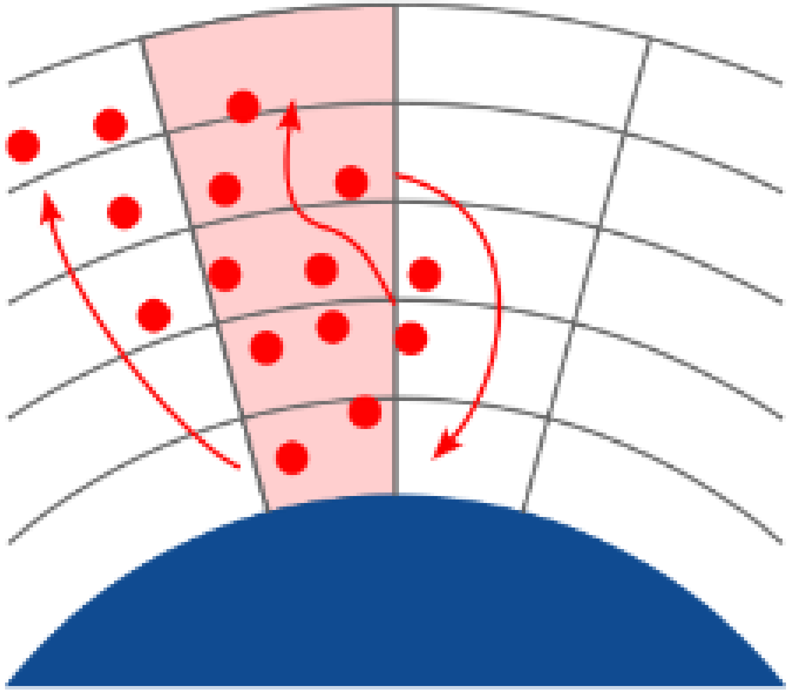
Studying infrasound propagation in the middle atmosphere with UA-ICON: parameterisation and characterisation of gravity waves with the Multi-Scale Gravity Wave Model

Samuel Kristoffersen (CEA), Constantino Listowski (CEA), Georg-Sebastian Voelker (Leibniz Institute for Baltic Sea Research), Ulrich Achatz (Goethe University) Julien Vergoz (CEA), and Alexis Le Pichon (CEA)

Thanks to R. Wing and G. Baumgarten (IAP); S. Khaykin and A. Hauchecorne (LATMOS) for the Lidar data.

Infrasound and Gravity Waves - MSGWaM-3D

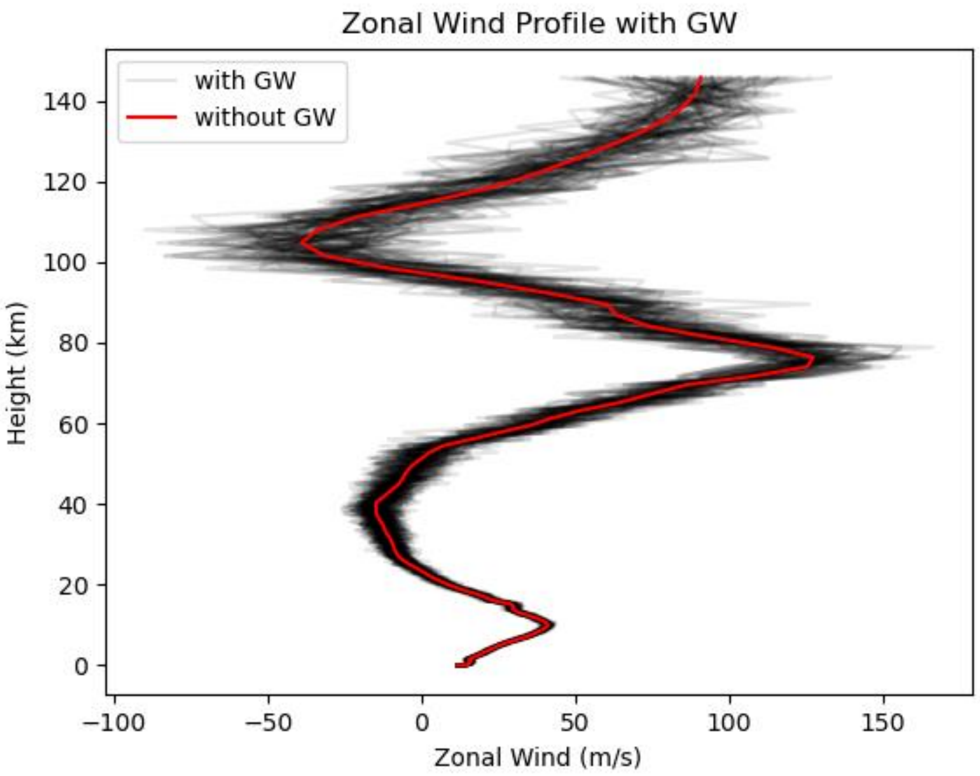
- Infrasound is used to monitor compliance with the Comprehensive Nuclear Test-Ban Treaty (CTBT).
  - 3D parameterization provides more realistic background atmospheric fields (e.g. wind, temperature etc.) through GW breaking.
  - Global GW spectral parameters allow for estimation of the GW perturbations, which cause partial reflections of acoustic waves
- 3D transient (MSGWAM-3D) – GW energy is transported 3-dimensionally through the atmosphere.
- This 3D GW transport allows for more realistically parameterized GWs.
- **Objective: improve infrasound atmospheric specifications with respect to the impact of GWs.**



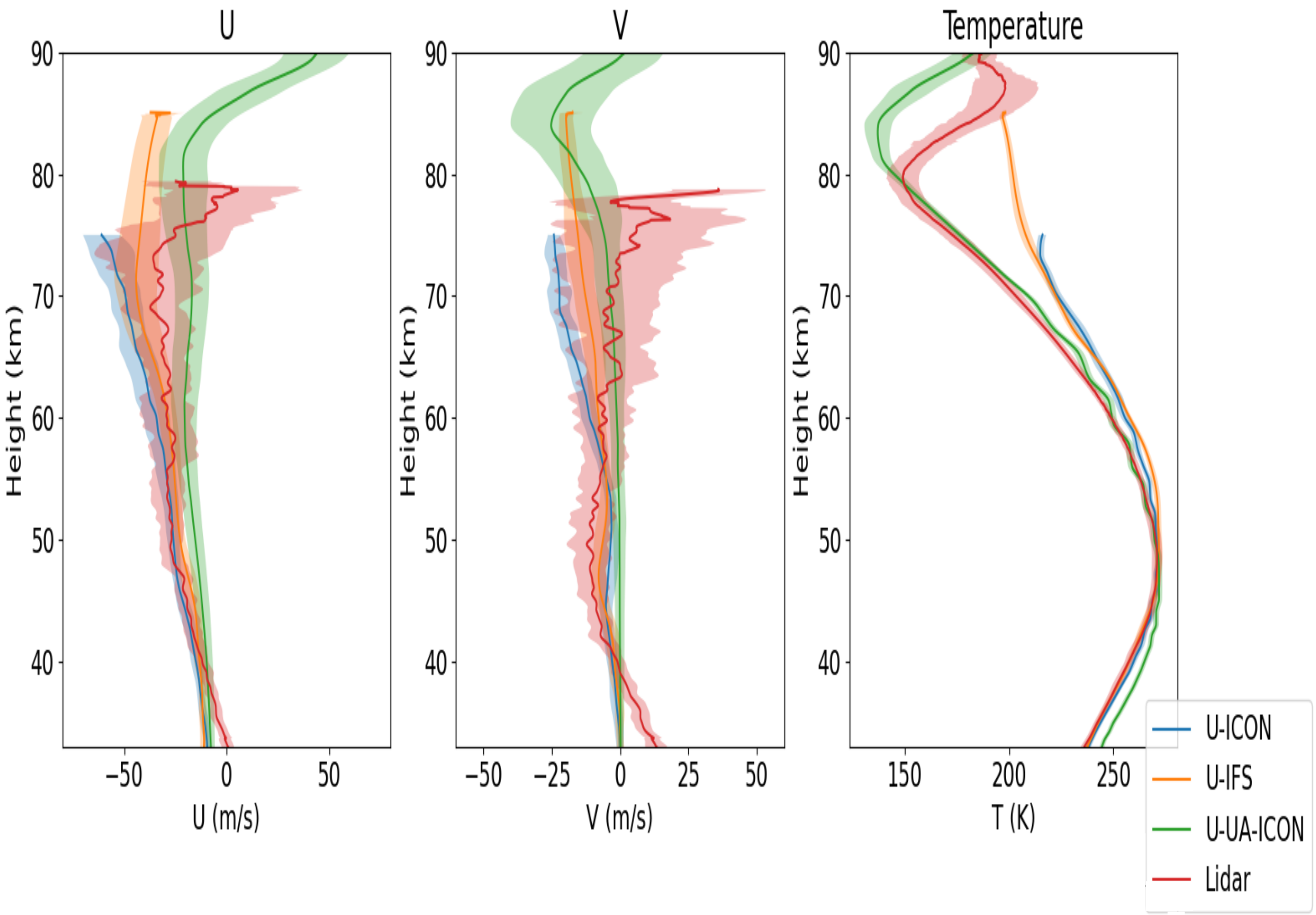
Voelker, G. S *et al.* (2024) https://doi.org/10.5194/egusphere-egu24-18795.

UA-ICON with MSGWaM Lidar comparison

Simulated GW perturbations using the MSGWaM-3D model



Validation of simulations with high-resolution Lidar measurements



Conclusions

- Infrasound propagation is highly dependent on atmospheric conditions (temperature, wind etc.) in the middle atmosphere.
  - Currently at CEA, operational (IFS) model is used with a climatology for the Mesosphere and Lower Thermosphere (MLT).
  - UA-ICON provides these atmospheric parameters up to the MLT.
  - MSGWaM GW parameterizations provide improved background temperature profiles compared to default GW parameterizations (C*).
- Lidar comparisons during the summer of 2023 show good agreement with MSGWaM
- The Hukkakero reference event further demonstrates the importance of correct MLT model predictions
  - With GW perturbations, the stratospheric and mesospheric arrivals are better represented.
  - GW perturbations can have a significant impact on the source location, and therefore need to be properly accounted for.
- Further Lidar comparisons at different locations and during different seasons are necessary to further verify MSGWaM GW parameterisations.
- Validate MSGWaM vertical GW spectra using Lidar and radiosonde observations.

