Mapping Air Pollution eMissions (MAPM): Investigating the effects of instrument uncertainties on Bayesian inverse estimation of urban $PM_{2.5}$ emissions - An Observing System Simulation Experiment approach

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Research objective

The MAPM project is developing a tool that can be used to infer particulate matter (PM) emissions sources on city scale from in situ PM concentration measurements using an inverse modelling framework. Observing System Simulation Experiments (OSSEs) provide a means to inform the design of the PM measurement network such that the network results in optimal inferred emissions maps - for example, one question that can be addressed with an OSSE is "What combinations of low, medium and high quality PM measurements lead to inferred pollution emissions maps with the lowest uncertainties and highest spatial resolutions?". Here we present two sets of OSSEs, conducted for Christchurch New Zealand, to investigate the sensitivity of inferred emissions to measurement uncertainties (**OSSE #1**) and to the number of PM instruments being part of the network (**OSSE #2**).

Experimental design

- The OSSEs were performed by taking output from a Lagrangian particle dispersion model (FLEXPART), driven by a local numerical weather prediction model (WRF) and a 'true' emissions map, to generate 'true' PM concentration time series (referred to as true measurements) at 49 sites over Christchurch (Fig. 1) - both sets of experiments are using the same 'true' emissions and PM concentrations covering the period of 1 to 14 July 2019.
- The true emissions (Fig. 1a) are perturbed to generate prior emissions used by the inversion for all experiments.
- **OSSE #1: different measurement uncertainty characteristics,** associated with two types of instruments (i) ES-642 (lower uncertainty, higher cost about NZ$20,000 each) and (ii) ODIN (higher uncertainty, low cost about NZ$600 each), were used to perturb the true measurements, generating synthetic measurements with an associated measurement uncertainty (Fig. 2).
  - 5 different combinations of the number of the different instruments were explored (Fig. 3).
- **OSSE #2:** synthetic measurements from a subset (e.g. 7, 17, 27, 37 and 47) of the 49 sites using either ES-642s or ODINs were used as input to test the sensitivity of the inverse system on the number of measurement sites.

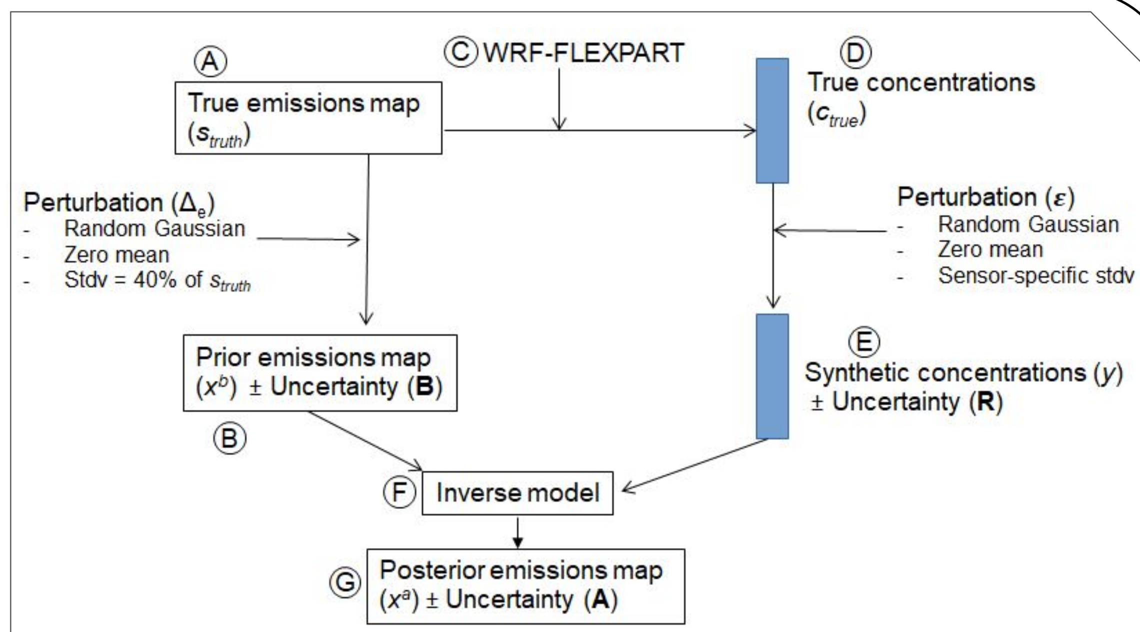

Figure 2. A schematic diagram summarising the set-up of the experiments.

