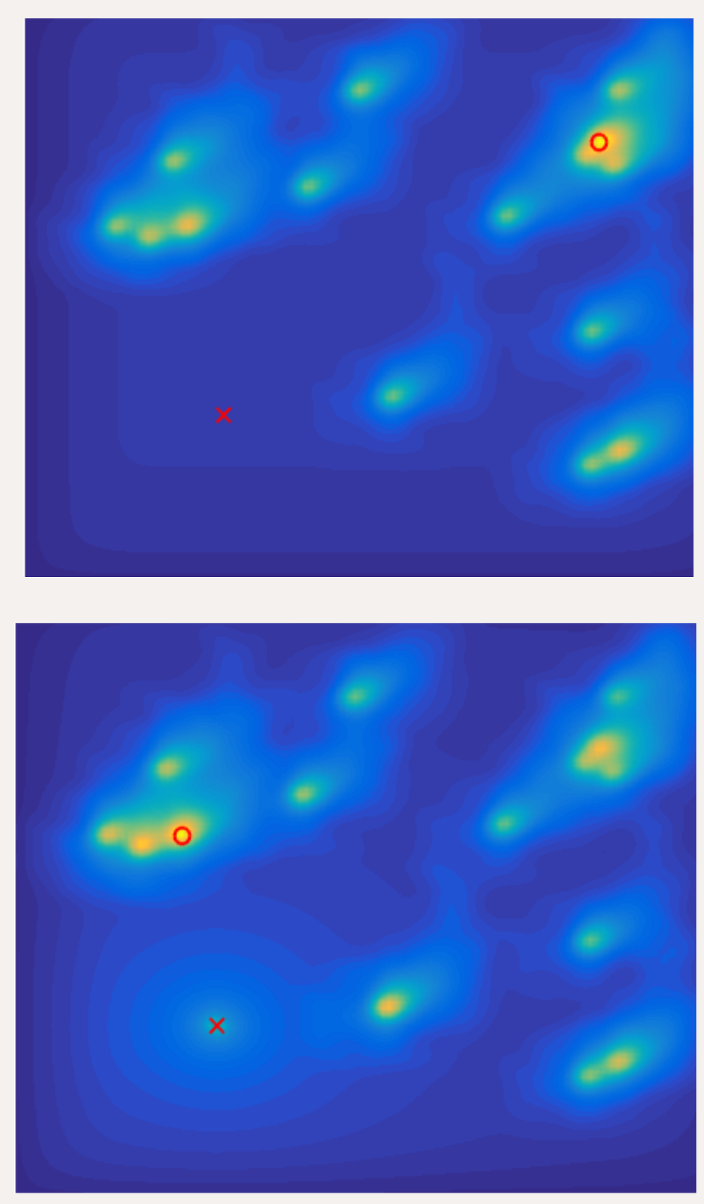
Create a leak detection map

Based on our belief on where a leak most likely will take place, and the monitoring area placed in each location, the likelihood for detecting a leak is summed up. As shown in the upper panel below.



The locations with highest probability for detecting a leak (red circle) for the first measurement when starting at the red cross. ***Upper:*** *The location of the ring is independent of location of the red cross, i.e. it is only dependent on the underlying probability and monitoring fields.* ***Lower:*** *The location ring is dependent on where we start out. When accounting for travel time a location closer by will result in more rapid reduction in probability of a leak.*

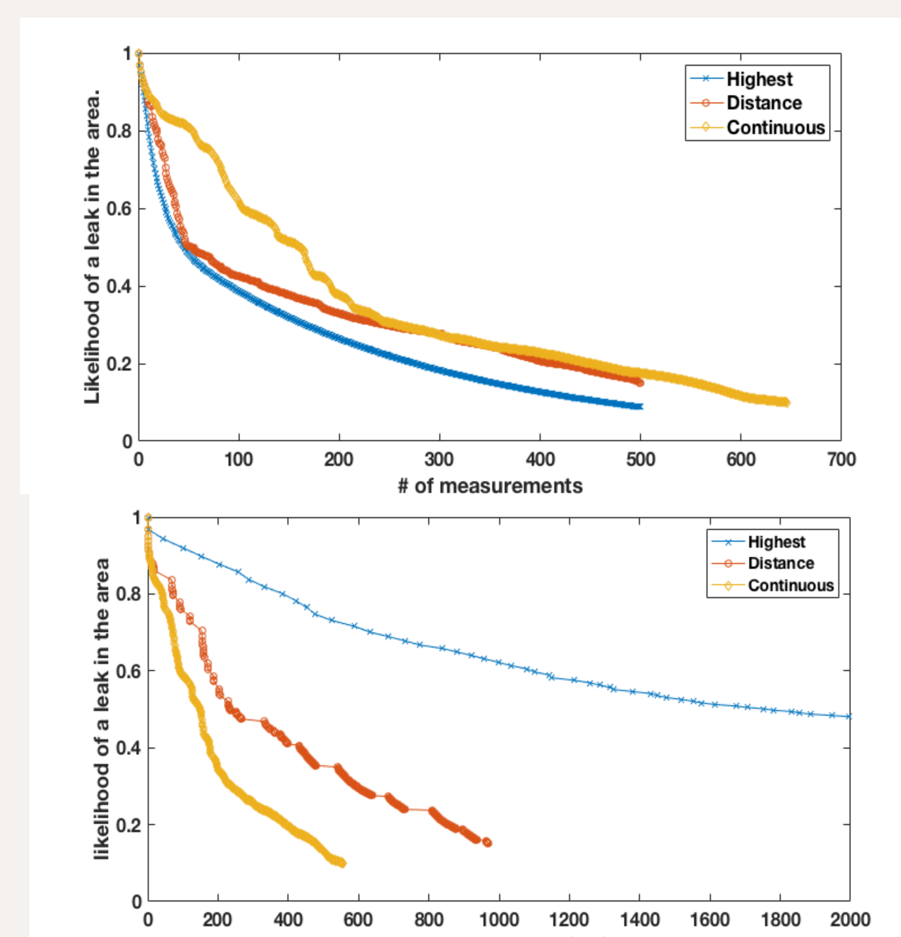
Three strategies

Three different approaches has been used when selecting the next location to measure:

1. Move immediately to the location which will reduce $\Sigma p(\mathbf{x})$ most.*(Highest)*
2. As for 1. but weigh the different locations with inverse of distance from present location. *(Distance)*
3. As for 2. but do continuous measurements while moving toward the target location. *(Continuous)*.

Resulting survey paths

The resulting paths are shown in the figure to the far left. The paths ranges from the randomly looking paths for the *Highest* approach to the orderly path for the *continuous* case. In the *Distance* case the most likely locations are covered first (connected with red lines) thereafter the background areas are covered by more continuous measurements.



*The remaining probability of a leak to be active in the area as function of (**upper**) number of measurements taken and (**lower**) distance traveled.*

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