Using satellite data assimilation techniques to exploit infrasound measurements

Javier Amezcua (University of Reading, Tec de Monterrey)

NCEO/DARC training course
Applications lecture

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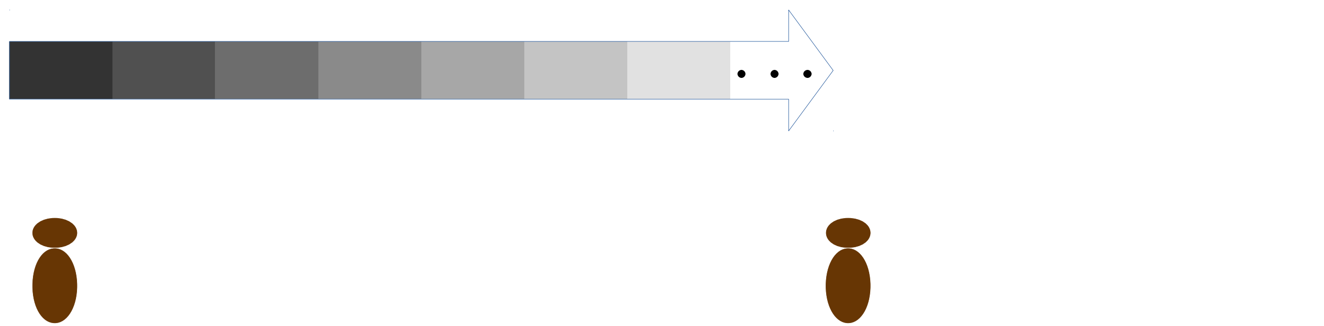
Data Assimilation Research Centre

University of Reading

(Infra)sound paths

Sound propagation

Sound waves propagate away from the source. They can find **obstacles,** and/or suffer **attenuation** in a medium.



I can hear the music

I can't hear the music

$$\text{attenuation} \propto \text{frequency}^{\alpha}$$

Finding paths

I can actually hear the music!

Finding paths

I can actually hear the music!

Don’t forget other directions.

The ARISE project (infrasound)

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European Commission

THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION

HORIZON 2020

ARISE Project

The ARISE2 project is a collaborative infrastructure Design Study project (2015-2018) funded by the H2020 European Commission. It includes 24 institutes and universities, belonging to 10 European member states, 3 associated countries, 1 international organization and 3 African countries.

> more on the Arise European project

Technologies

Infrasound IMS network and European infrasound network (atmospheric waves and inversions in the stratosphere).
LIDAR of the NDACC network (stratospheric wind and temperature).
The project will also use complementary stations including **radars, wind radiometers and ionospheric sounders. It also use satellite observations.**

> more about technologies

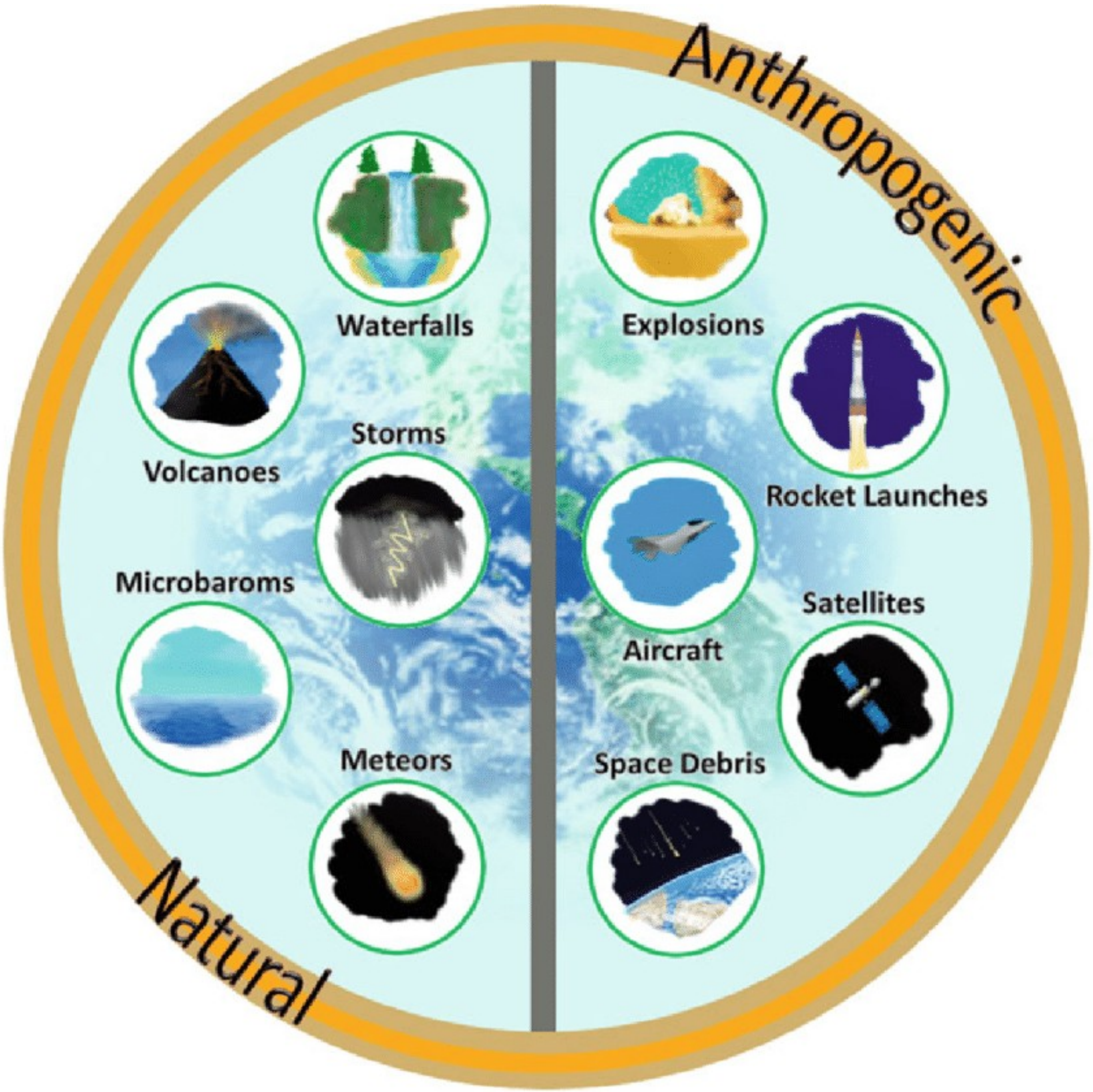
Highlights

ARISE meetings

Thanks to the ARISE support by the French MRSEI ANR program, the following ARISE meetings were organized to ensure the project continuation:

- January 24-25, 2019 : Paris (France), organized by Versailles University (UVSQ) and CEA
- April 10, 2019 Vienna (Austria) during the EGU2019 meeting
- June 5-6, 2019 Budapest (Hungaria) organized by CSFK
- September 10-11 Paris (France) organized by

Infrasound



0.1-1 Hz

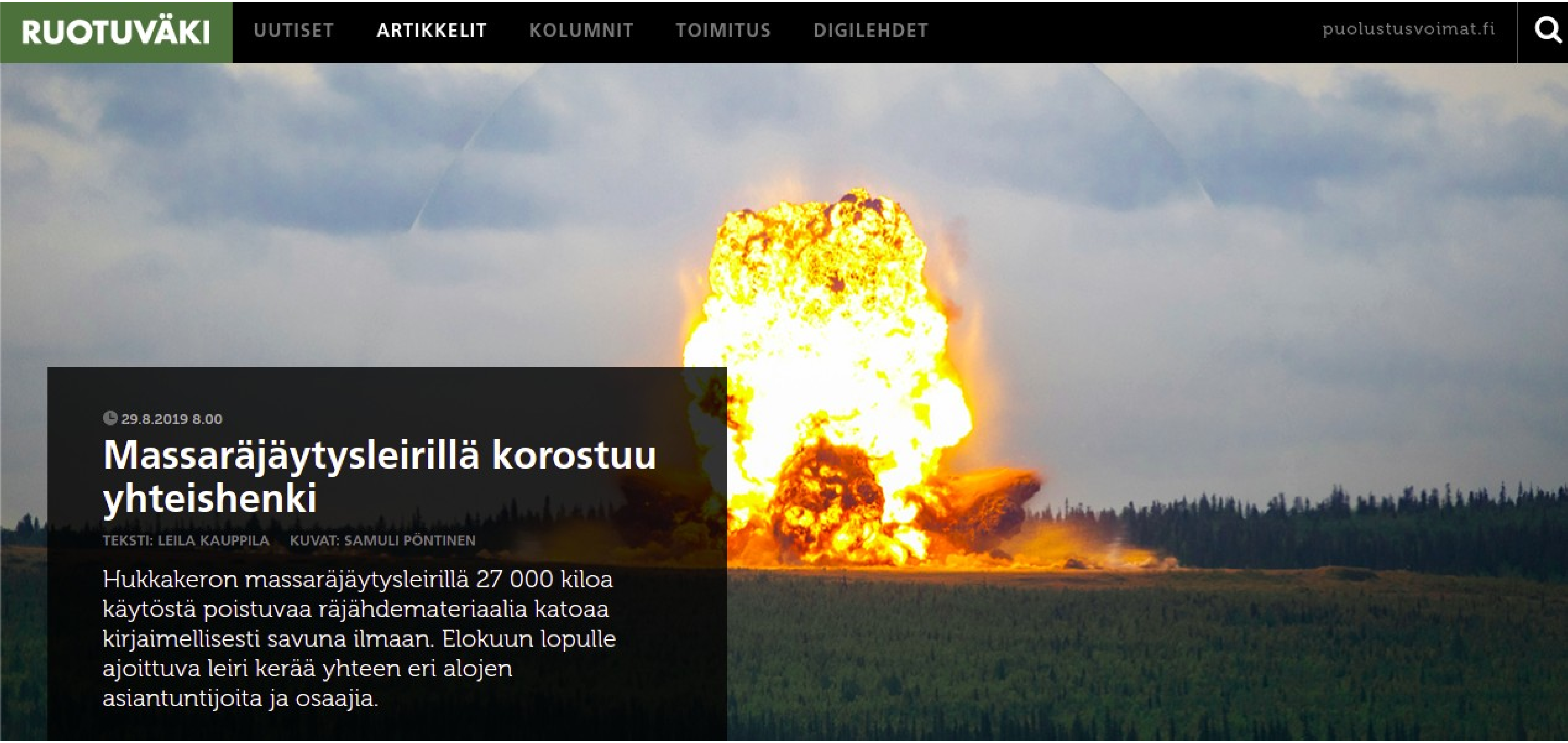
It can travel long distances.

$$\text{attenuation} \propto \text{frequency}^{\alpha}$$

It is affected as it travels through an atmospheric slab.