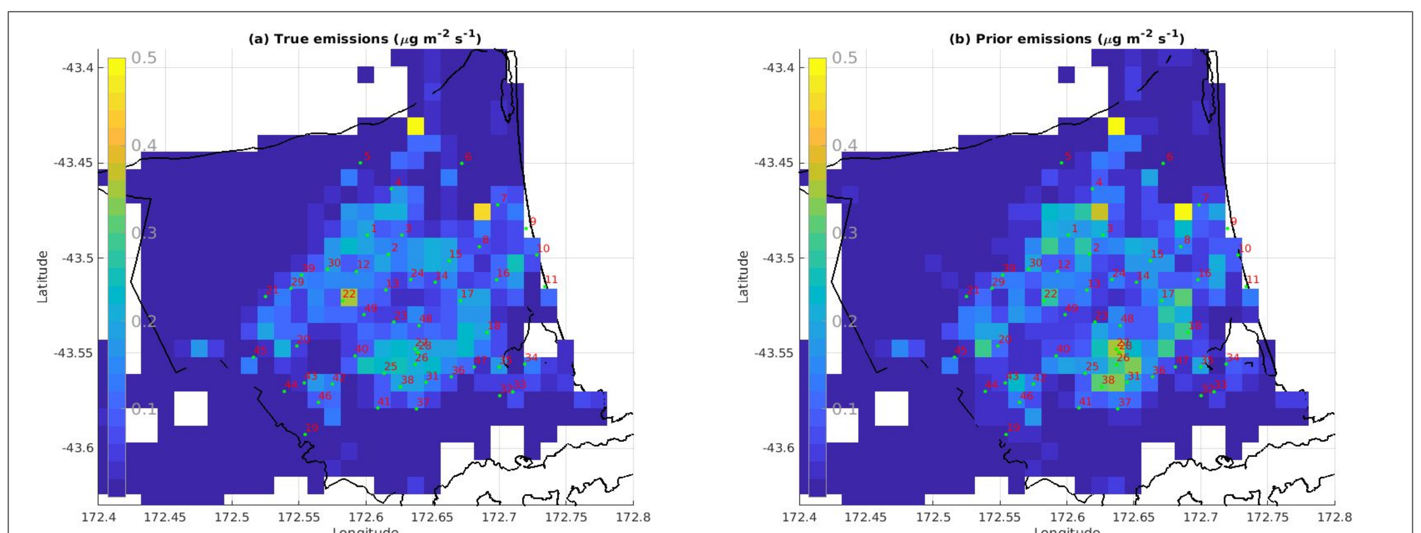

Figure 1. (a) The 'true' daily mean PM emissions for Christchurch and (b) the prior emissions used in the inversion. 49 potential measurement sites are also shown.

The following metrics (following Nathan et al. 2018) were used to quantify the degree of improvement between the true emissions map and the inferred emissions maps:

$$Gain = 1 - \left(\frac{\sum|True\ emissions - Posterior\ emissions|}{\sum|True\ emissions - Prior\ emissions|}\right) \qquad Error\ reduction = \left[1 - \frac{diag(A)}{diag(B)}\right] \times 100\%$$

Where **A** is the posterior covariance matrix that describes the uncertainty in our posterior emissions estimates and **B** the prior covariance matrix, with the prior uncertainty set to be 40% of the true emissions value at each grid cell.

Higher Gain = better emissions estimates after the inversion.
Higher error reduction = reduced uncertainties on the posterior.

Results and key findings

OSSE # 1

Uncertainty characteristics:

- ES-642 instrument have lower bias over a reference instrument (here TEOM) than the ODINs.
- Depending on the PM concentrations the mean bias of the ES-642 varied between -0.5 and -15.7 μg m^{-3}, while for the ODINs, the mean bias varied between -1.6 and 23.8 μg m^{-3}.

Key findings:

- The combination of 47 ES-642s and 2 ODINs results in the best gain and error reduction.
- With such a dense measurement network, however, even using 7 ES-642s and 42 ODINs can already infer the true emissions (within uncertainties).