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Outline

1. Infrasound Background
2. Atmospheric Models
3. MSGWaM – Gravity wave spectra and perturbations
4. Lidar Comparisons
5. Infrasound Results
6. Conclusions
7. Bonus Slides – Source localization

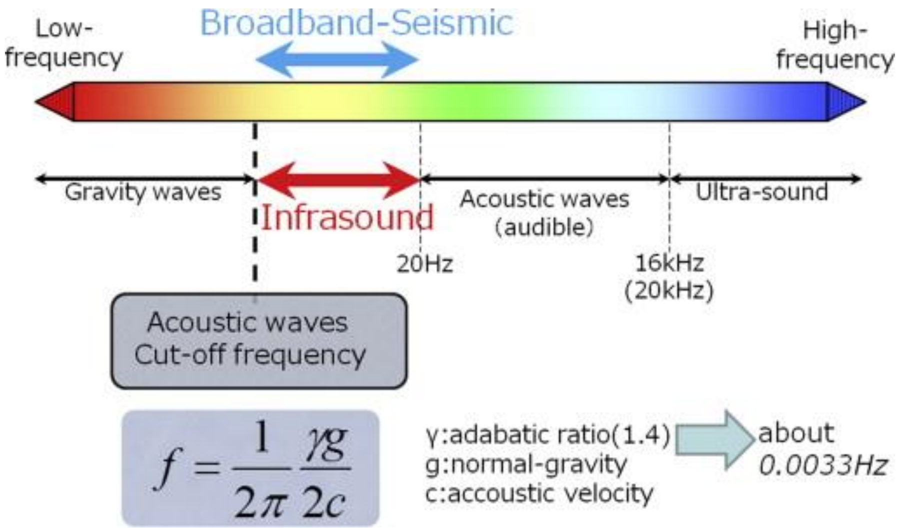
Sharing is encouraged

Sharing is encouraged

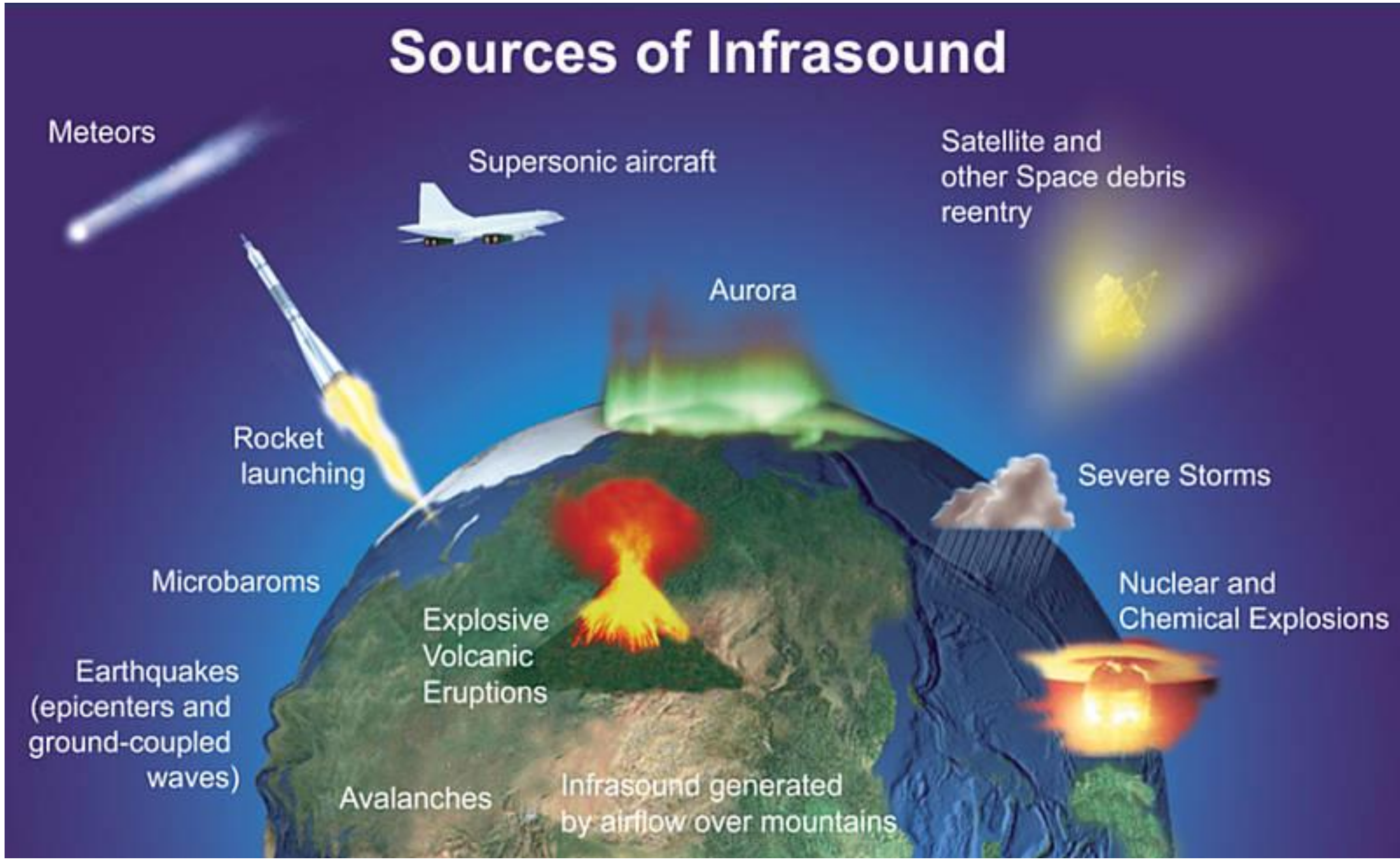
1. Infrasound Background

Infrasound Background

- Infrasound are pressure waves, at frequencies below human hearing range
- Large international IS network to monitor atmospheric IS sources (e.g. explosions, earthquakes, volcanoes etc.)



Takahiko Murayama et al., *Infrasound array observations in the Lützow-Holm Bay region, East Antarctica,* Polar Science, Volume 9, Issue 1, 2015, https://doi.org/10.1016/j.polar.2014.07.005.

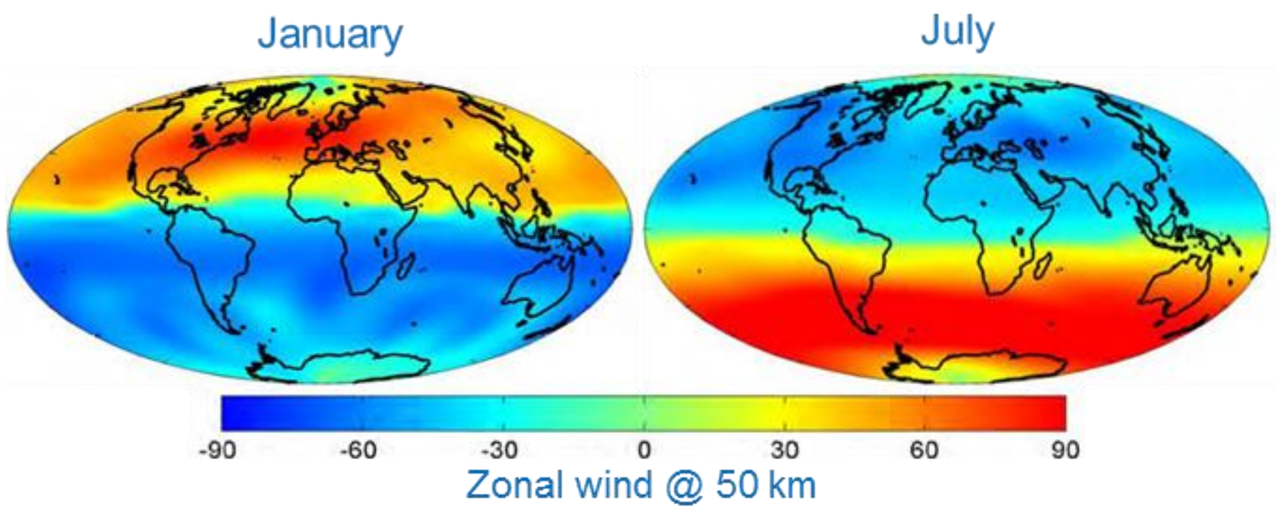


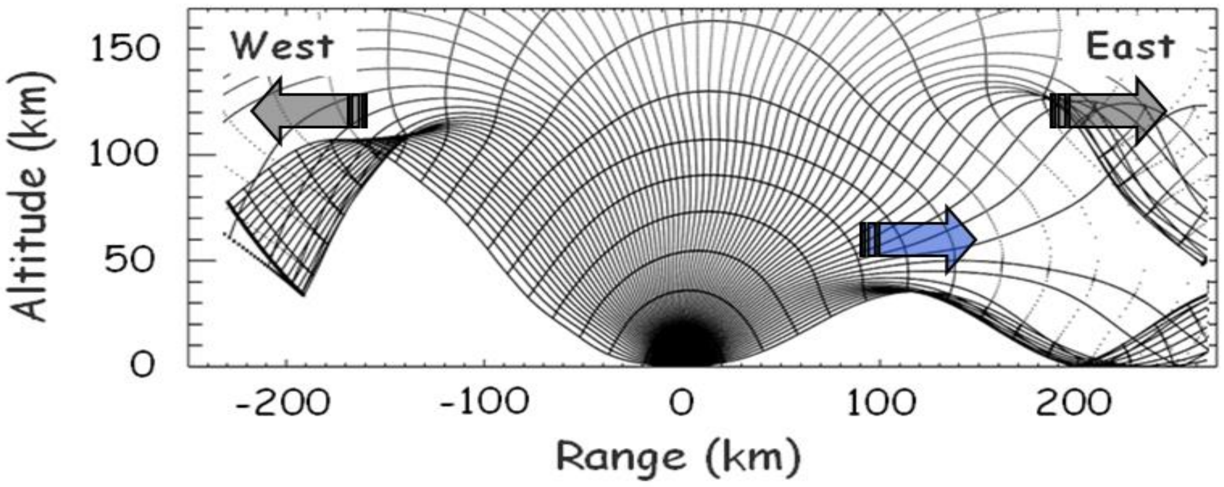
https://www.ctbto.org/our-work/monitoring-technologies/infrasound-monitoring

Infrasound propagation

https://www.ctbto.org

- Temperature and wind conditions in the middle atmosphere play an important role in infrasound propagation.
- $c_{eff} = \sqrt{\gamma R_d T} + \vec{u} \cdot \hat{n}$
- Due to atmospheric temperature inversions and semi-annual oscillations, acoustic wave-guides can form greatly changing infrasound observations.
- Accurate atmospheric profiles up to the thermosphere are necessary to predict infrasound trajectories.
- UA-ICON provides a means to predict these middle atmospheric wind and temperature profiles.