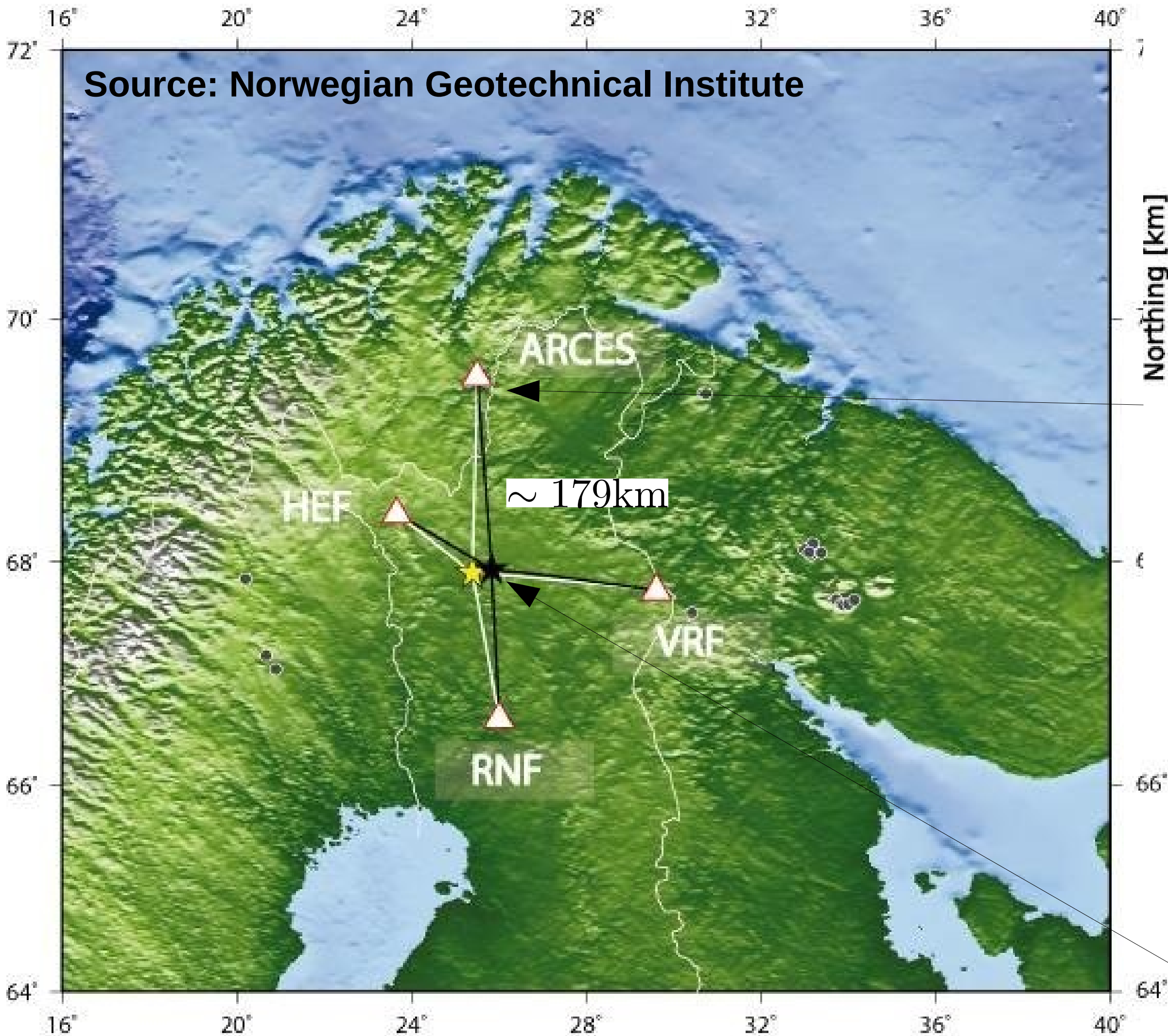
From Silver and Brown (2019)

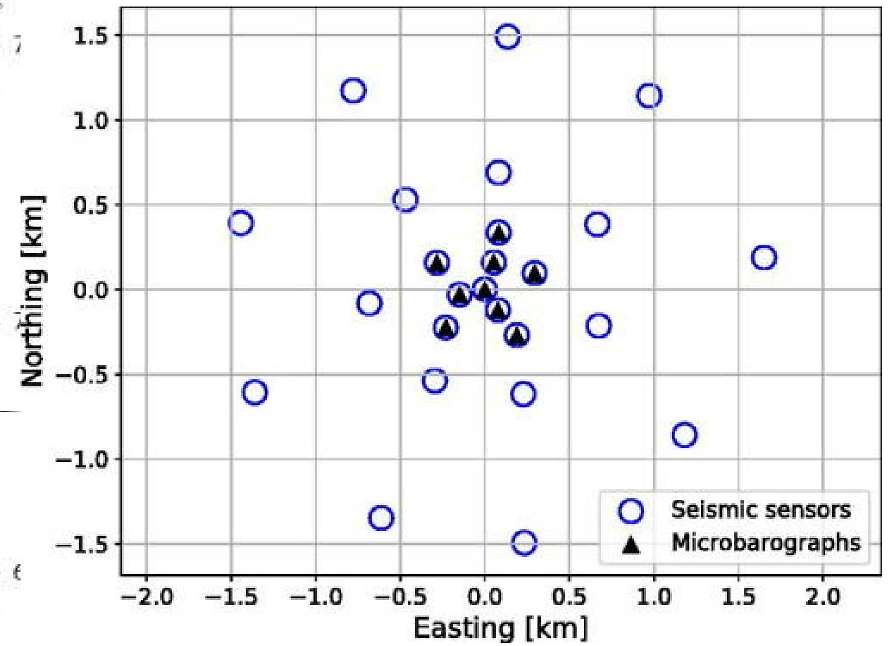
Sources of infrasound waves



Finland’s summer pastime is to detonate excess ammunition in the summer.