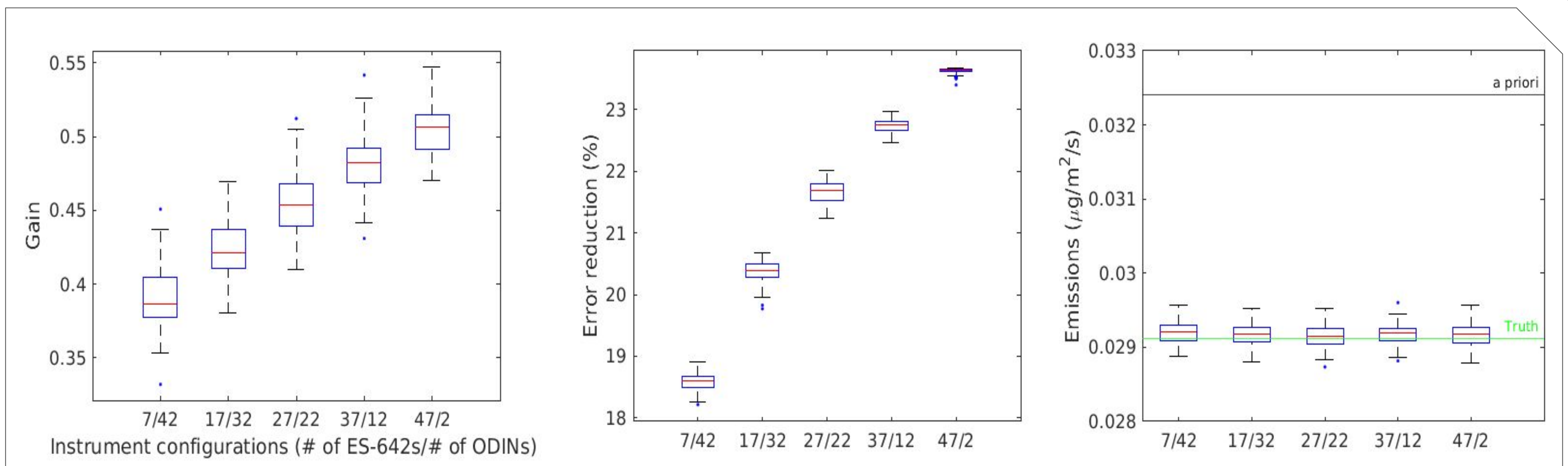

Figure 3. Box-whisker plots summarising (left) gain, (centre) spatial mean error reduction, and (right) spatial mean posterior emissions (excl. grid-cells with zero emissions) estimates using 49 measurement sites with different instrument configurations between the ES-642s and the ODINs. The instruments were randomly located on the 49 potential locations, and the inversion was performed 100 times for each experiment. Median values are represented by the red lines.

OSSE #2

Key findings:

- A dense network of low cost sensors (i.e. 27 ODINs) can improve the overall quality of emissions maps similar to or even better than a sparse network of higher cost sensors (i.e. 7 ES-642s) with much lower deployment cost (NZ$16,200 vs. $140,000), based on both the gain and error reduction values. (Note: assuming sensor mean bias = 0)
- The error reductions are generally good within the area of measurement network and poor outside the area where the emissions are very low (i.e. blue pixels in Figure 5).

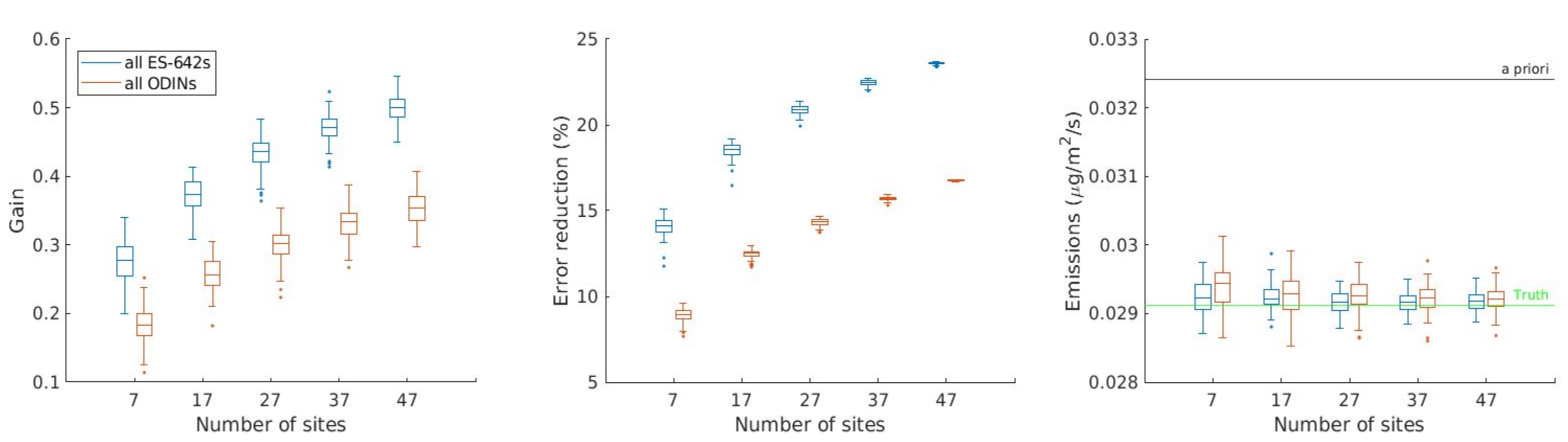

Figure 3. Box-whisker plots summarising (left) gain, (centre) spatial mean error reduction, and (right) spatial mean posterior emissions estimates using 7, 17, 27, 37 and 47 of the 49 sites with all ES-642s (blue) or all ODINs (red) instruments. The site locations were selected randomly out of 49 potential locations, and the inversion was done 100 times, respectively. Zero emission pixels were ignored for the calculations.