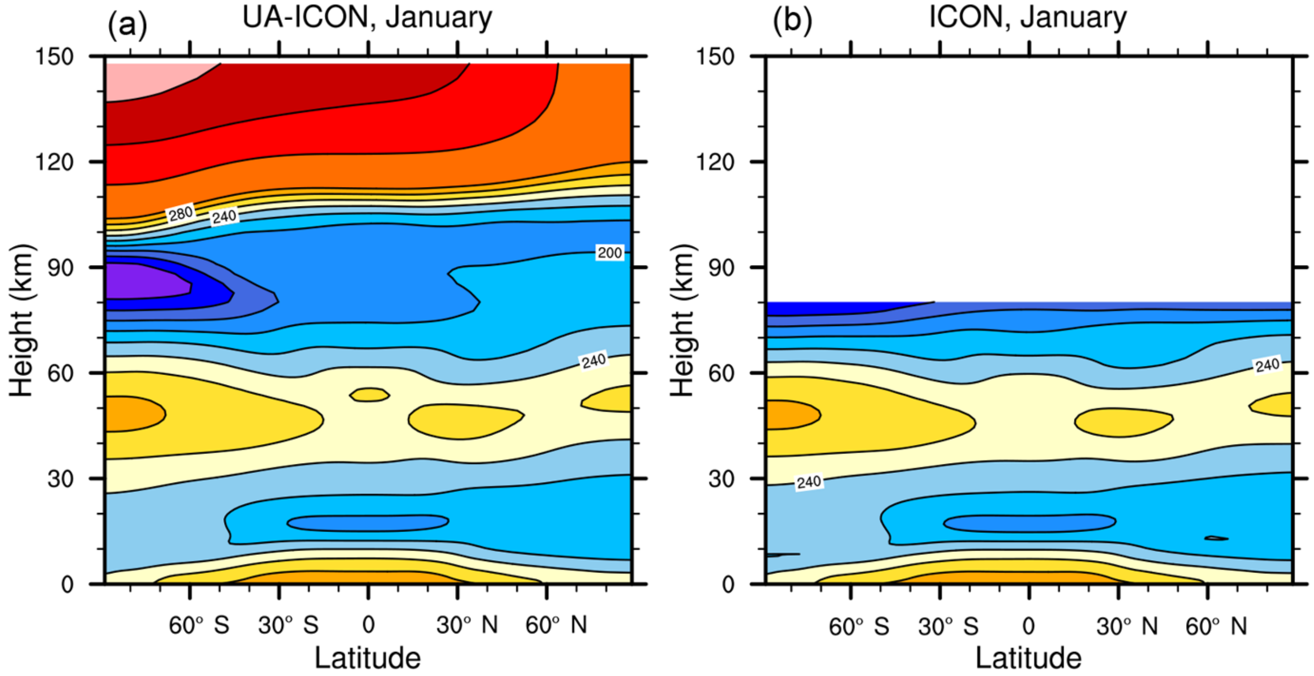


2. Atmospheric Models

Atmospheric models (IFS and UA-ICON)

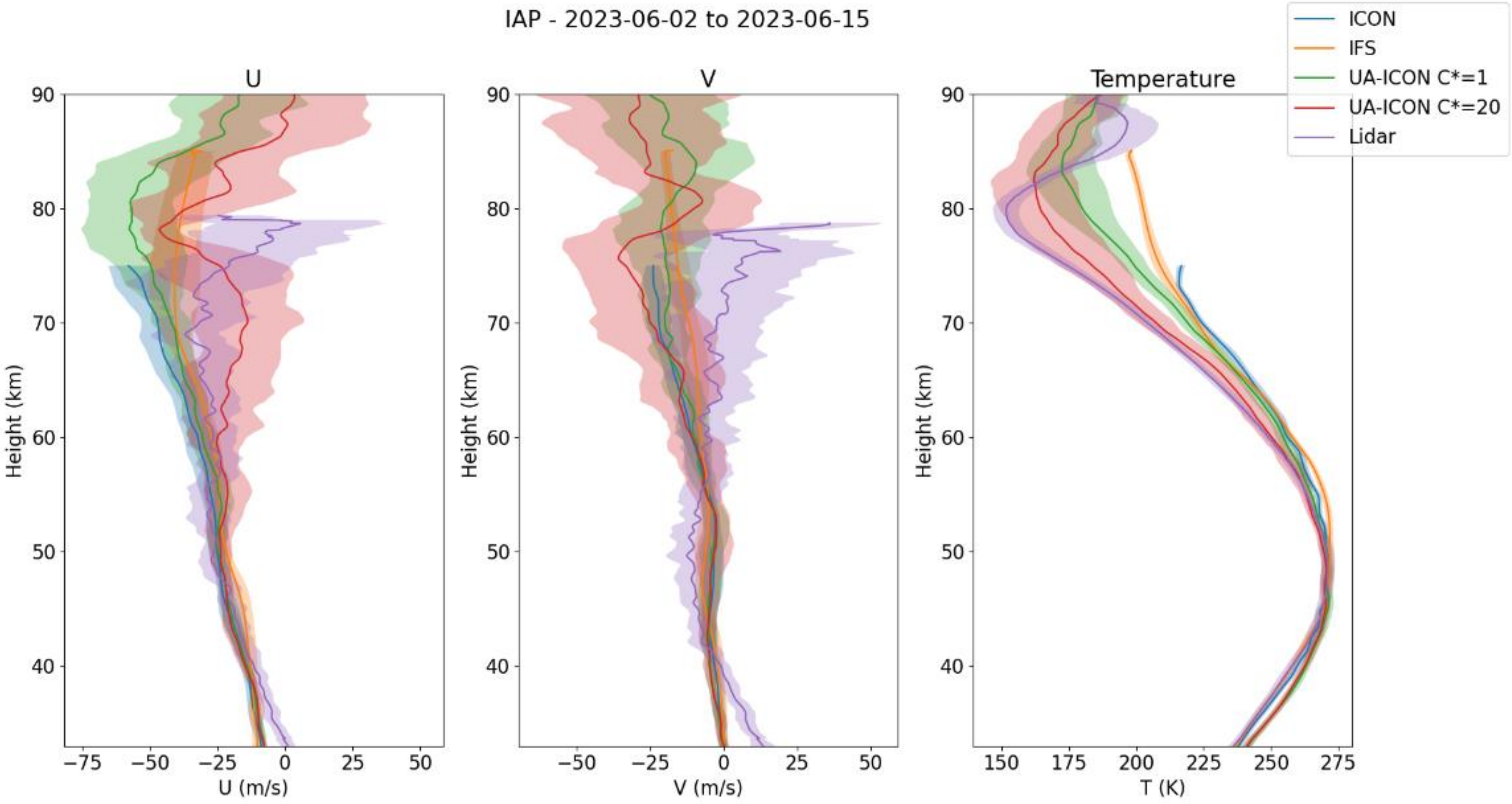
- Integrated Forecast System (IFS)
  - 6-hourly forecast
  - **80 km model top/137 levels**
  - ~9 km resolution
  - CEA has access to degraded version (~50 km resolution), once per day.
- ICOsahedral Non-hydrostatic (ICON)
  - 6-hourly forecast
  - **75 km model top/120 levels**
  - ~13 km resolution
  - Non-hydrostatic model
- Upper Atmosphere (UA) – ICON
  - **150 km model top/120 levels**
  - **Sponge layer above 110 km**
- **UA-ICON provides much better resolution of waves (e.g. GWs) through use of the non-hydrostatic atmosphere, and higher model top**.

Borchert, S. et al. (2019) https://doi.org/10.5194/gmd-12-3541-2019, 2019.



UA-ICON Lidar comparison
using default GW parameterization

- ICON and IFS and UA-ICON with C*=1 (default) overestimate summertime mesopause temperature.
- UA-ICON with increased C* better matches T.
- In general, not significant differences in the winds are shown here.

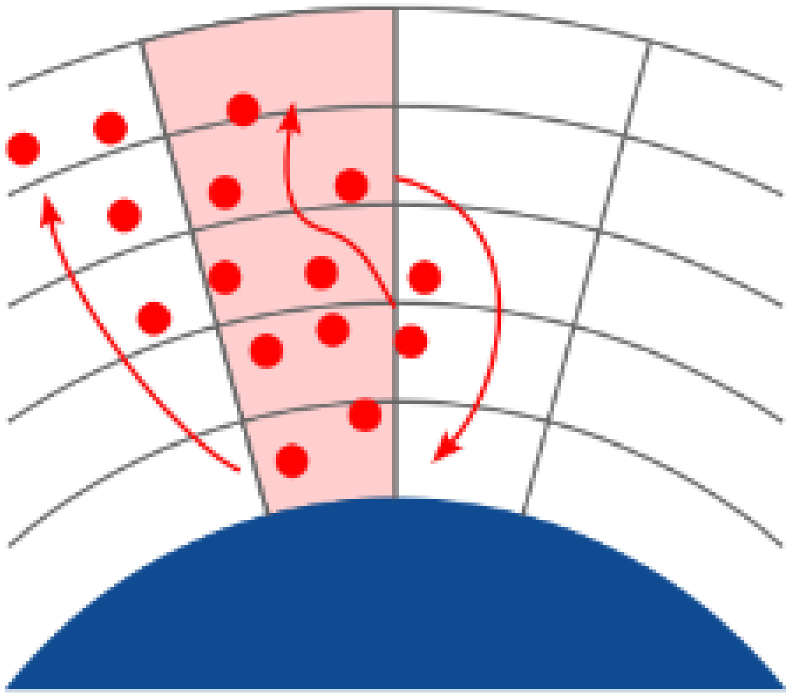


→ Kristoffersen *et al.* (in prep.)

3. MSGWaM

MSGWaM-3D

- 1D (commonly used parameterizations) – GW energy and momentum is instantly transported for each.
- 1D transient – there is a finite time for energy to be transported throughout the entire column.
- 3D transient (MSGWAM-3D) – GW energy is transported 3-dimensionally through the atmosphere.
- This 3D GW transport allows for more realistically parameterized GWs.
- Infrasound context:
  - 3D parameterization provides more realistic background atmospheric fields (e.g. wind, temperature etc.)
  - Global GW spectral parameters allow for estimation of the GW amplitudes.



Voelker, G. S *et al.* (2024) https://doi.org/10.5194/egusphere-egu24-18795.

Estimation of GW spectra

We start with the assumption that the spectrum follows a modified Desaubies spectrum:

$$F_u = \frac{2\pi < u'^2 >}{\eta m^*} \frac{\left(\frac{m}{m^*}\right)^2}{1 + \left(\frac{m}{m^*}\right)^5}$$

Where

$$2\pi < u'^2 > = \frac{KE}{\rho};\ \eta = \frac{\pi}{5} \frac{1}{\sin\left(\frac{3}{5}\pi\right)}$$