Ammunition explosions in Finland

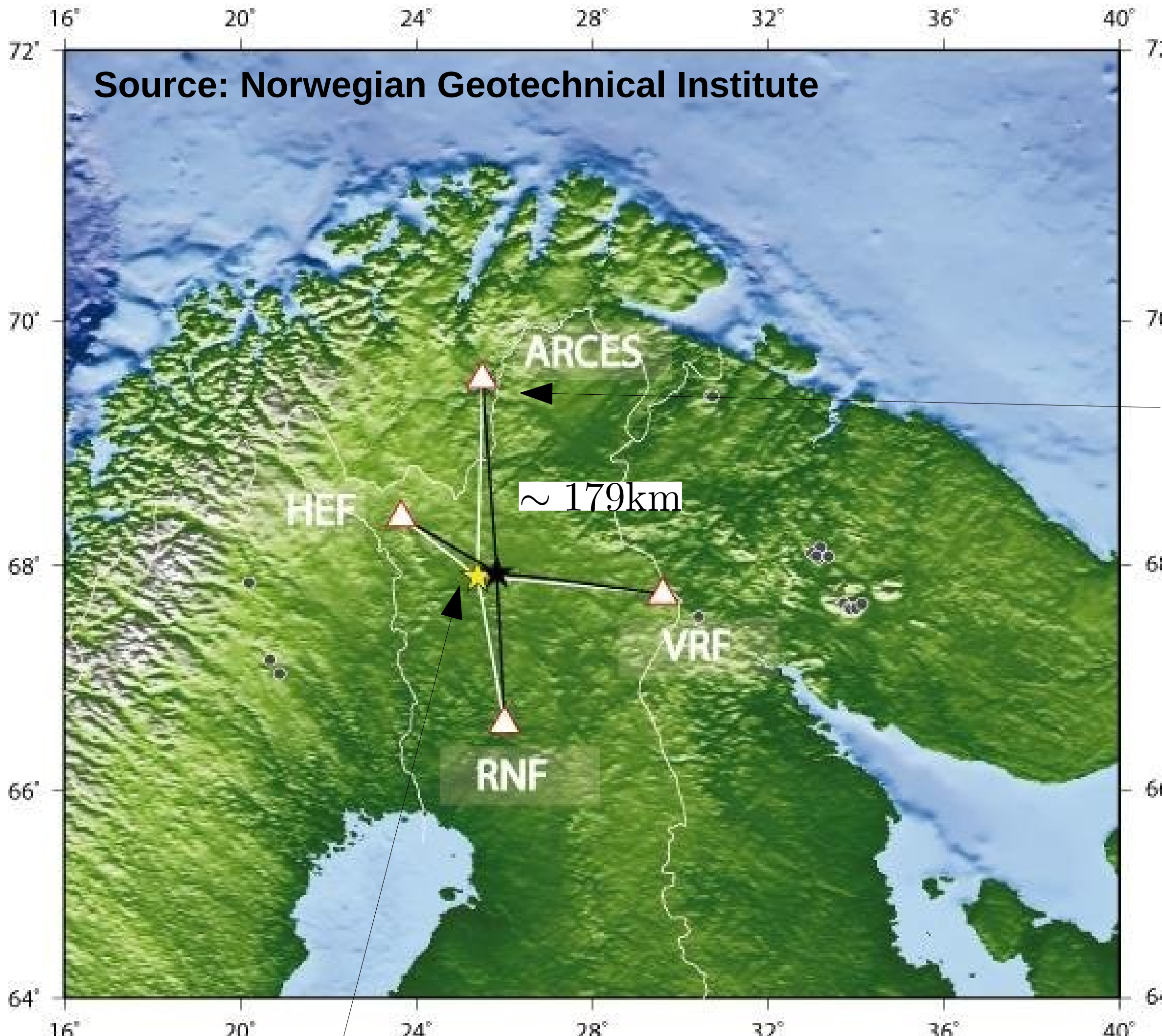




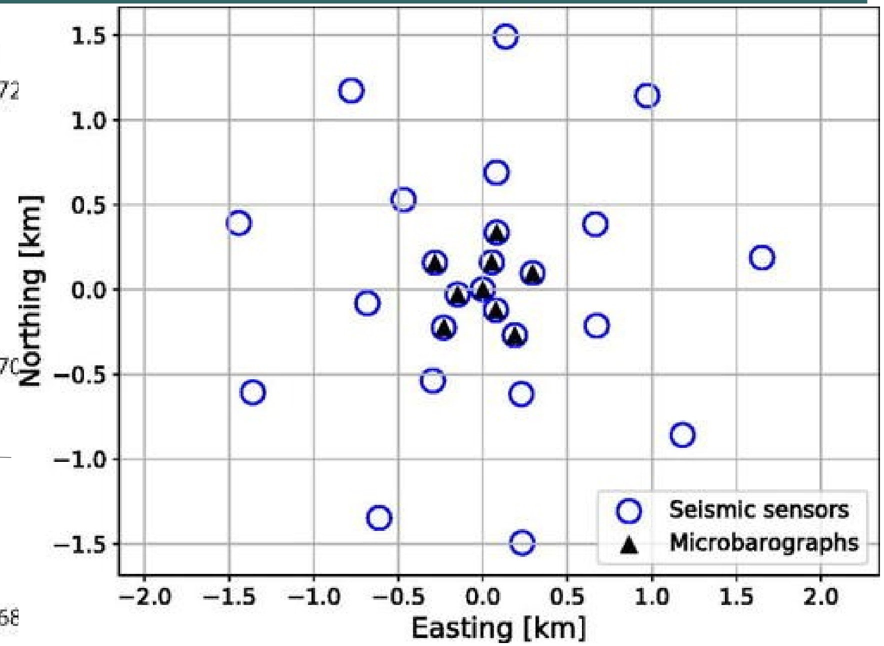
From Blixt et al 2019.

Hukkakero

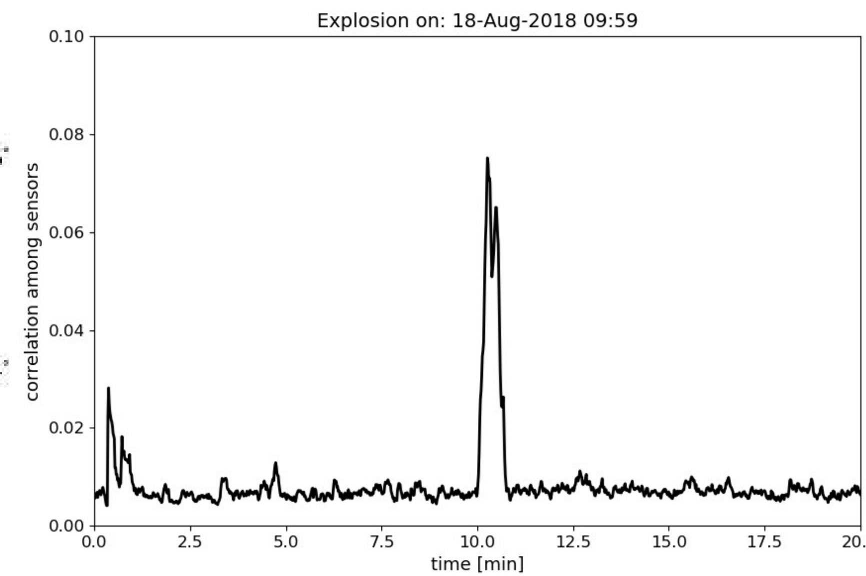
Ammunition explosions in Finland



Hukkakero



From Blixt et al 2019.



The data assimilation process

Data Assimilation

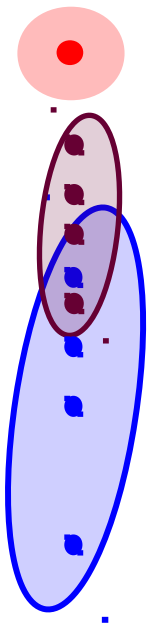
DA is the process of **combining information** from different sources in an **optimal** way. Generally, these sources are **models** and **observations**.

This has the aim of getting a **better estimate** of the state of a **system**.

Optimal includes –among other things- to **consider the uncertainty** (or conversely, the precision) of the sources.

Analysis step in Kalman methods

The KF is a particular case of **Bayesian estimation**, based on the first **two statistical moments**.



Innovation (coming from obs)

$$\bar{\mathbf{x}}^a = \bar{\mathbf{x}}^b + \mathbf{K}\left(\mathbf{y} - h\left(\bar{\mathbf{x}}^b\right)\right)$$

background

Gain (weigths and spreads information)

Observation operator

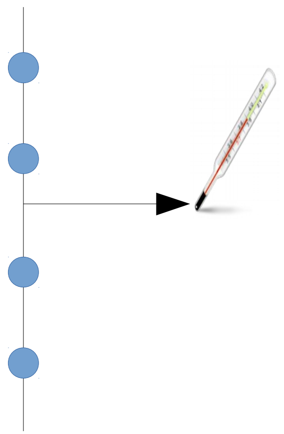
$\mathbf{K}$ contains information about the background error covariance $\mathbf{B}$

This simple **linear equation** is **optimal** in the presence of **Gaussian errors** and **linear operators**. Otherwise it can still be useful, but it can need extra steps (e.g. linearisations and iterations).

Examples with different observational settings

How to observe?

Radiosonde



h: interpolator

Direct observations are the easiest.

Location of observation and grid points may not be the same. May need **interpolation**.

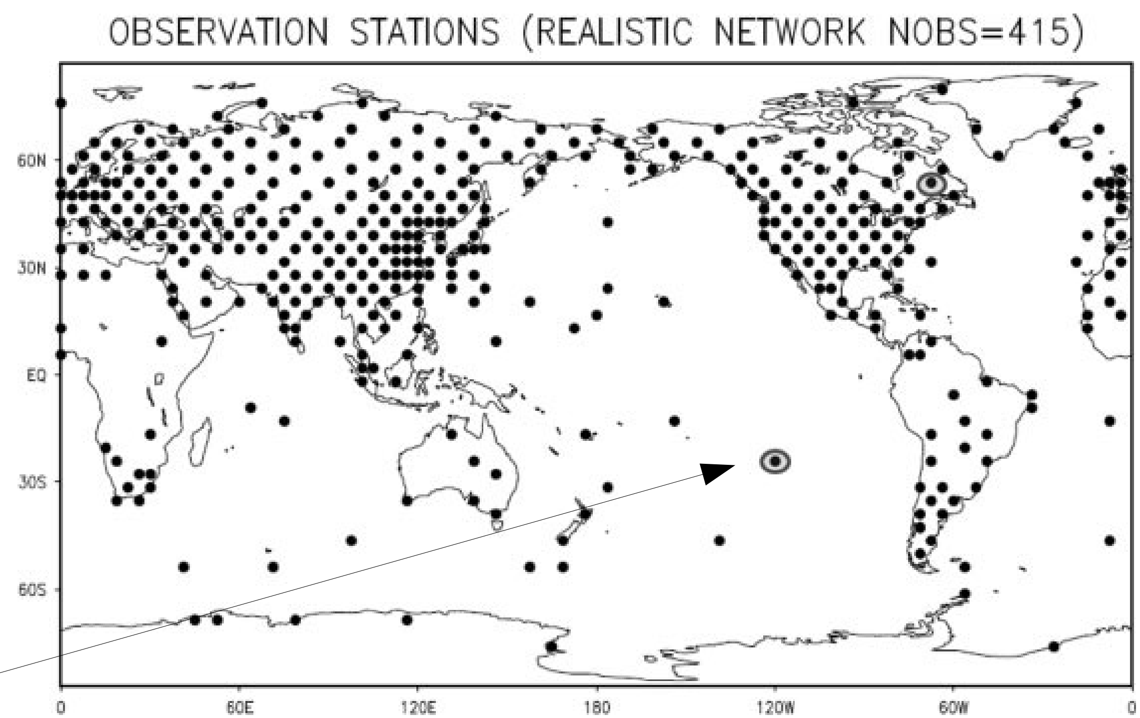
The **information** is spread through **covariances**.

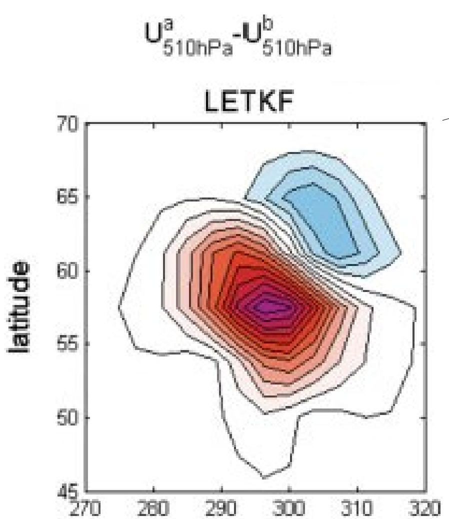
A simple DA process

Background: atmospheric variables on a lat-lon grid.

Observation: radiosonde measuring a variable at a given height.

Analysis: updated atmospheric variables on a lat-lon grid.





Analysis increment for zonal wind in the middle atmosphere. Red is positive, blue is negative.