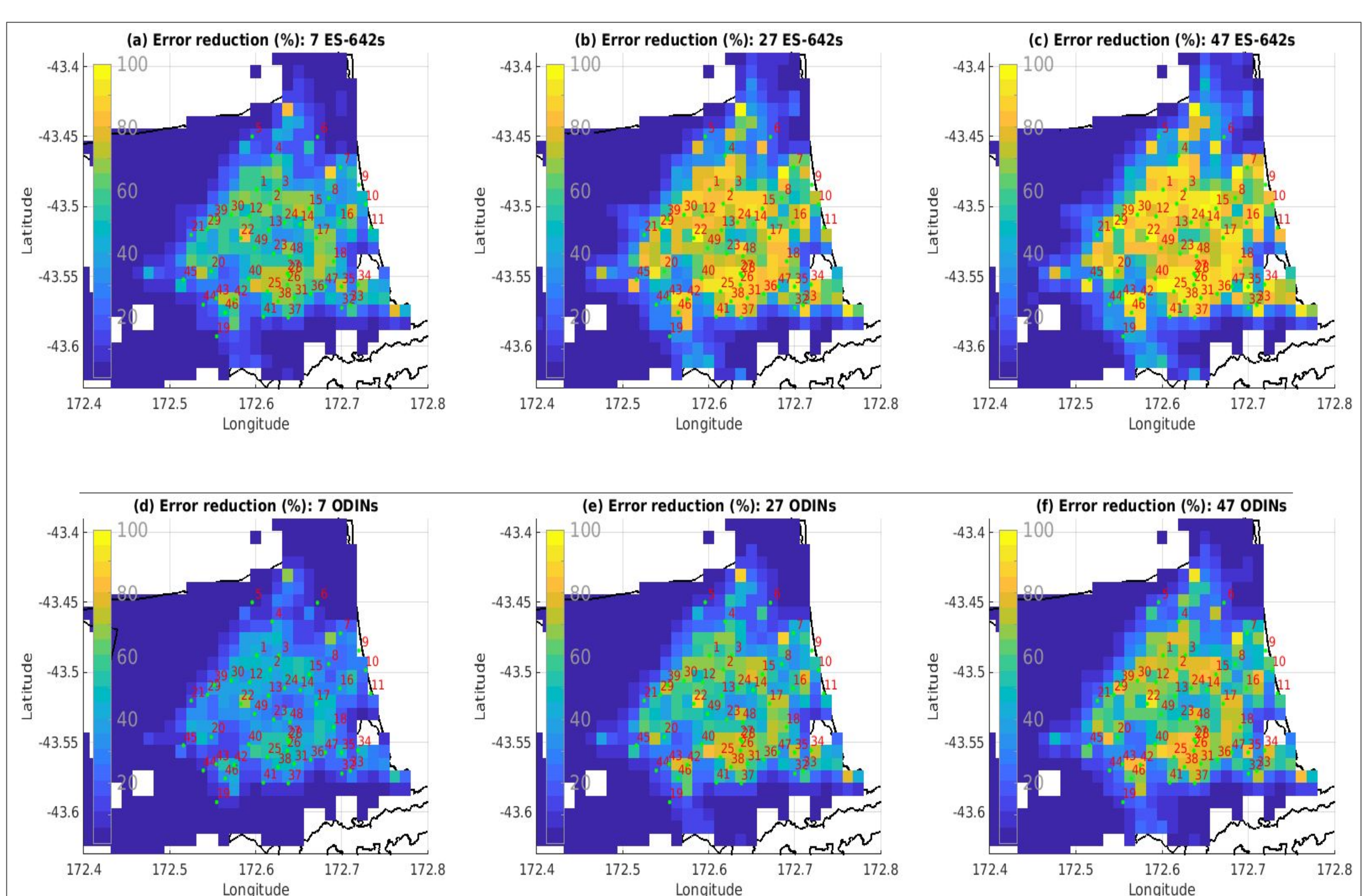

Figure 5. Mean error reduction maps using (left) 7, (centre) 27, and (right) 47 measurement sites with (top) ES-642s and (bottom) ODINs. The site locations were selected randomly out of 49 potential locations, and the inversion was done 100 times, respectively.

Conclusion

- Although a dense network of low cost sensors (27 ODINs) can improve the overall quality of emissions maps better than a sparse network of higher cost sensors with much lower deployment cost, the low cost sensors may require more maintenance cost and more frequent sensor calibrations (Bulot et al. 2019).
- Future work will investigate the sensitivity of the inversion system to (i) different meteorological conditions, and (ii) different true and prior emissions maps.

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MINISTRY OF BUSINESS, INNOVATION & EMPLOYMENT
HIKINA WHAKATUTUKI

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