$$< m^2 > = \frac{A_{m^2}}{A}$$

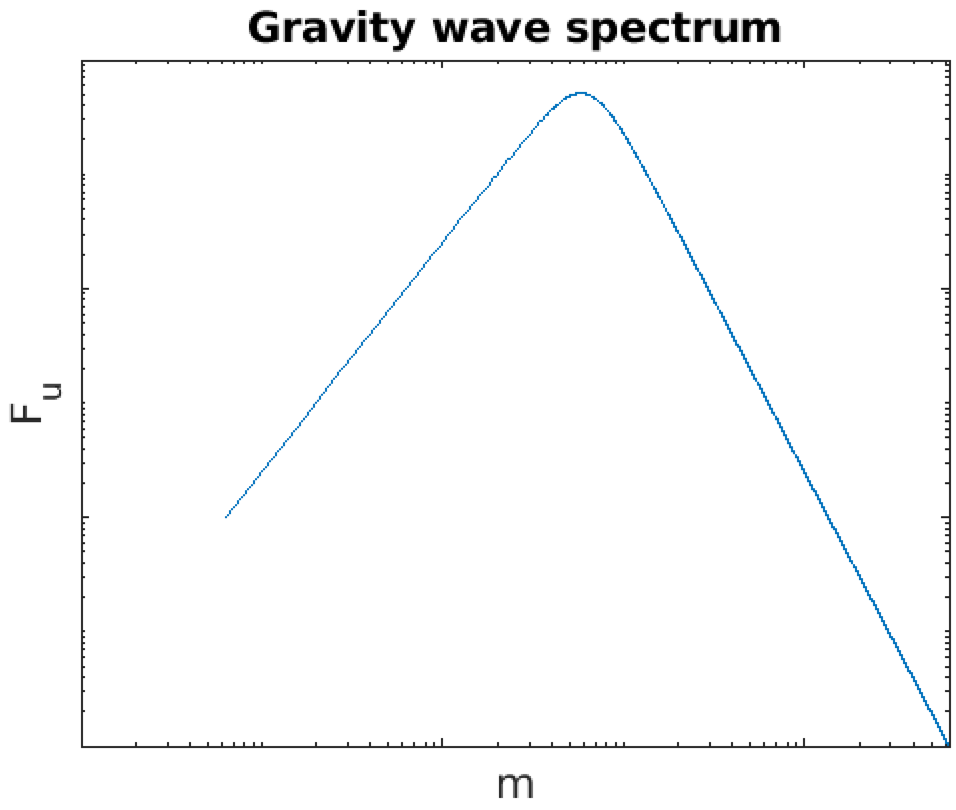
Where A is the wave action and

$$A_{m^2} = \int d^3k\, m^2\, N$$

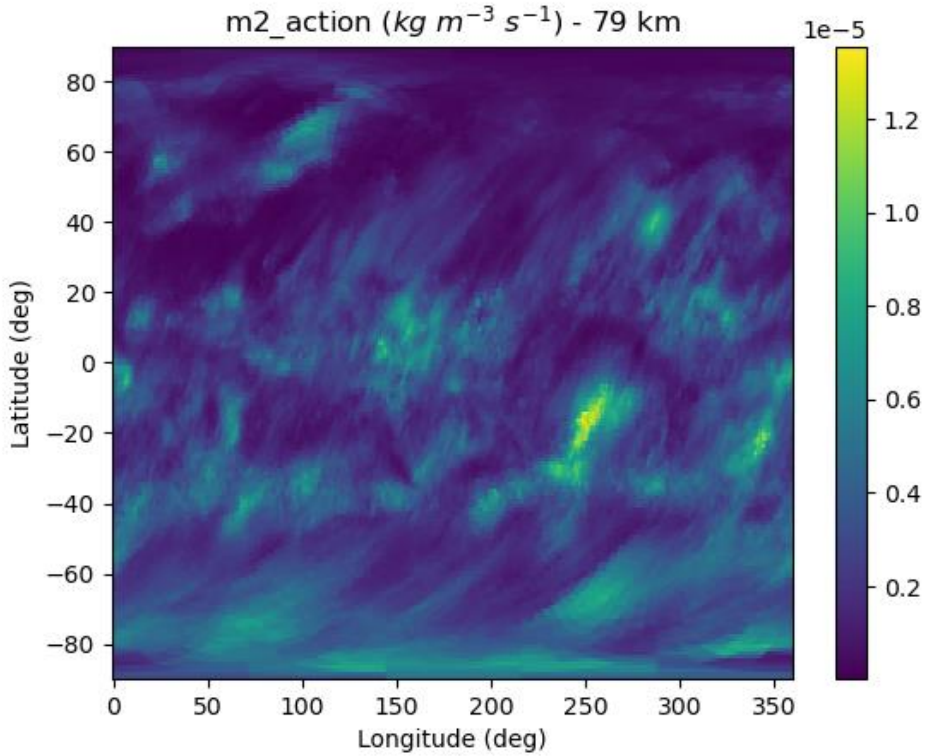
Where N is the phase-space wave-action density

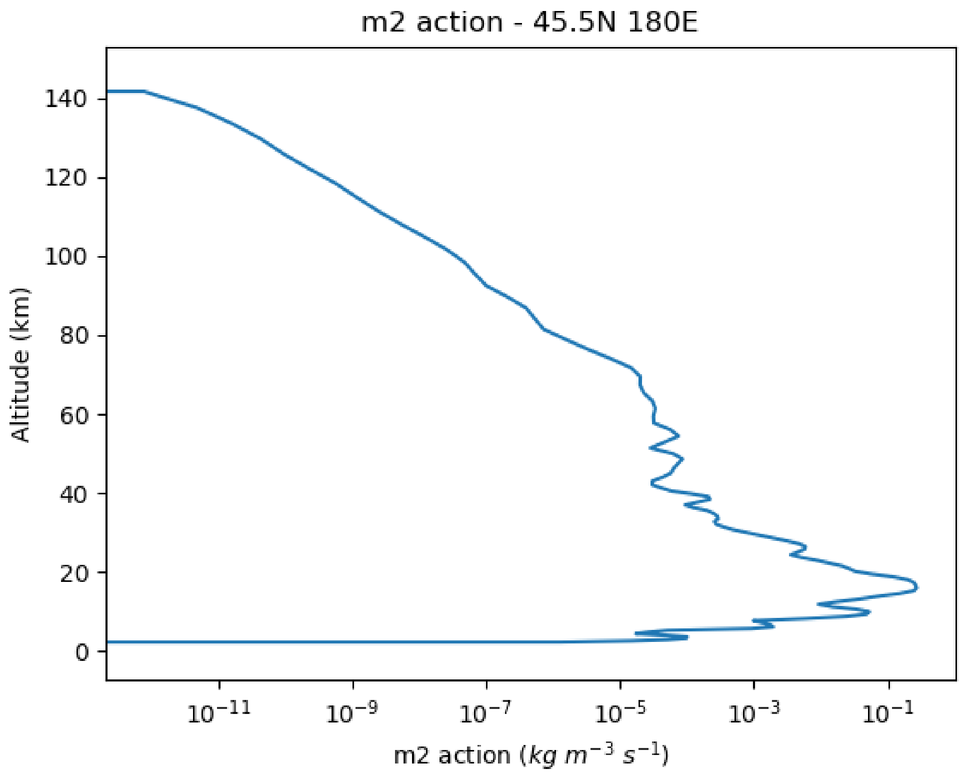
Finally, m* is approximated by

$$m^* = \sqrt{< m^2 >}$$

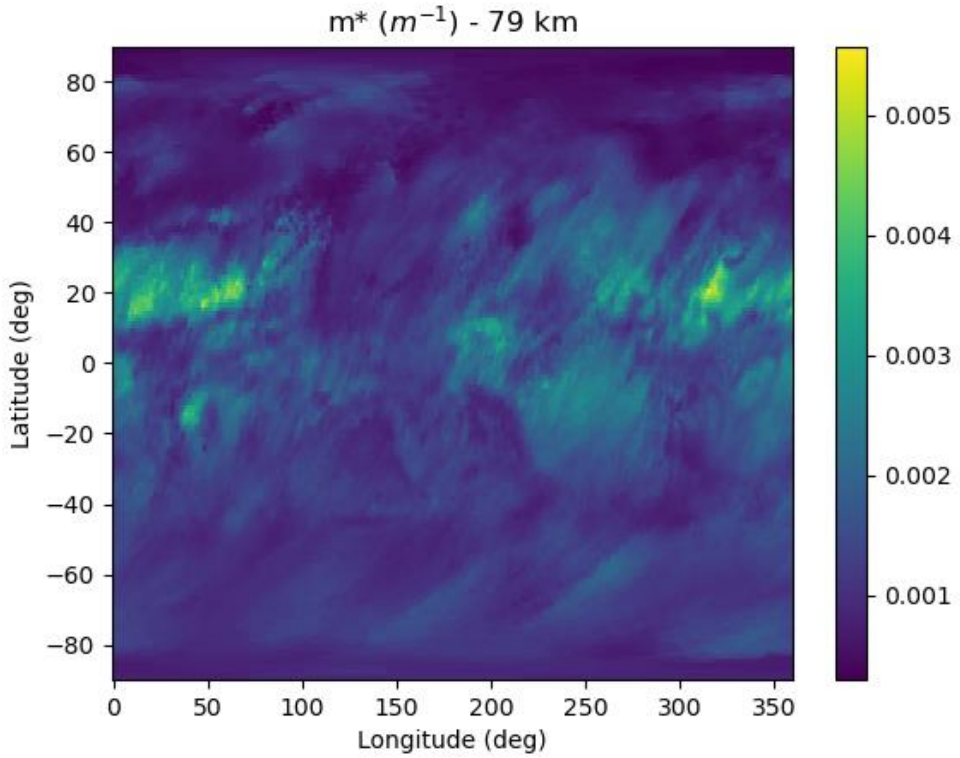


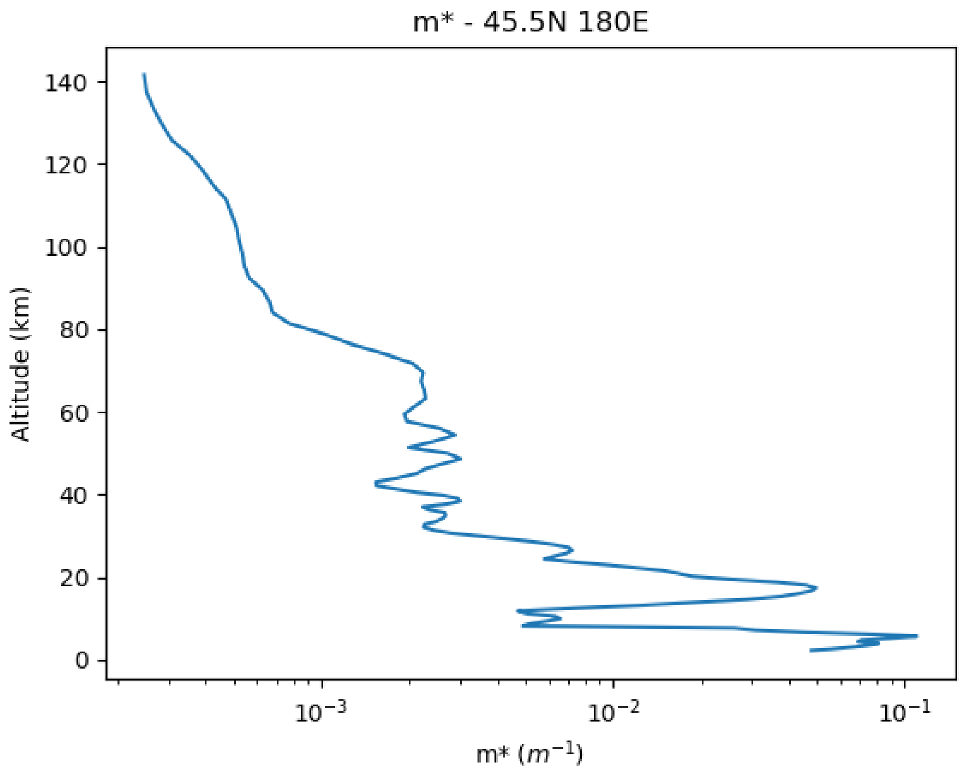
Map of A <m^2> and example profile





Map of m* and example profile





Estimation of GW perturbations

From the GW spectra, we estimated the GW perturbations

$$\hat{F}_u(z) = |F_u(z)|^{\frac{1}{2}} (\sin\phi_0 + j\cos\phi_0)$$

$$|F_u|^{\frac{1}{2}} = \sqrt{\frac{2\pi < u'^2 >}{\eta m^*} \frac{\left(\frac{m}{m^*}\right)^2}{1 + \left(\frac{m}{m^*}\right)^5}}$$