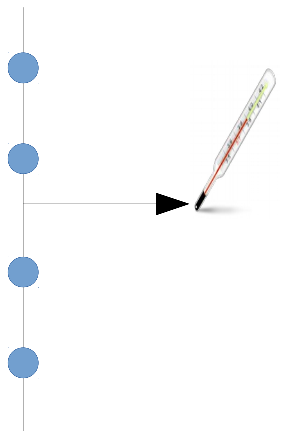
The **quality of the background covariance is vital**.

For **small ensembles** may need to **artificially ignore long-distance correlations**.

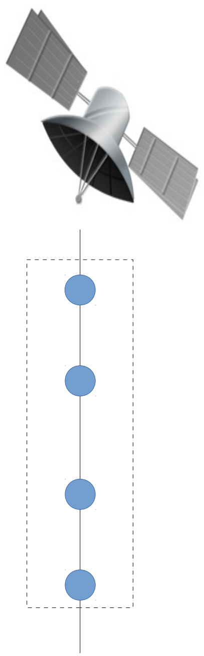
Figures from Amezcua et al, 2013.

How to observe?

Radiosonde



h: interpolator

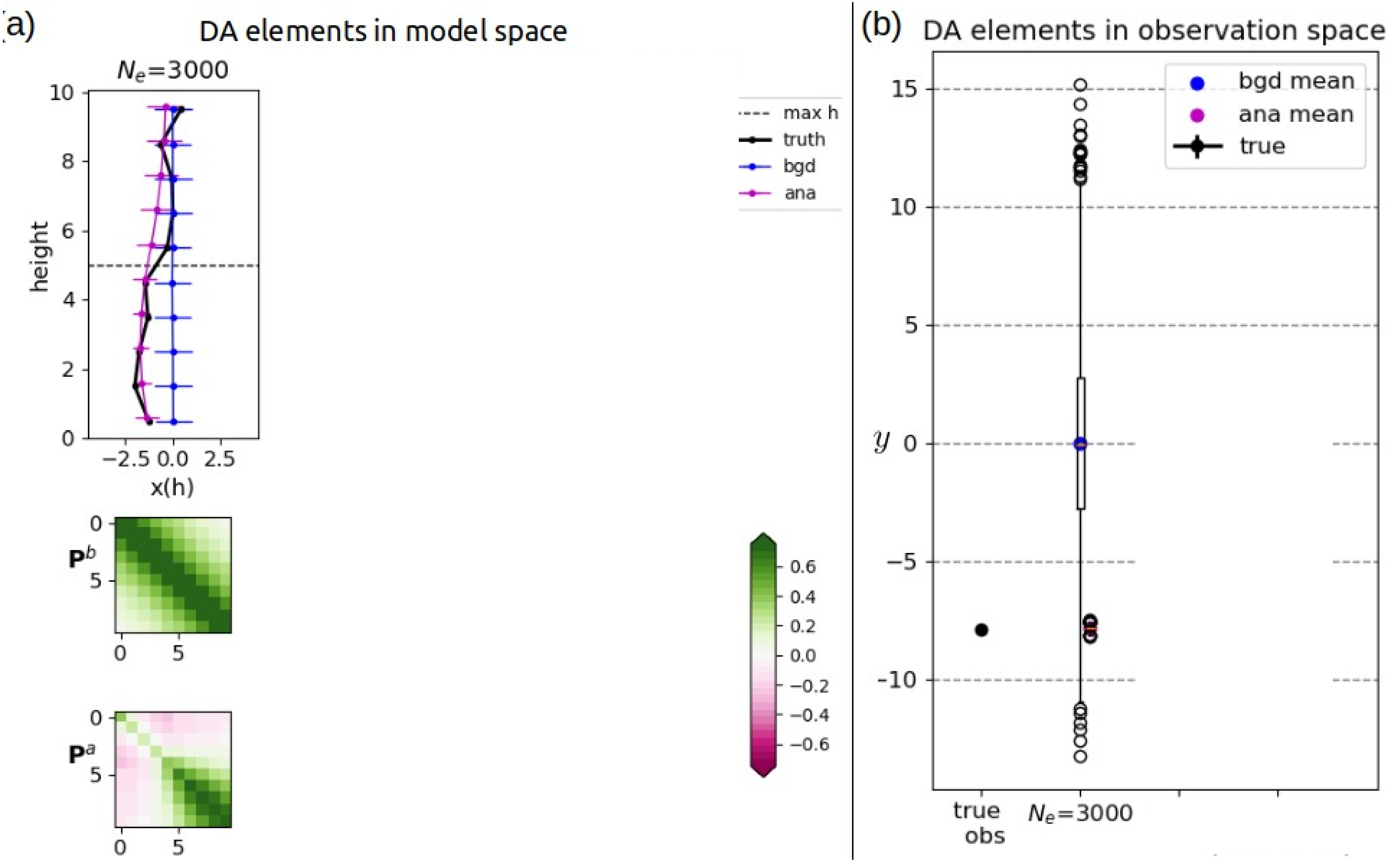


h: radiative transfer model

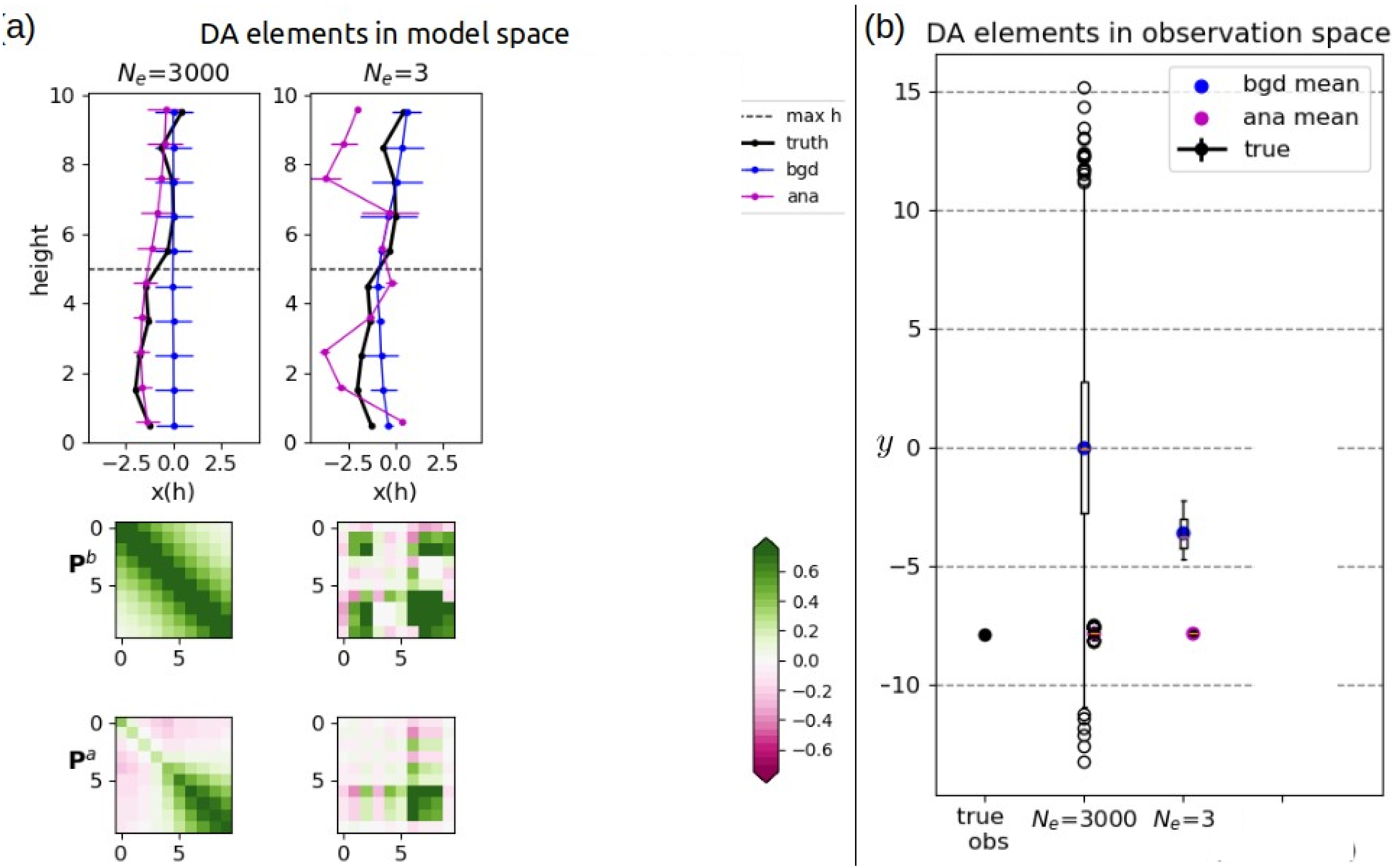
With integrated observations, it is more **difficult to ‘clean’ the background covariance**. How can we define ‘distances’ between variables and observations?

We exploit the techniques coming from **satellite data assimilation**. In particular the **Modulated Ensemble Kalman Filter** (Bishop and Hodyss, 2017).

Simple example: observation is the sum of lower layers



Simple example: observation is the sum of lower layers



Cleaning covariances with integrated observations

Article Type: Research Article

Vertical Covariance Localization for Satellite Radiances in Ensemble Kalman Filters

William F. Campbell[1], Craig H. Bishop[1], and Daniel Hody...

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Print Publication: 01 Jan 2010

DOI: https://doi.org/10.1175/2009MWR3017.1

Page(s): 282 – 290

Article Type: Research Article

Gain Form of the Ensemble Transform Kalman Filter and Its Relevance to Satellite Data Assimilation with Model Space Ensemble Covariance Localization

Craig H. Bishop[1], Jeffrey S. Whitaker[2], and Lili Lei[3]

View More +

Print Publication: 01 Nov 2017

DOI: https://doi.org/10.1175/MWR-D-17-0102.1

Small ensemble sizes

When using few ensemble members, we need **localisation**.

When using the geometric model, we could directly use **model space localisation.** For products, we **had the TLM**.

$$\mathbf{P}_{loc} = \mathbf{P} \circ \mathbf{L}_{model} \qquad \mathbf{P}_{loc}\mathcal{H}^\top = (\mathbf{P} \circ \mathbf{L}_{model})\,\mathcal{H}^\top$$

Directly applying localisation in observation space is not easy. No natural distances!

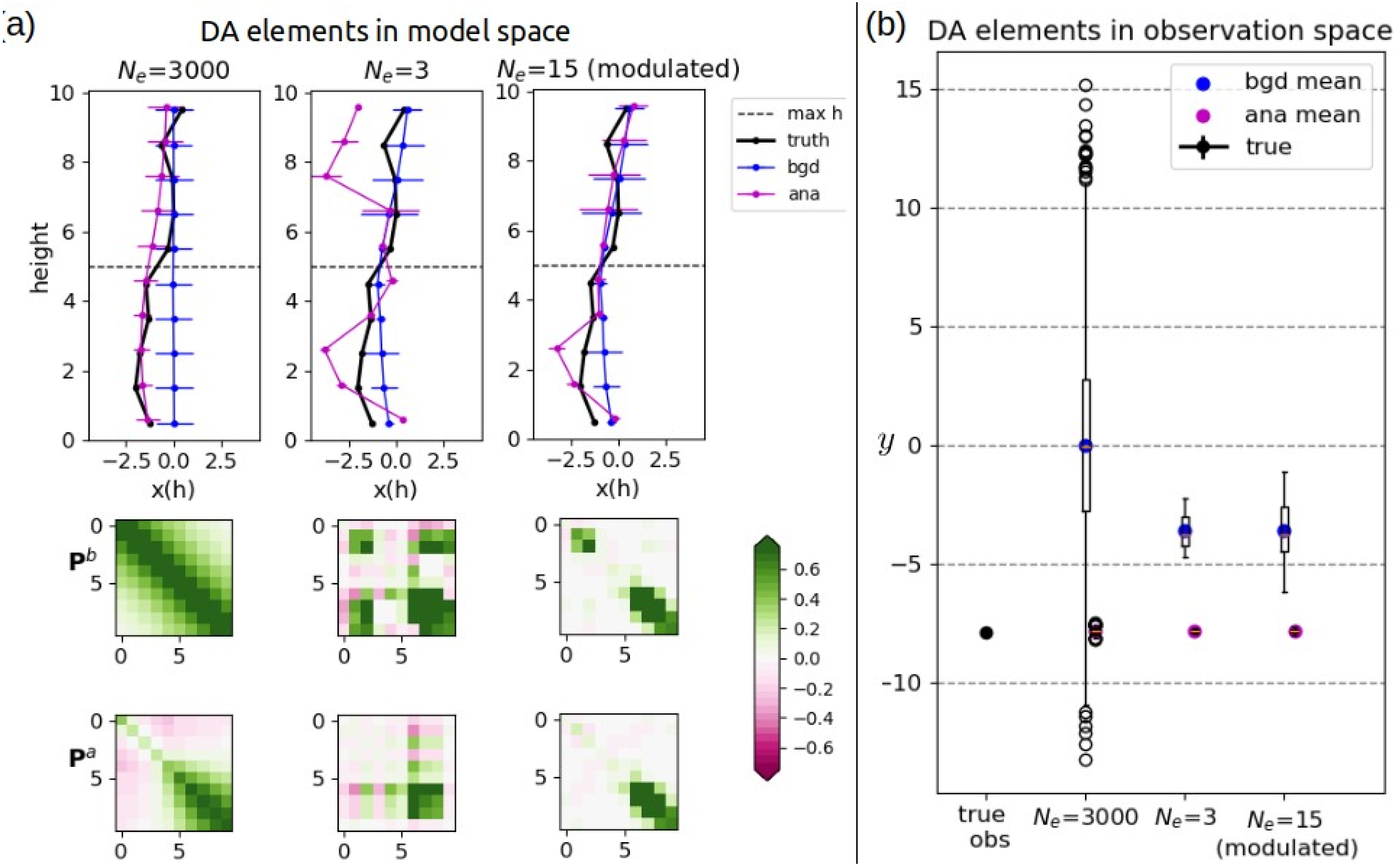
$$\left(\hat{\mathbf{X}}^b \hat{\mathbf{Y}}^{b\top}\right) \circ \mathbf{L}_{mixed} \qquad \left(\hat{\mathbf{Y}}^b \hat{\mathbf{Y}}^{b\top}\right) \circ \mathbf{L}_{obs}$$

In this case I use the Modulated ETKF (Bishop et al, 2017) which uses a **modulated ensemble**.

$$\mathbf{X}^b : \quad \bar{\mathbf{x}}^b, \hat{\mathbf{X}}^b$$

$$\hat{\mathrm{U}}^b = \left[\left(\mathbf{l}_1^{\frac{1}{2}} \circ \hat{\mathbf{x}}_1^b, \cdots, \mathbf{l}_1^{\frac{1}{2}} \circ \hat{\mathbf{x}}_{N_e}^b\right), \left(\mathbf{l}_2^{\frac{1}{2}} \circ \hat{\mathbf{x}}_1^b, \cdots, \mathbf{l}_2^{\frac{1}{2}} \circ \hat{\mathbf{x}}_{N_e}^b\right), \cdots, \left(\mathbf{l}_{N_\lambda}^{\frac{1}{2}} \circ \hat{\mathbf{x}}_1^b, \cdots, \mathbf{l}_{N_\lambda}^{\frac{1}{2}} \circ \hat{\mathbf{x}}_{N_e}^b\right)\right]$$

Modulated ETKF removes sampling errors

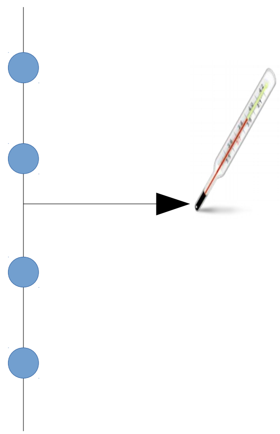


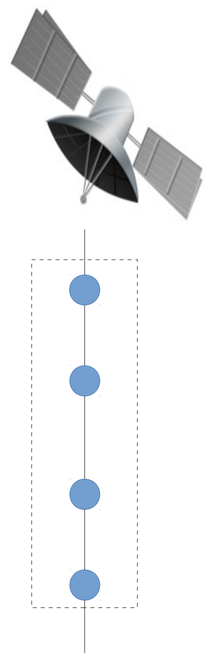
Doing DA with infrasound observations

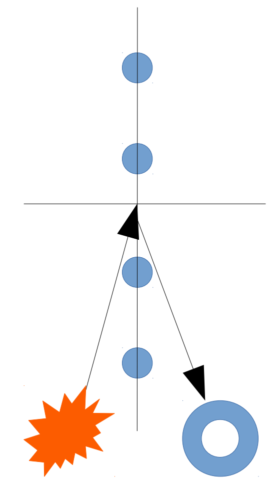
Infrasound observations

Radiosonde

Infrasound







h: interpolator

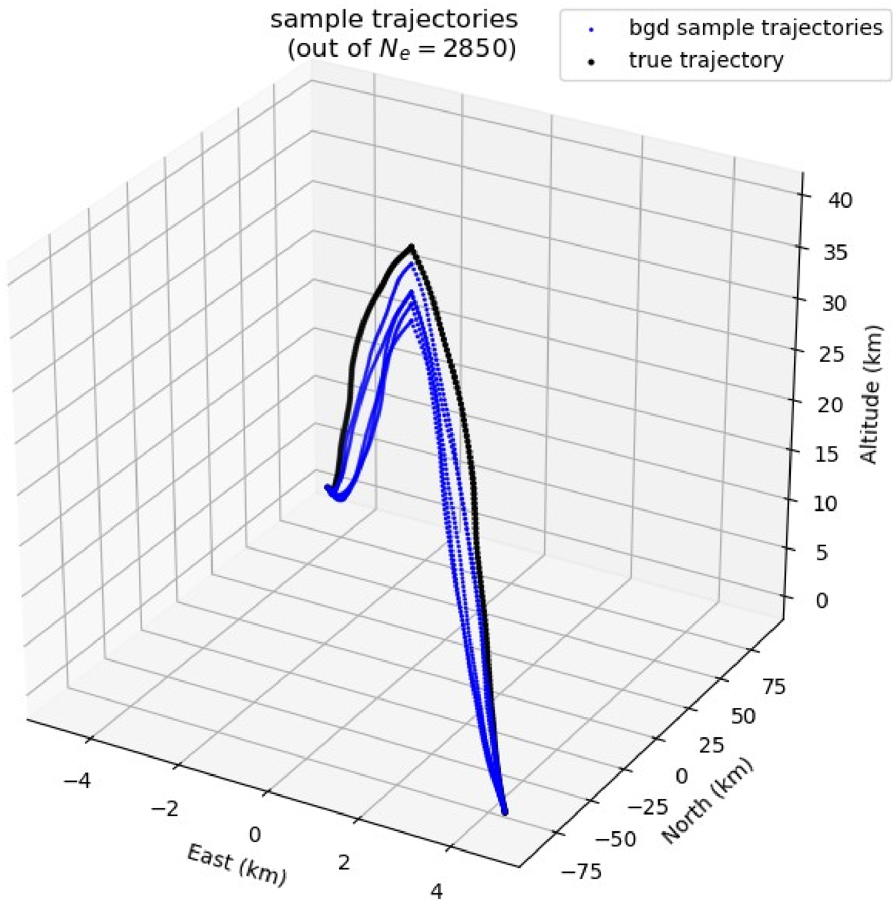
h: radiative transfer model

h: ray tracing model

Infrasound observations are not too different from satellite observations.

Differences: the trajectory is more complicated, the speed of sound is slower than the speed of light.