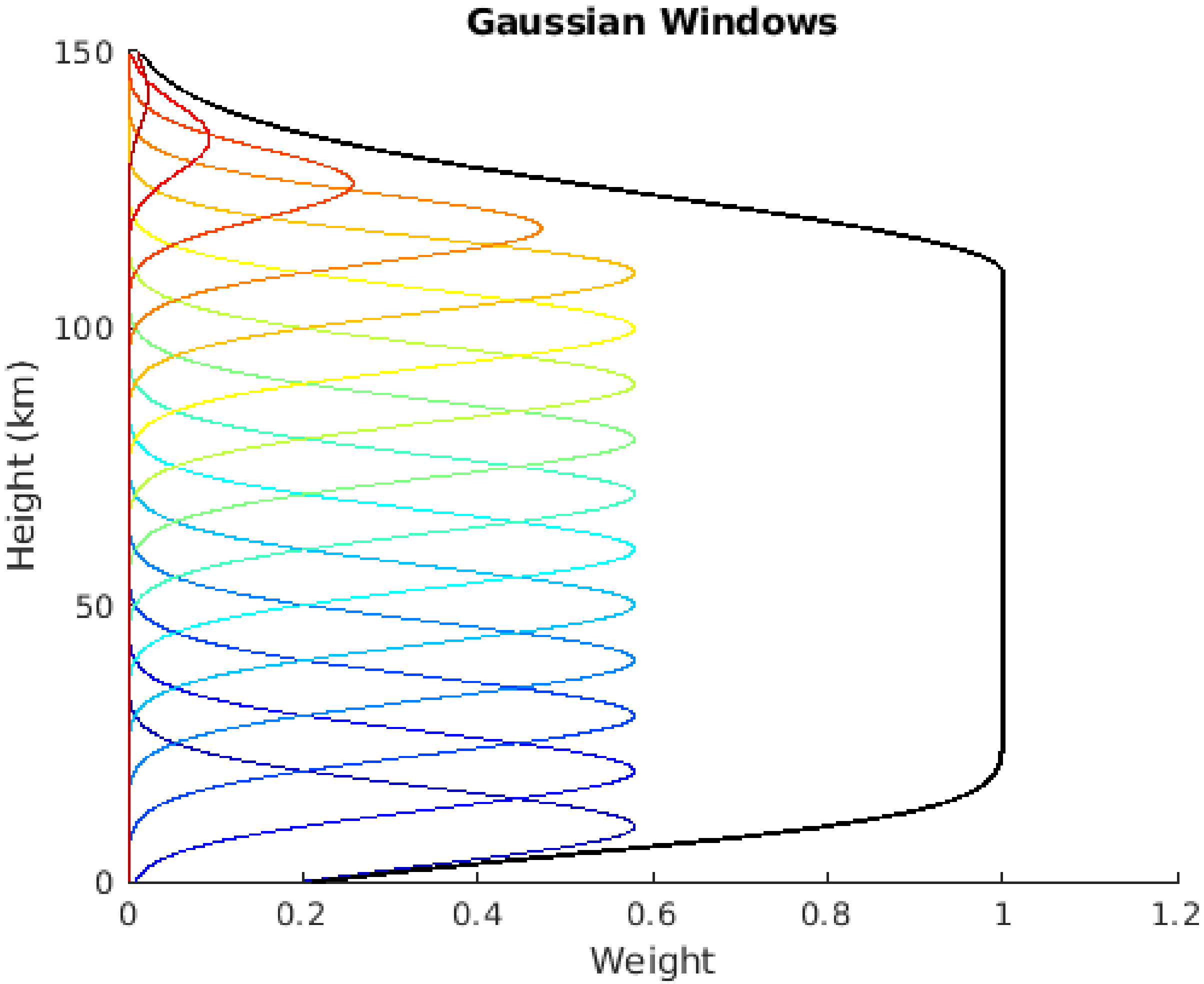
Where ϕ_0 is a randomly chosen reference phase.

$$u'_h(z) = \frac{1}{4\pi} \int \hat{F}_u(z) e^{-j2\pi f t} df$$

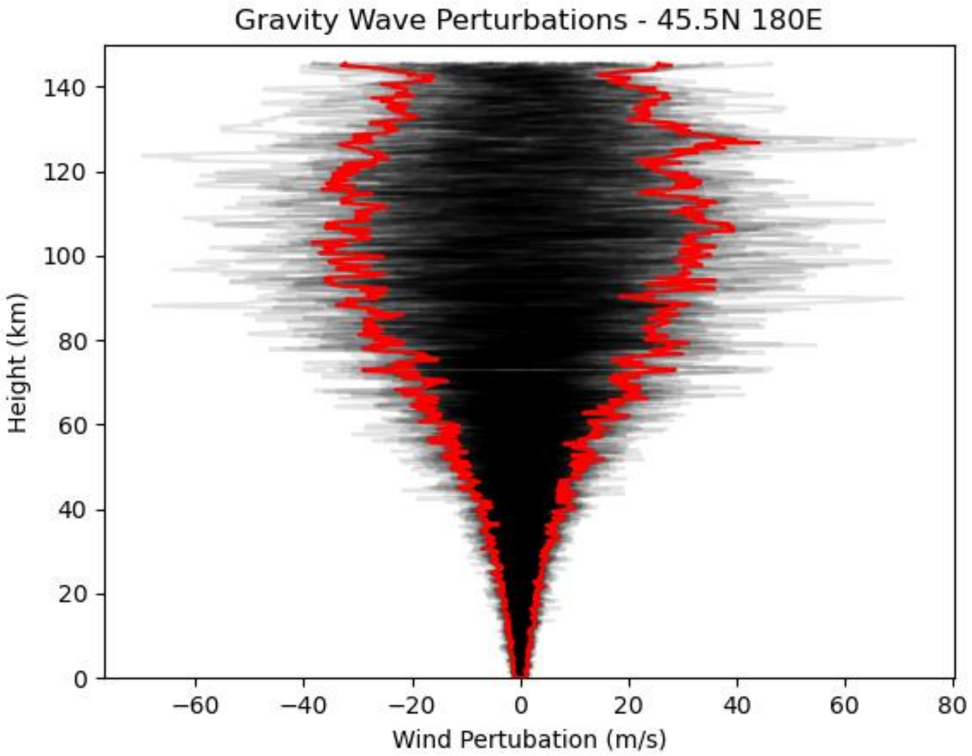
This procedure is performed for several altitude bands, and averaged

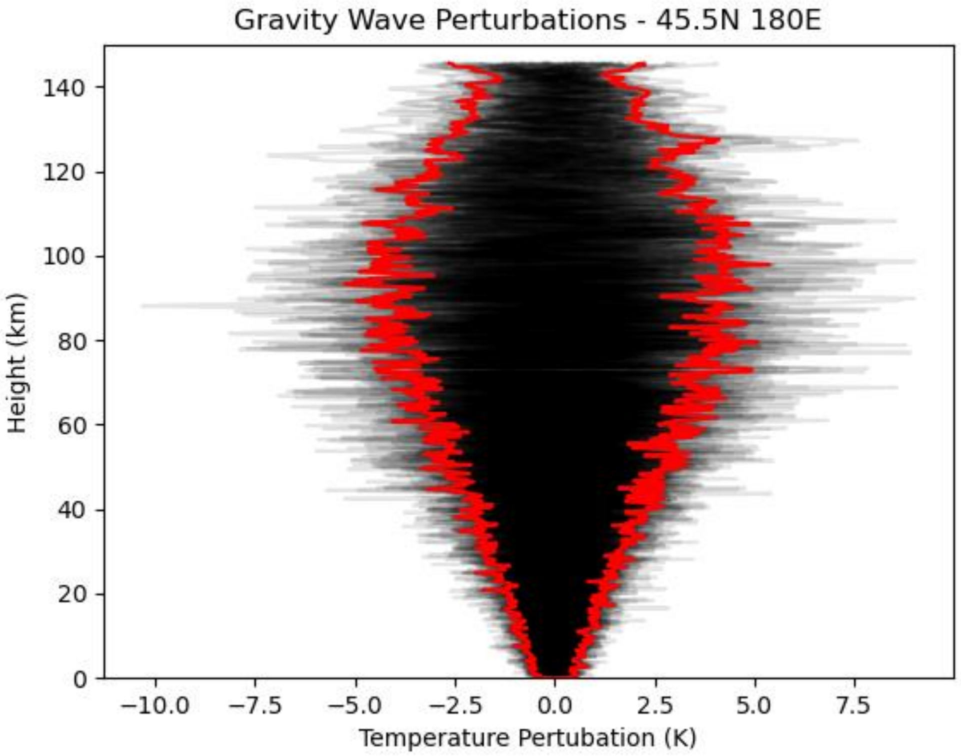
$$u' = \sum_z u'_h(z) \frac{2.108}{\sqrt{8\log 1.3015\ 2\pi}} e^{-\frac{\log 1.3015\,(z-z_h)^2}{\Delta h^2}}$$

Where Δh is chosen to be 10 km

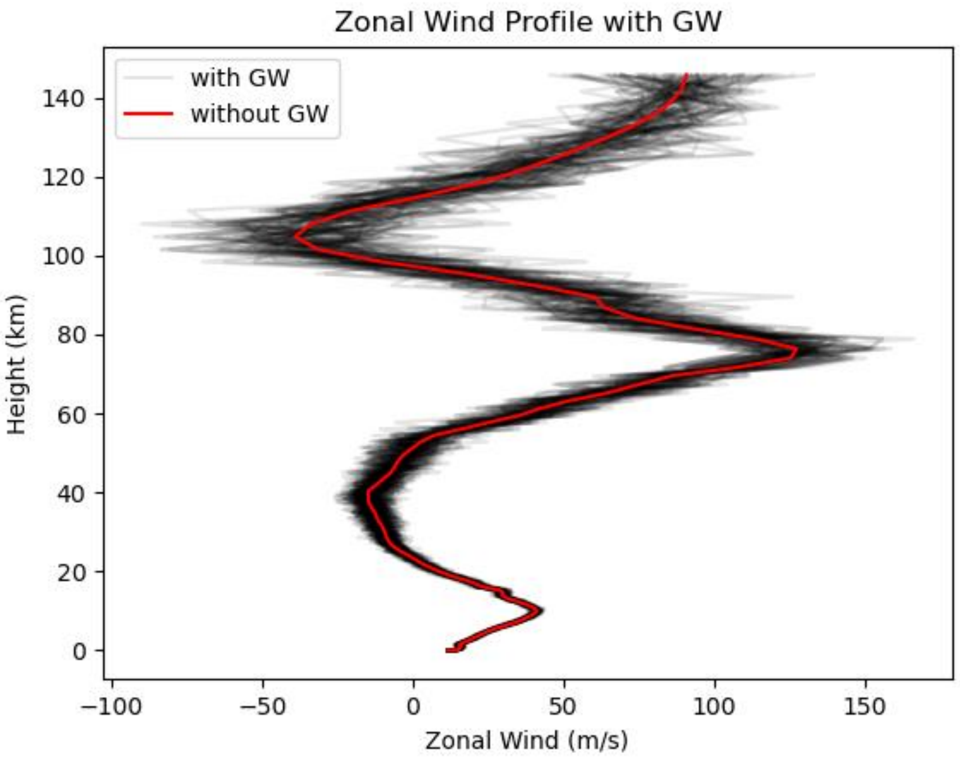


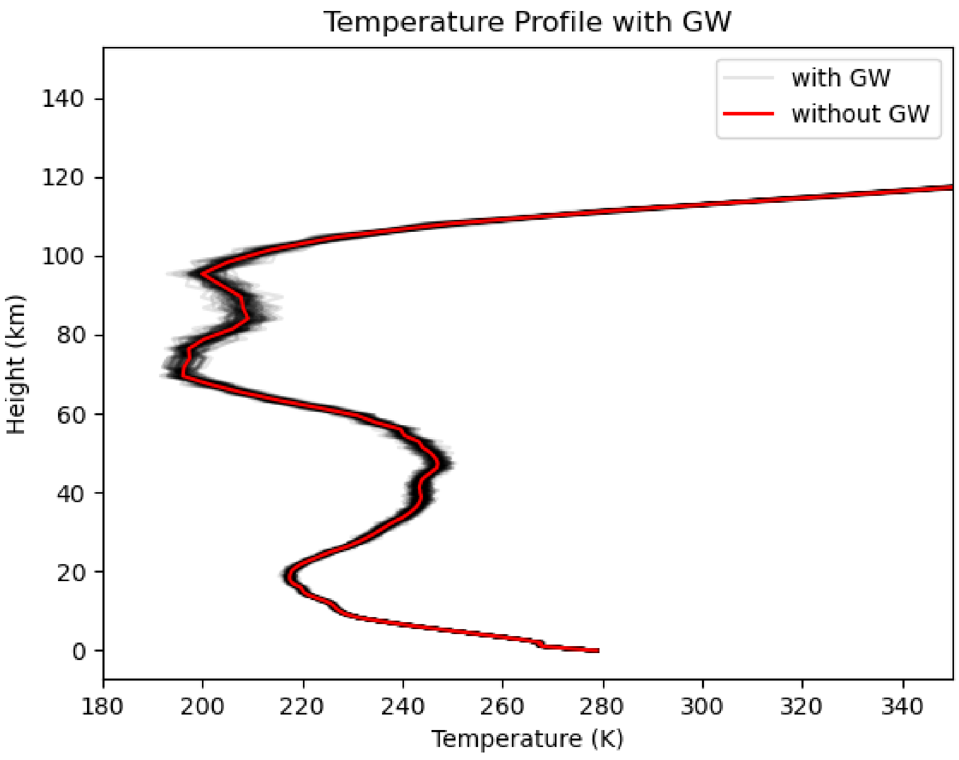
GW perturbation profile (wind and T)





Wind and T profile with/without GW



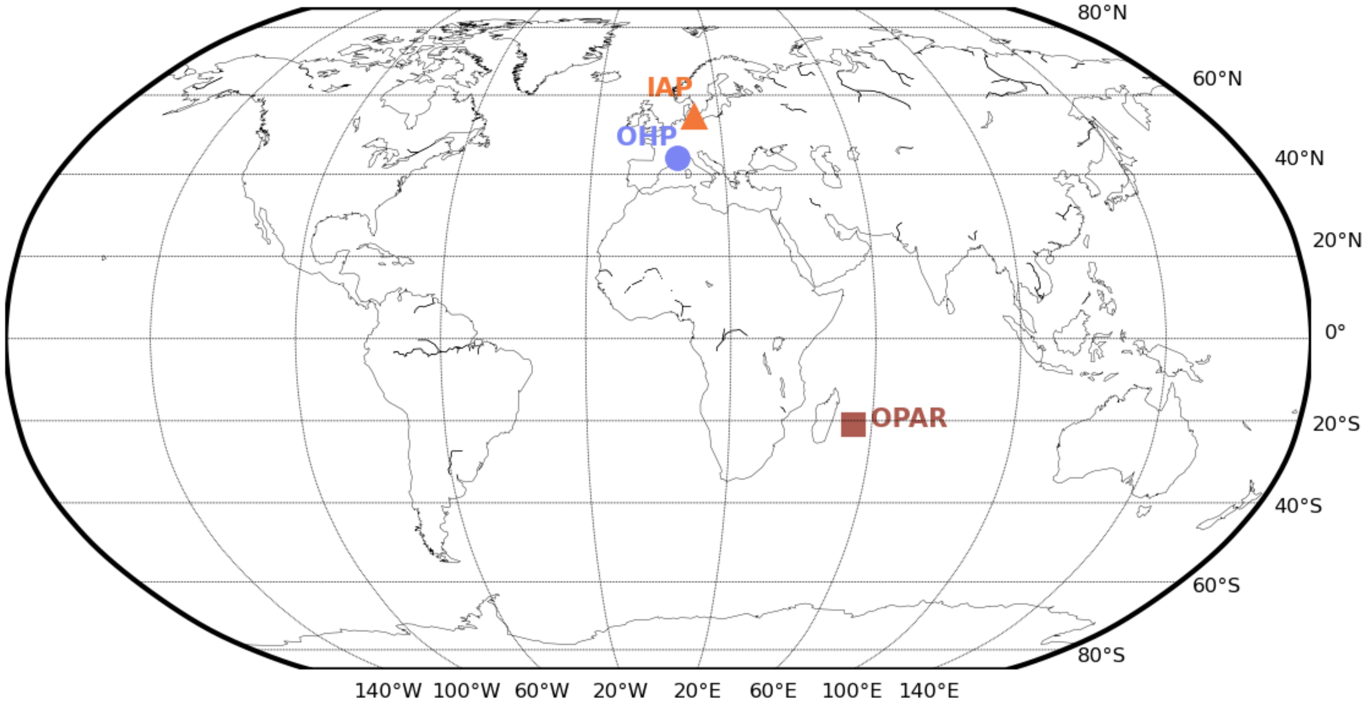


4. Lidar Comparisons

Validation of background wind and temperature

Sharing is encouraged

Lidar Atmospheric profiles

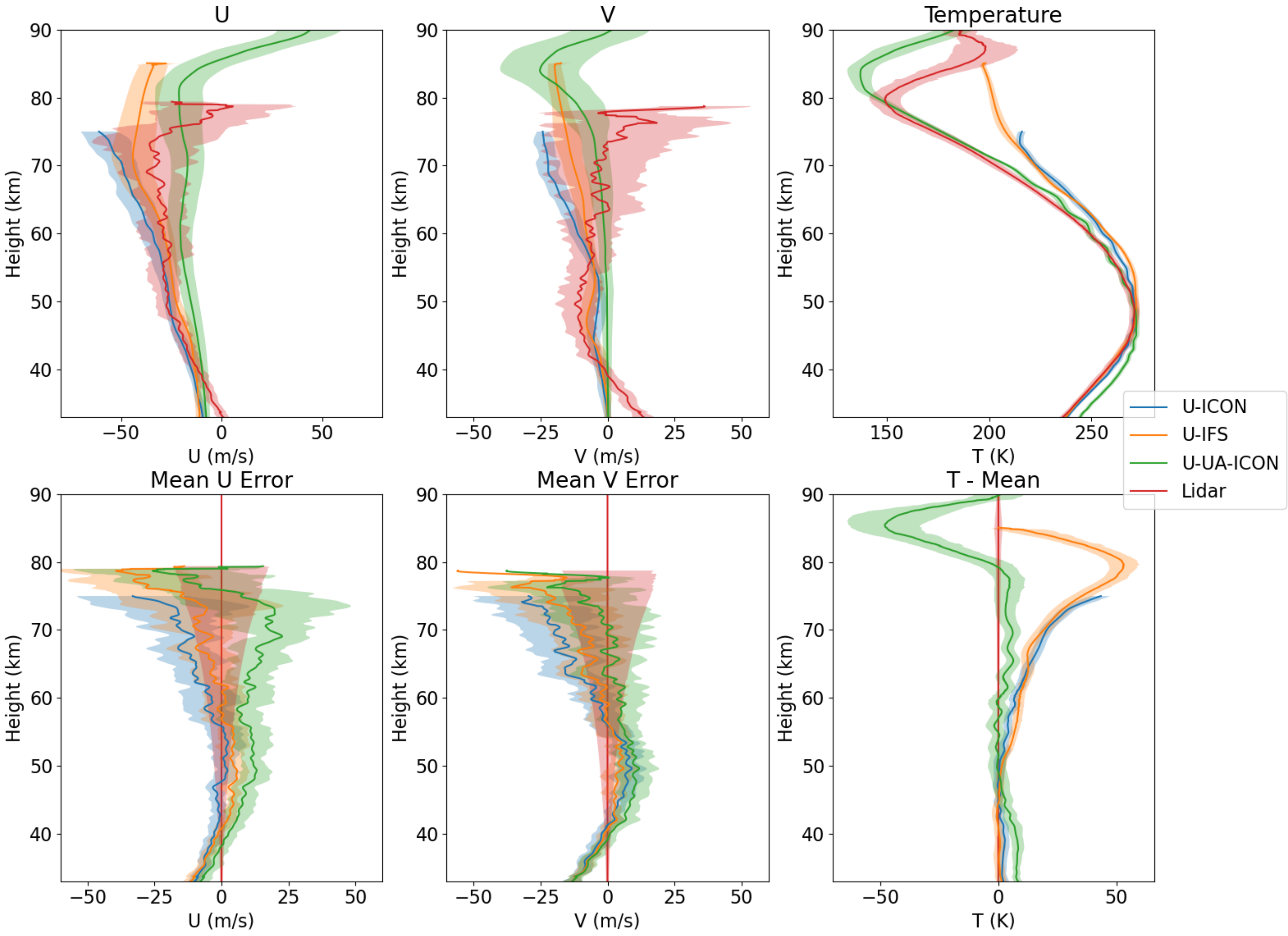


- Rayleigh/Mie/Raman Lidars measure wind and temperature profiles in the middle atmosphere (30-100 km).
- High vertical resolution allows for **model validation, and resolution of atmospheric gravity waves**.
- These three locations provide mid-latitude, and tropical comparisons.

https://www.iap-kborn.de/en/research/department-optical-soundings-and-sounding-rockets/instruments-and-models/alomar-rmr-lidar/

UA-ICON with MSGWaM Lidar comparison

- UA-ICON with MSGWaM temperatures match closely with mid-latitude summer mesosphere.
- Winds do not demonstrate any significant differences between the models and the observations.
- This demonstrates an larger background temperature gradients using MSGWaM GW parameterizations that better match the Lidar observations.