Our problem



State variables **Observations**

$$\mathbf{x} = \begin{bmatrix} \mathbf{u}(r,z,t) \\ \mathbf{v}(r,z,t) \\ \mathbf{T}(r,z,t) \\ Z_{max} \end{bmatrix} \quad \mathbf{y} = \begin{bmatrix} \delta_{ba} \\ t_{travel} \\ v_{app} \end{bmatrix}$$

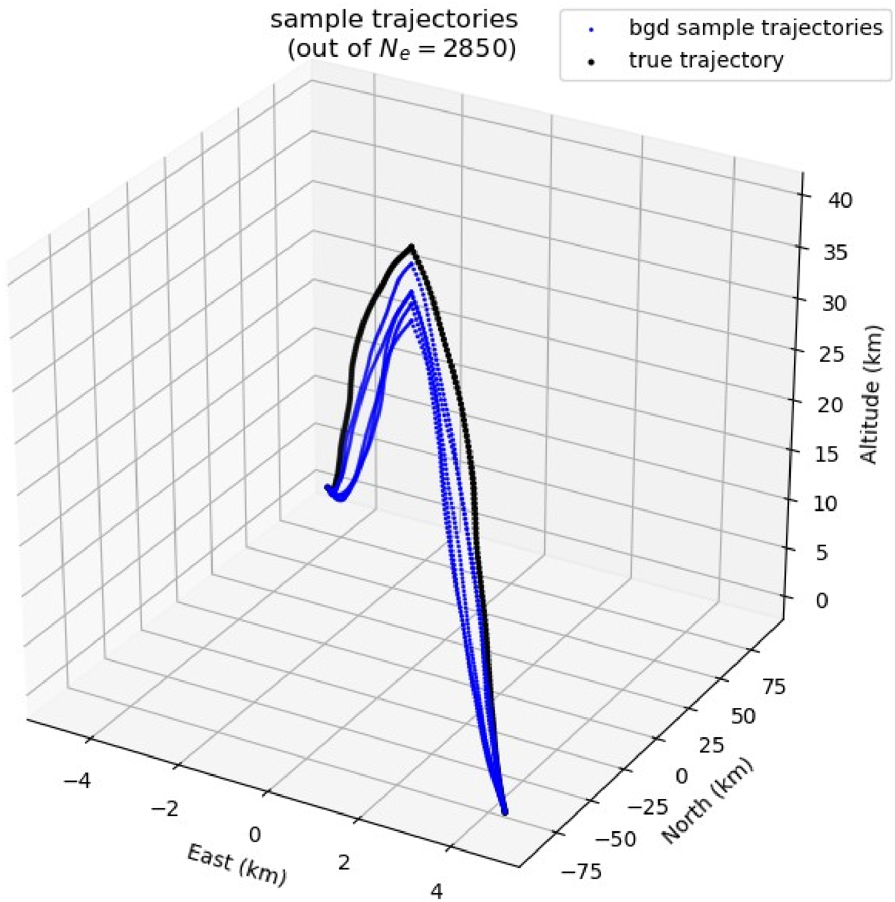
The exact problem is quite difficult.

We try to infer fields from three scalars.

The small scale features causing reflections are not well resolved in models.

We need simplifications.

Simplified



State variables **Observations**

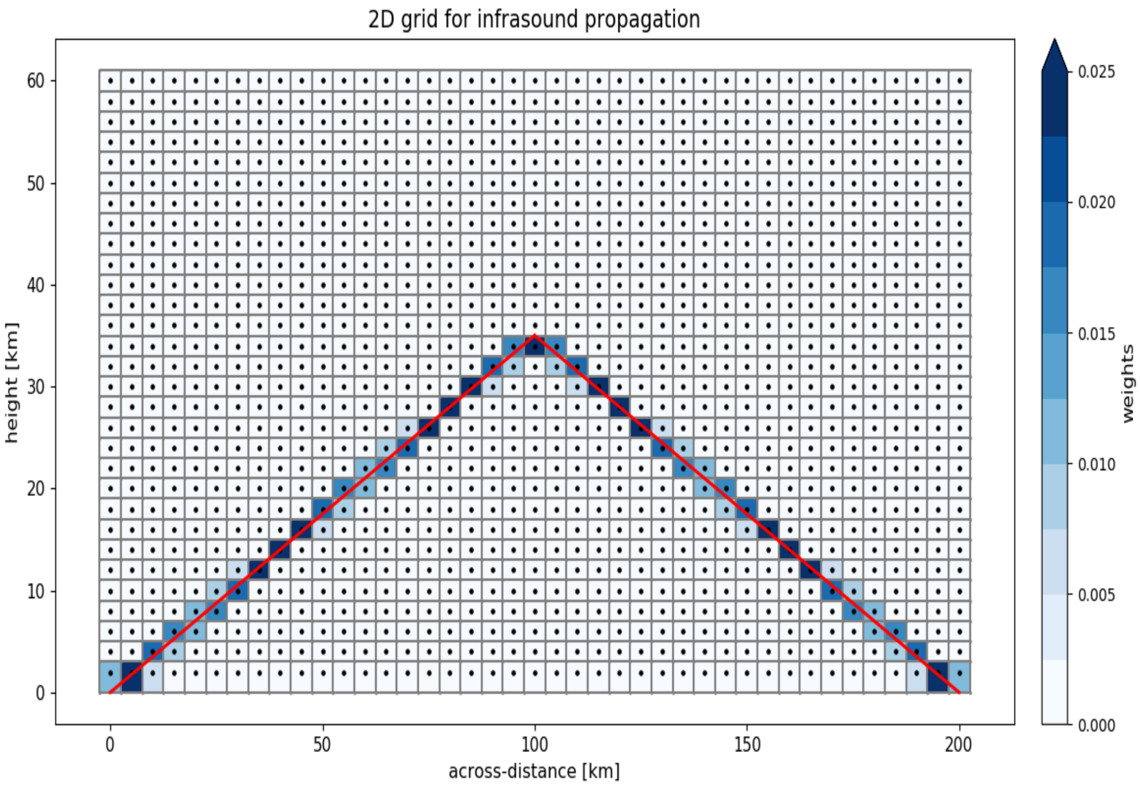
$$\mathbf{x} = \begin{bmatrix} \mathbf{u}(z) \\ \mathbf{v}(z) \\ \mathbf{T}(z) \\ Z_{max} \end{bmatrix} \qquad \mathbf{y} = \begin{bmatrix} \delta_{ba} \\ t_{travel} \\ v_{app} \end{bmatrix}$$

<u>Approximations:</u>

– Distance ~180 km, travel time ~10 min, so the **atmospheric fields are considered static while the wave travels**.

– Consider only **height dependence**.

Side note



State variables **Observations**

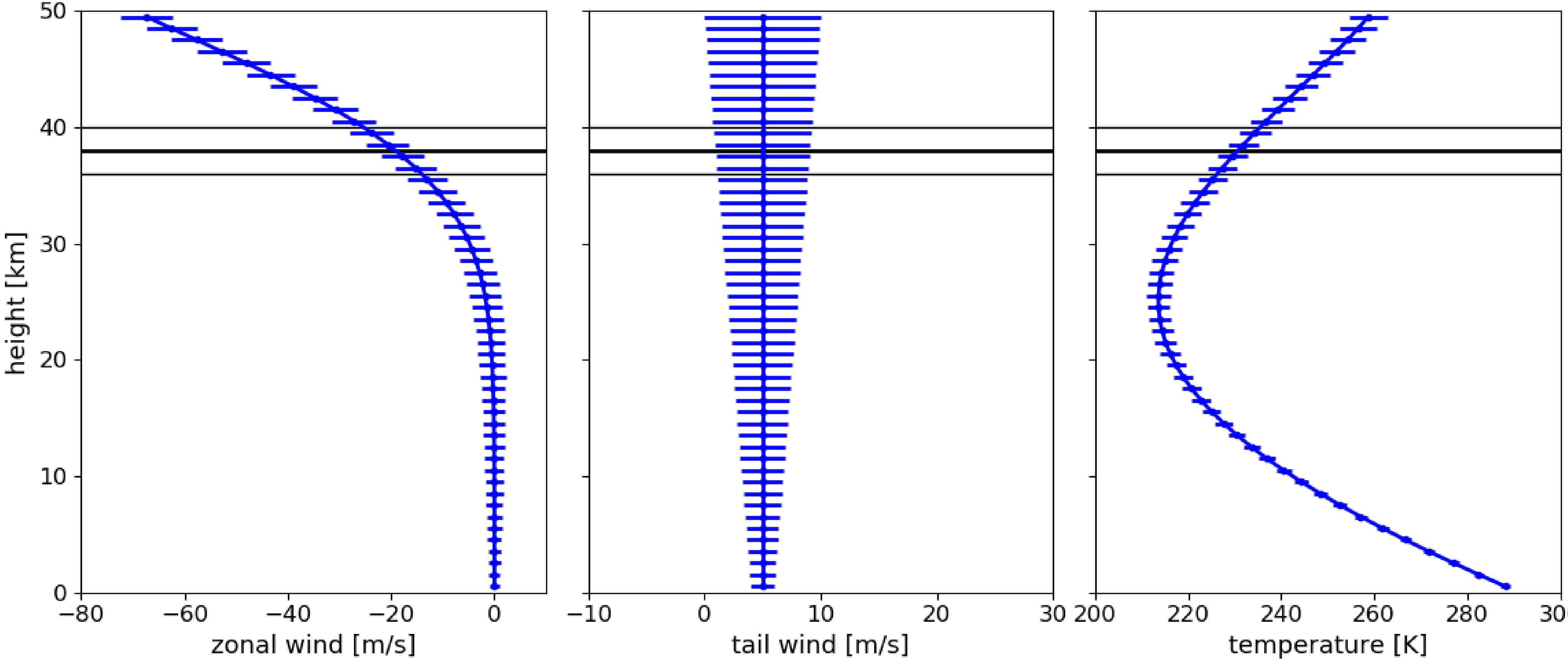
$$\mathbf{x} = \left[\mathbf{u}(x, z)\right] \qquad \mathbf{y} = \left[\delta_{ba}\right]$$

Consider height and along-track dependence.