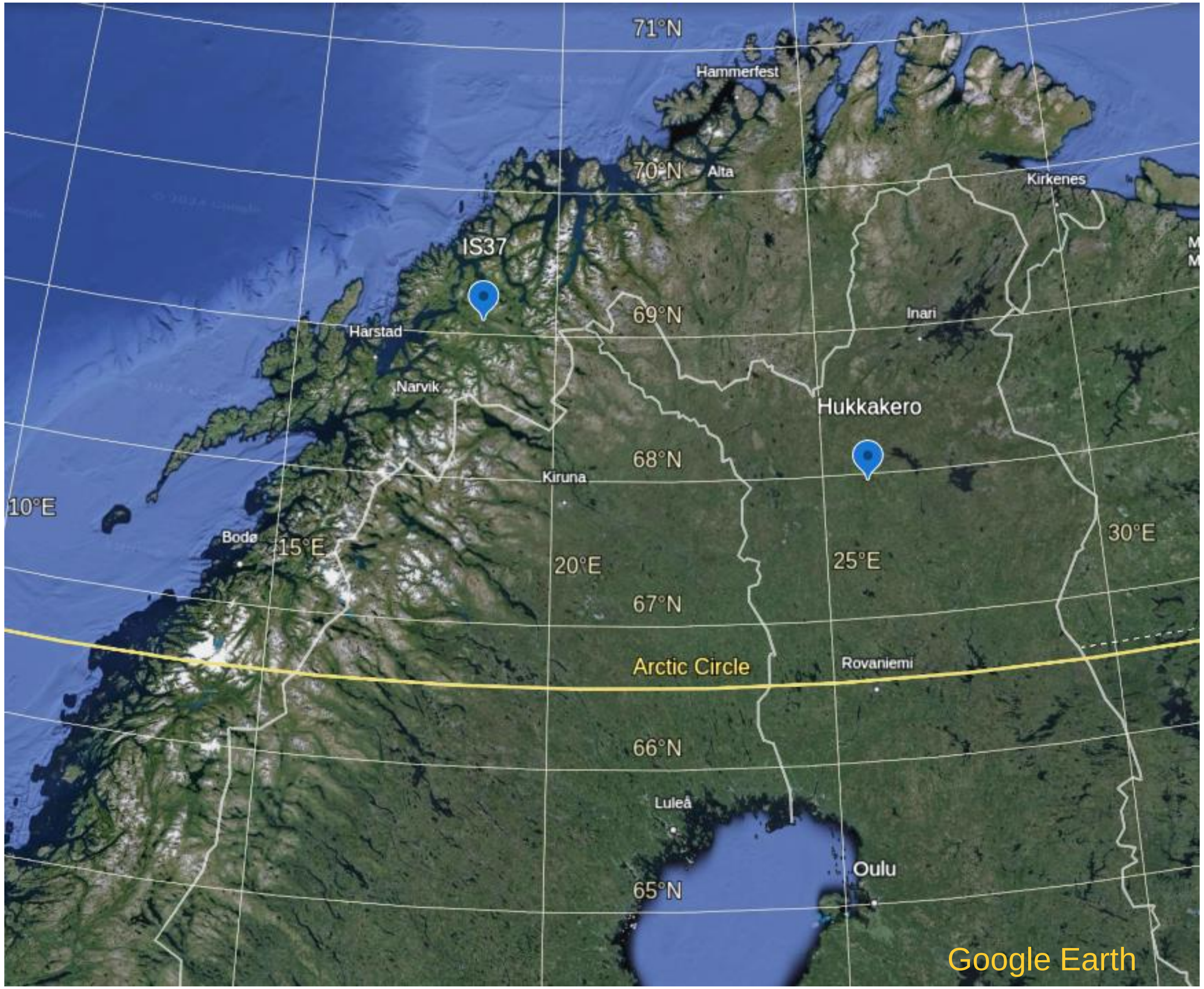
5. Infrasound Results

Hukkakero

Infrasound measurements – Hukkakero, Finland

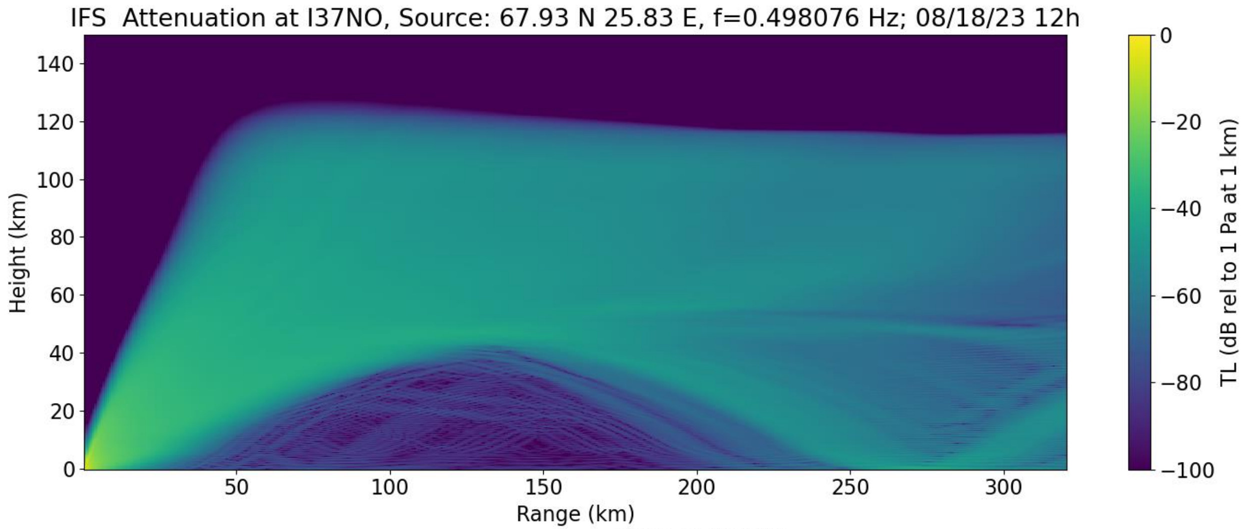
- At Hukkakero Finland munitions are destroyed every August.
- These ground-truth events provide an excellent reference for infrasound calibration.
- IS37 (69.1N 18.6E) is located approximately 320 km from this site.
- Signal and arrival time predictions were made using several different atmospheric model configurations (notably UA-ICON).
- UA-ICON run with MSGWaM-3D to compare improved parameterization with operational results.

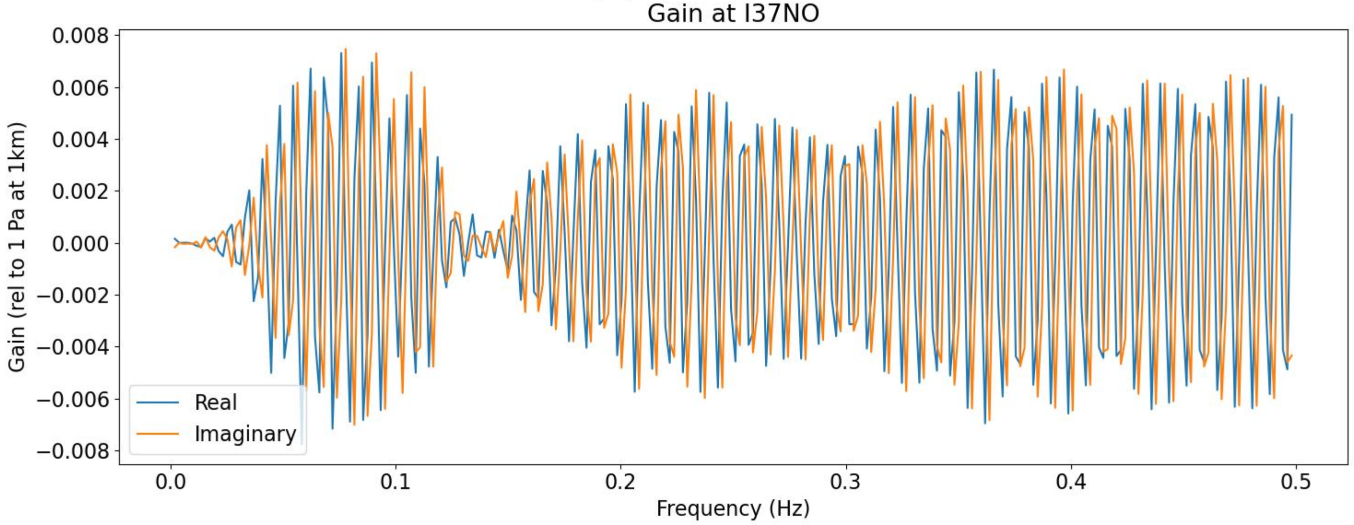
Blixt *et al.* 2019 https://doi.org/10.1121/1.5120183



Waveform from parabolic equations

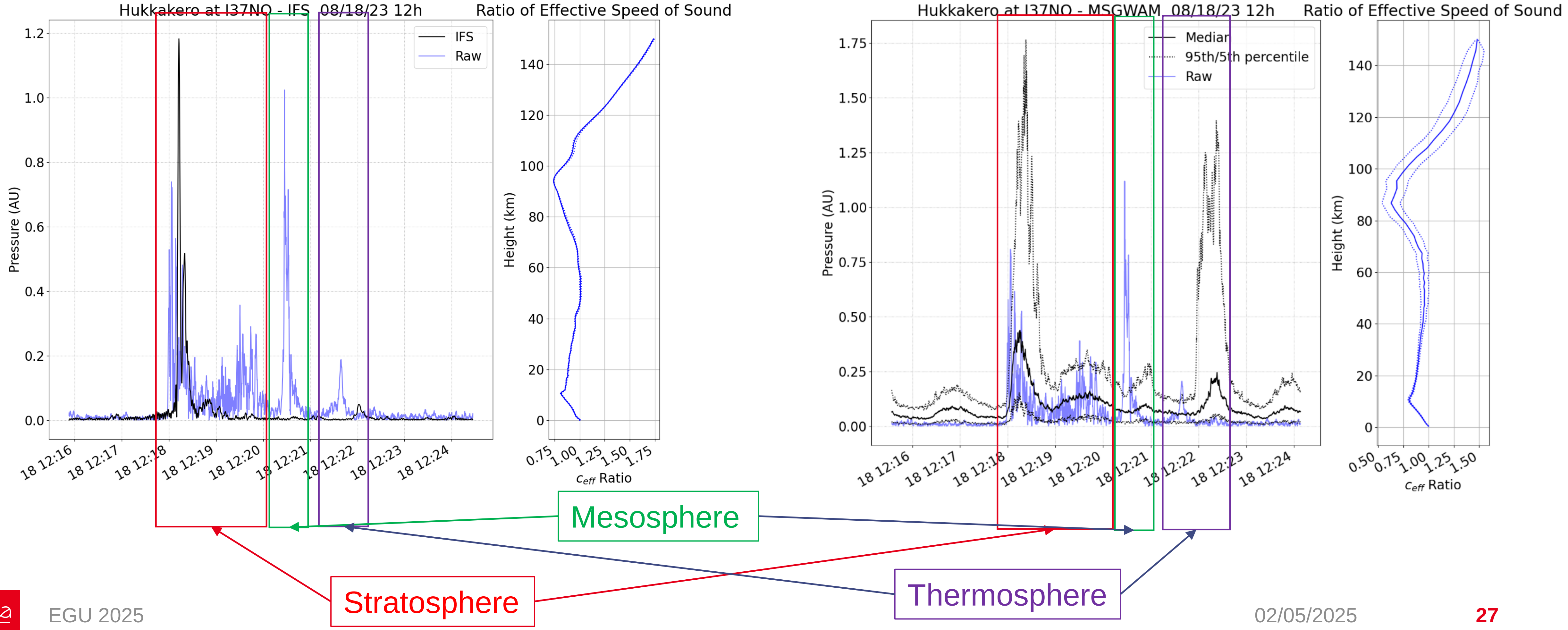
- NCPAProp calculates attenuation for a range dependent atmosphere as a function of frequency. (Waxler *et al.*, 2020, 10.5281/zenodo.4477089)
- Complex gain can be determined at station for all the frequencies of interest.
- Waveform is created by convolving the gain at the station with a source signal
- A simple sinusoidal impulse was used, but other more complicated sources could be chosen.