In the past we did 2D problems with a **simple geometric model** (Blixt et al, 2019) with 1 field and 1 observation.

The reflection height was considered given.

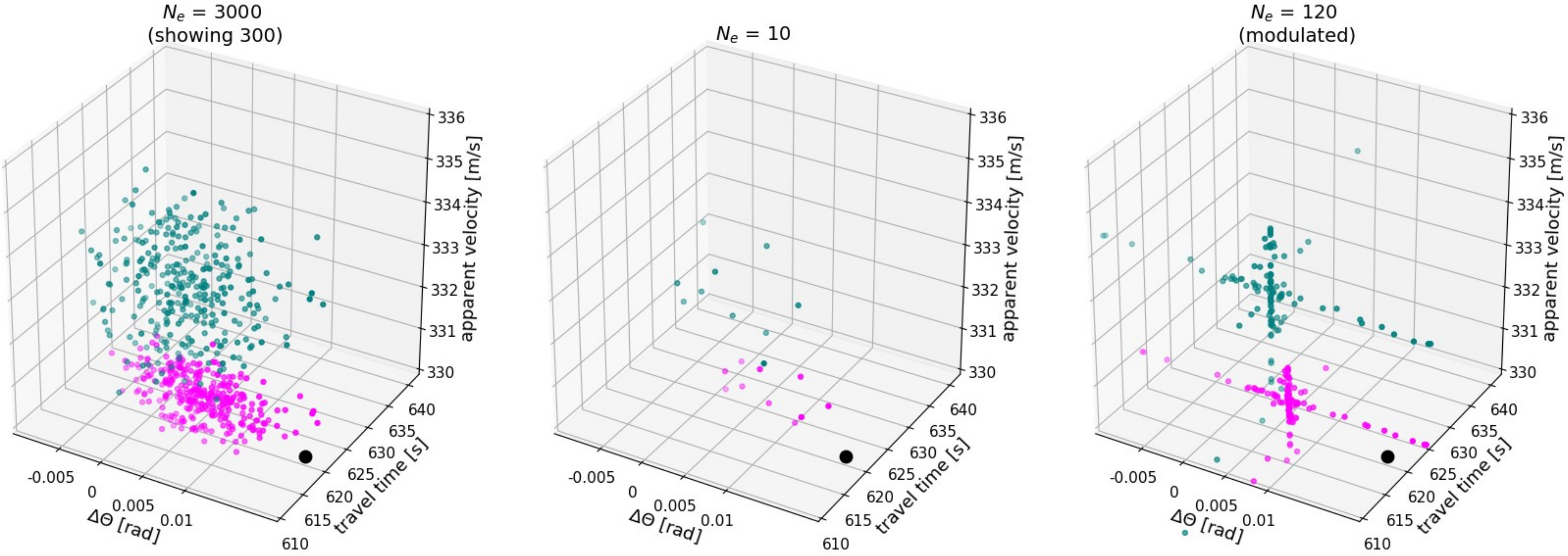
Current synthetic experiments



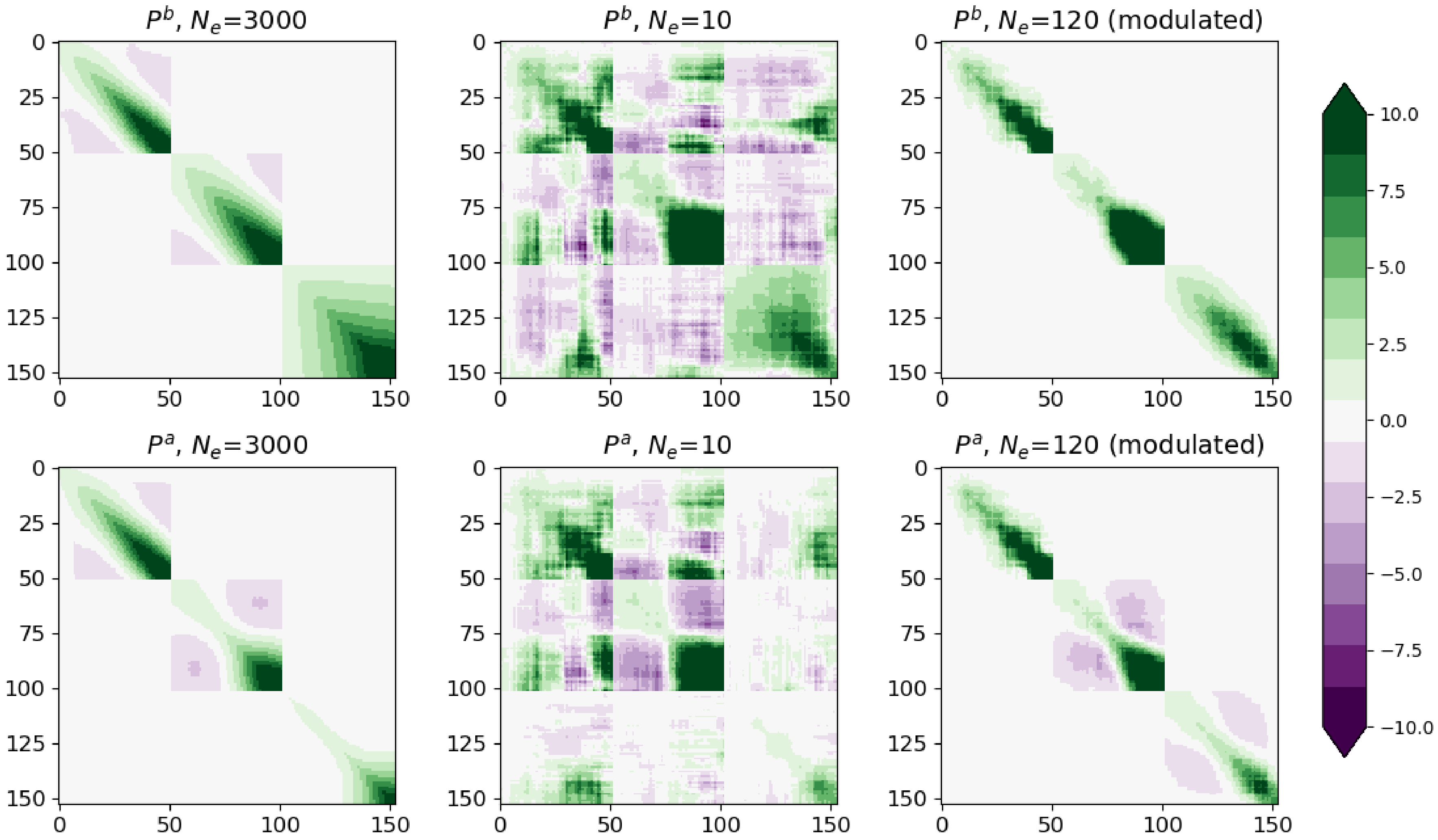
We generate $N_e + 1$ atmospheric profiles and maximum heights coming from a given distribution.

Results in observation space

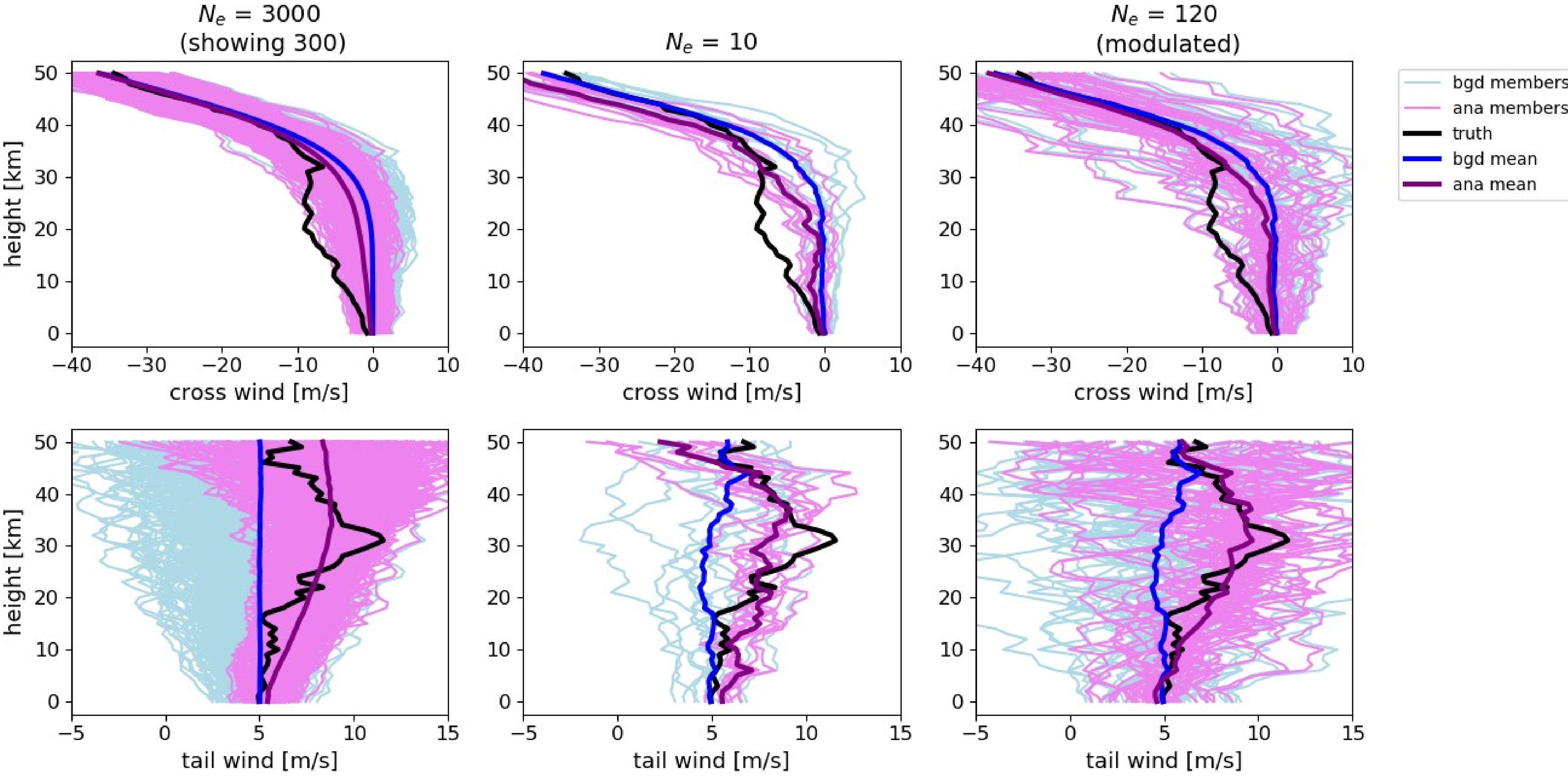
The ray-propagation algorithm is applied to every ensemble member.



Covariances

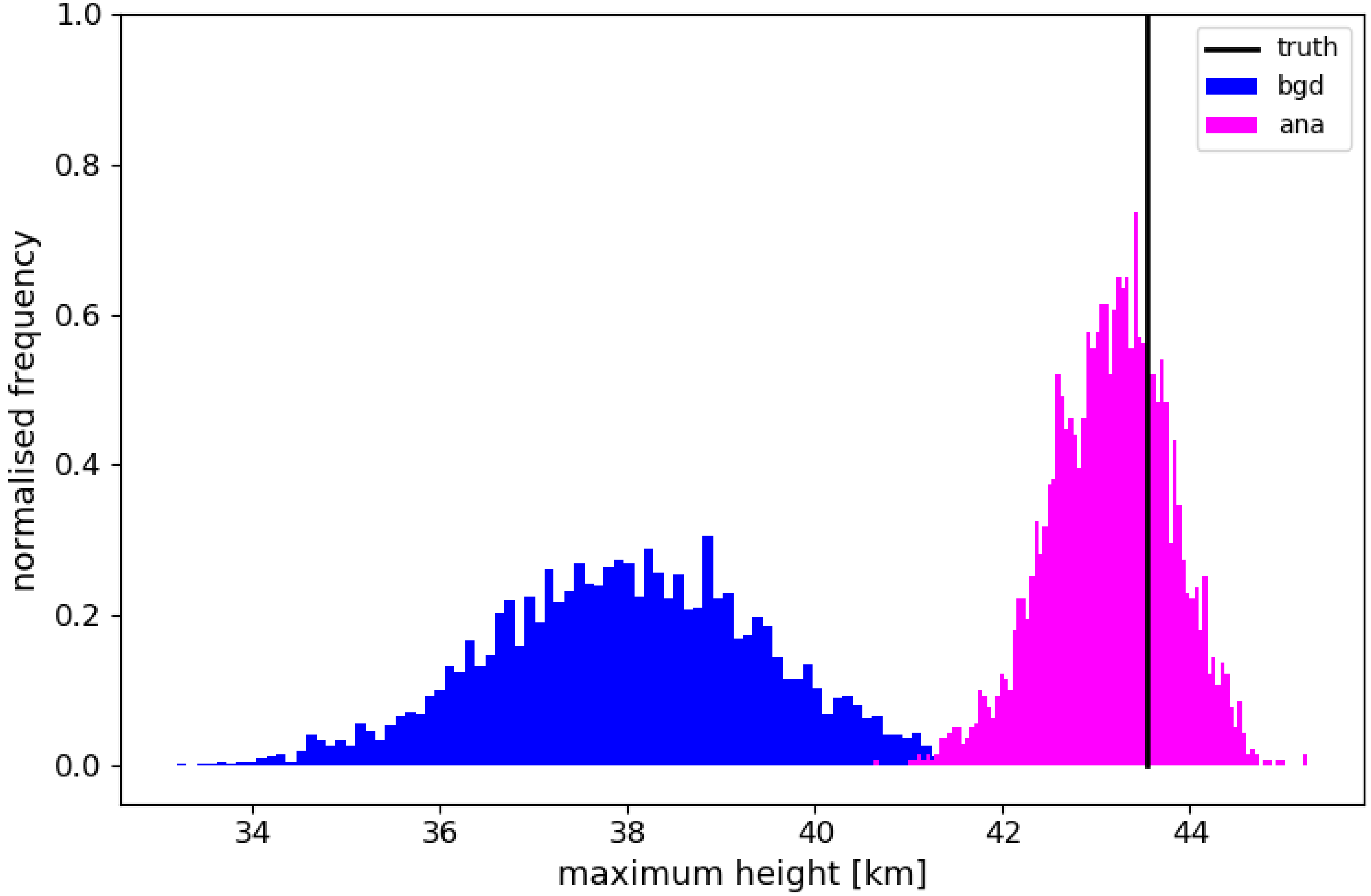


Results in model space



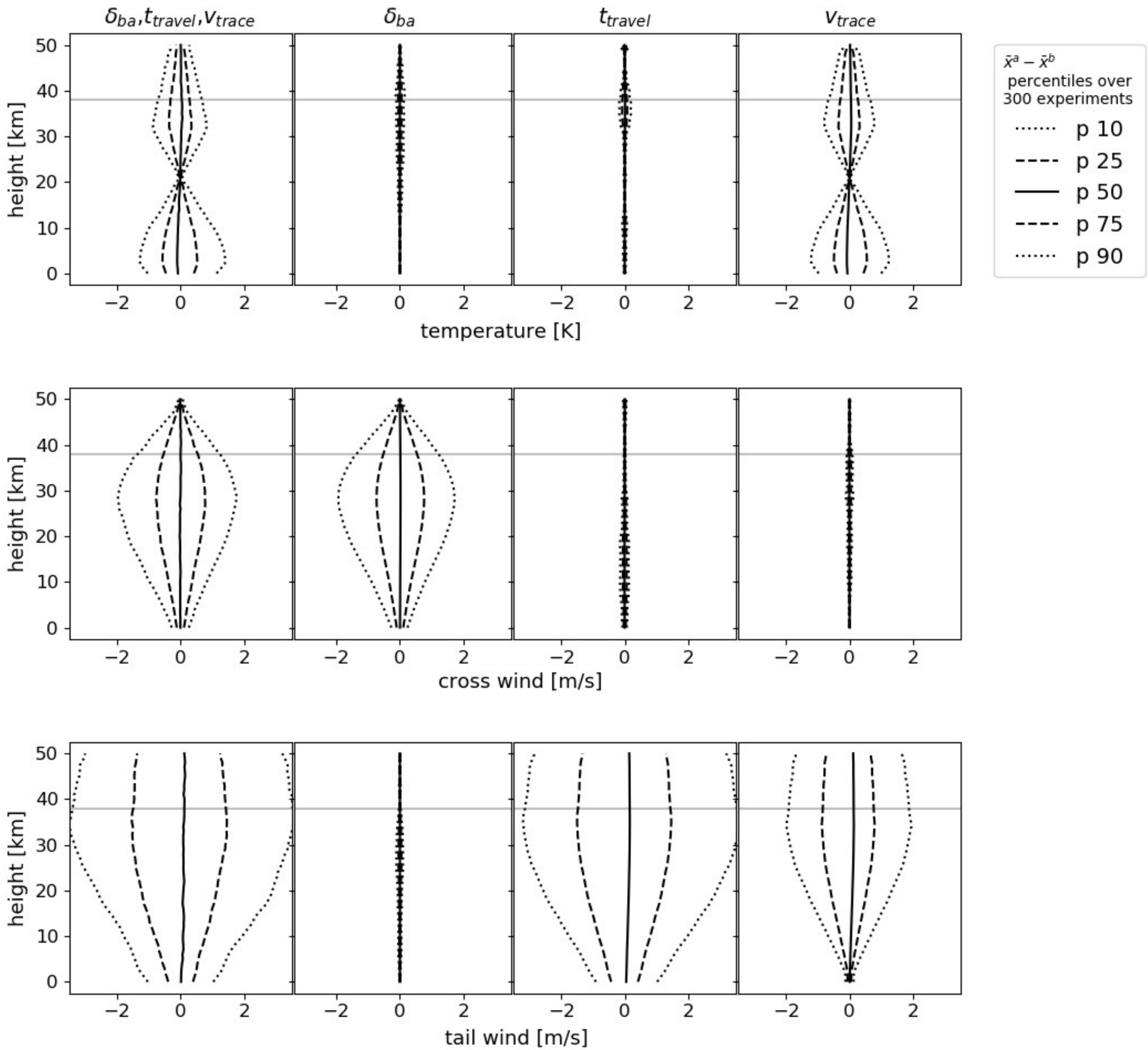
In model space, the quality of the background covariance is vital.

Results in model space



The heights are also updated (only large ensemble results shown).

Observation impact



Summary

Infrasound-related **measurements** contain **integrated information** of **atmospheric variables**. This can be exploited for poorly-observed regions.

Doing **DA with integrated quantities** and **small ensembles can be difficult**.

The **satellite DA** community has experience on this. We borrow a technique from them to solve our problem.

Next step: **assimilate ocean microbaroms**. More difficult since it is continuous emission and long-distance propagations.

Works:

– Amezcua, J, Näsholm, S, Blixt, EM, Charlton-Perez, AJ. (2020) Assimilation of atmospheric infrasound data to constrain tropospheric and stratospheric winds. QJR Meteorol Soc. 2020; 146: 2634– 2653. https://doi.org/10.1002/qj.3809

– Amezcua, J. & Barton, Z.(2021) Assimilating atmospheric infrasound data to constrain atmospheric winds in a two-dimensional grid. QJR Meteorol Soc, 147, 3530–3554. Available from: https://doi.org/10.1002/qj.4141

– Amezcua, J, Näsholm, S, Vera-Rodriguez (2022). Using satellite data assimilation techniques to assimilate infrasound observations into a full ray-tracing model. The Journal of the Acoustical Society of America. *In preparation*.