Waveform estimation

- IFS – short stratospheric return, and slightly late thermospheric return
- MSGWaM – elongated (double peaked) stratospheric return, mesospheric and thermospheric returns
- MSGWaM provides much more realistic waveform estimations.
- Inclusion of gravity wave perturbations is essential for proper waveform reproduction.

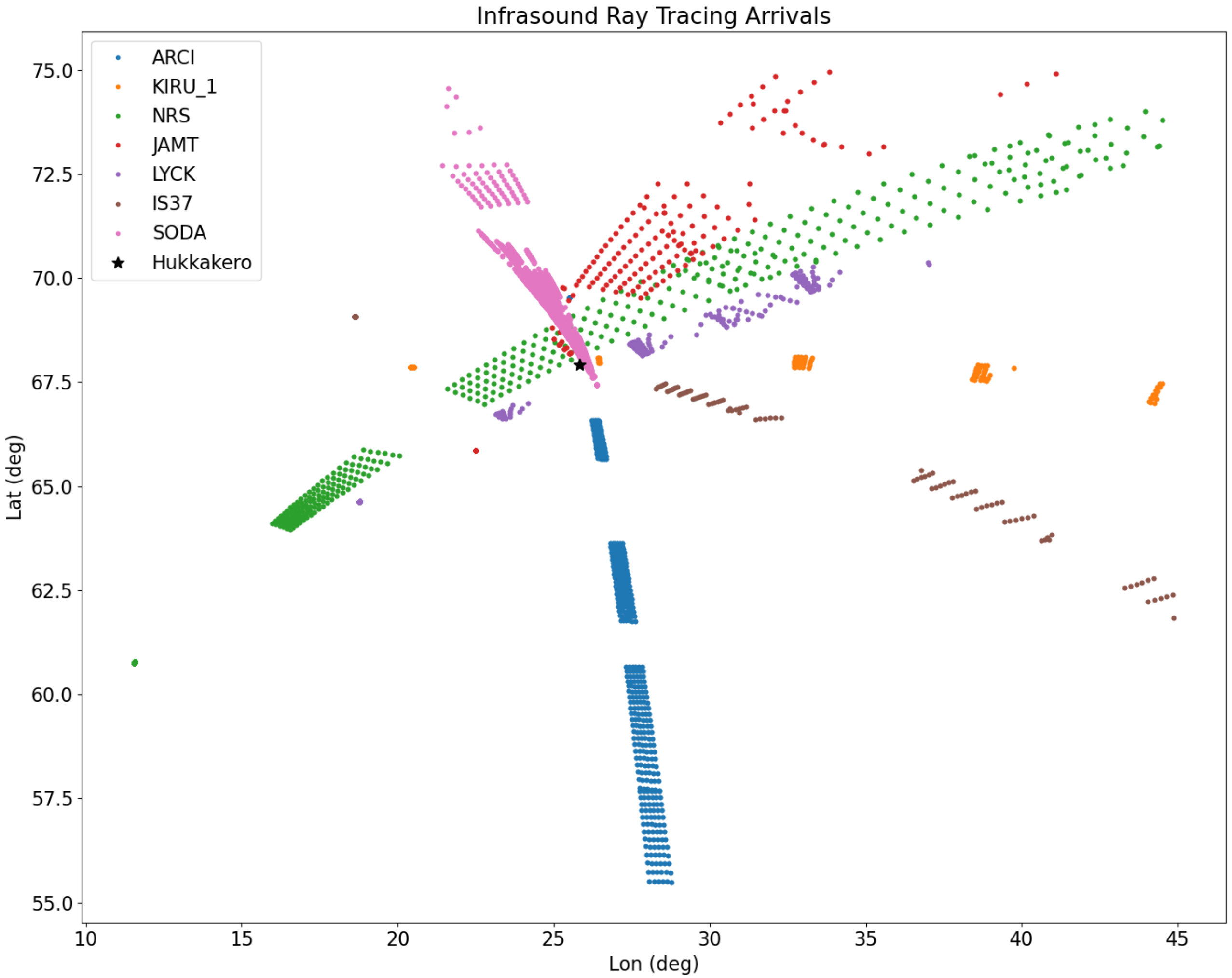


3D infrasound ray tracing

- 3D ray tracing can be used to predict the infrasound trajectory in time and space.
- Source location can be determined using predicted trajectories of observations from 2 or more stations.
- Bayesian inference is used to determine the probability of a source location.

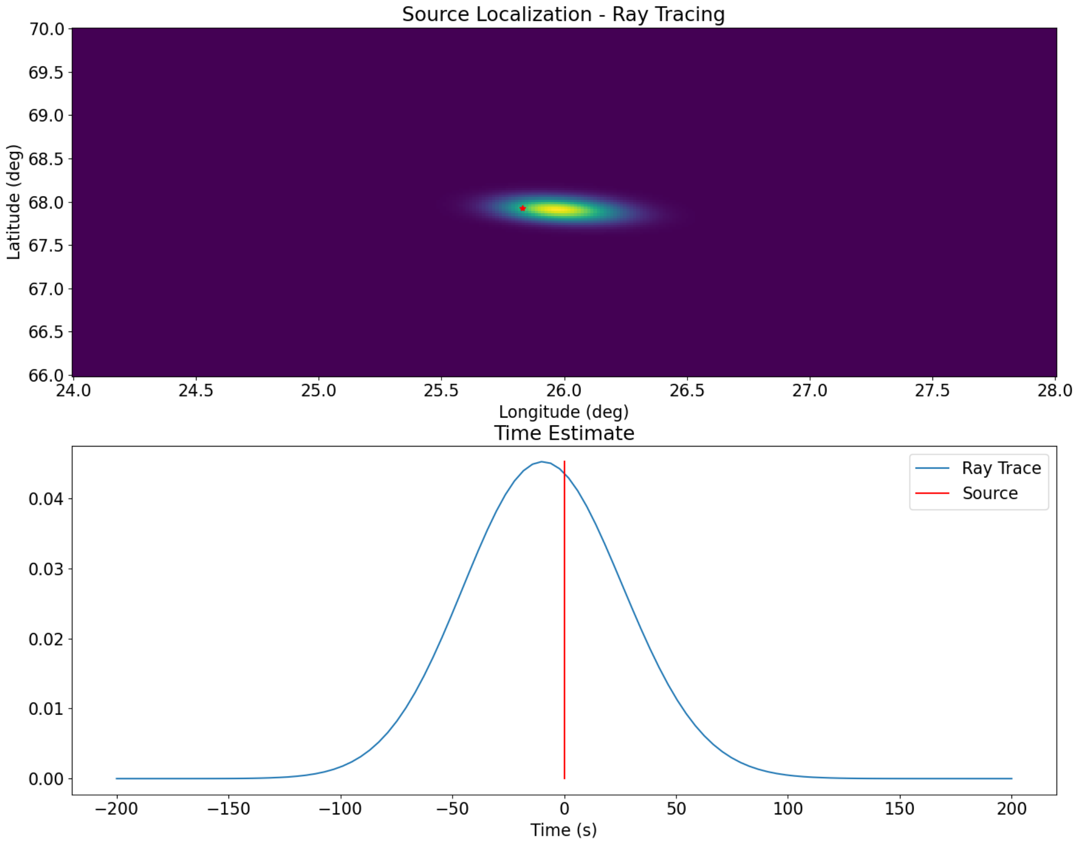
$$P(S|Obs) = \frac{P(Obs|S)P(S)}{\int P(Obs|S)P(S)dS}$$

- Use of 3D ray tracing allows for cross-wind azimuthal deviations of the infrasound trajectory to be taken into account.

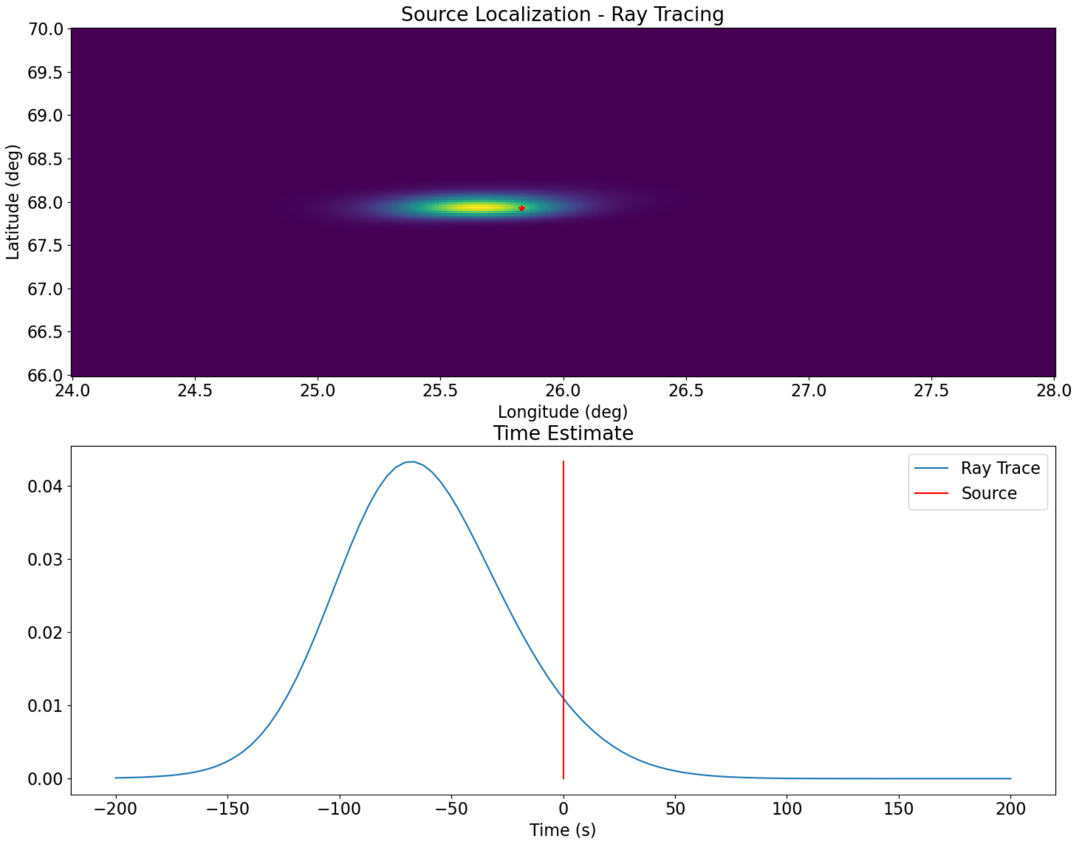


Source localization

IFS

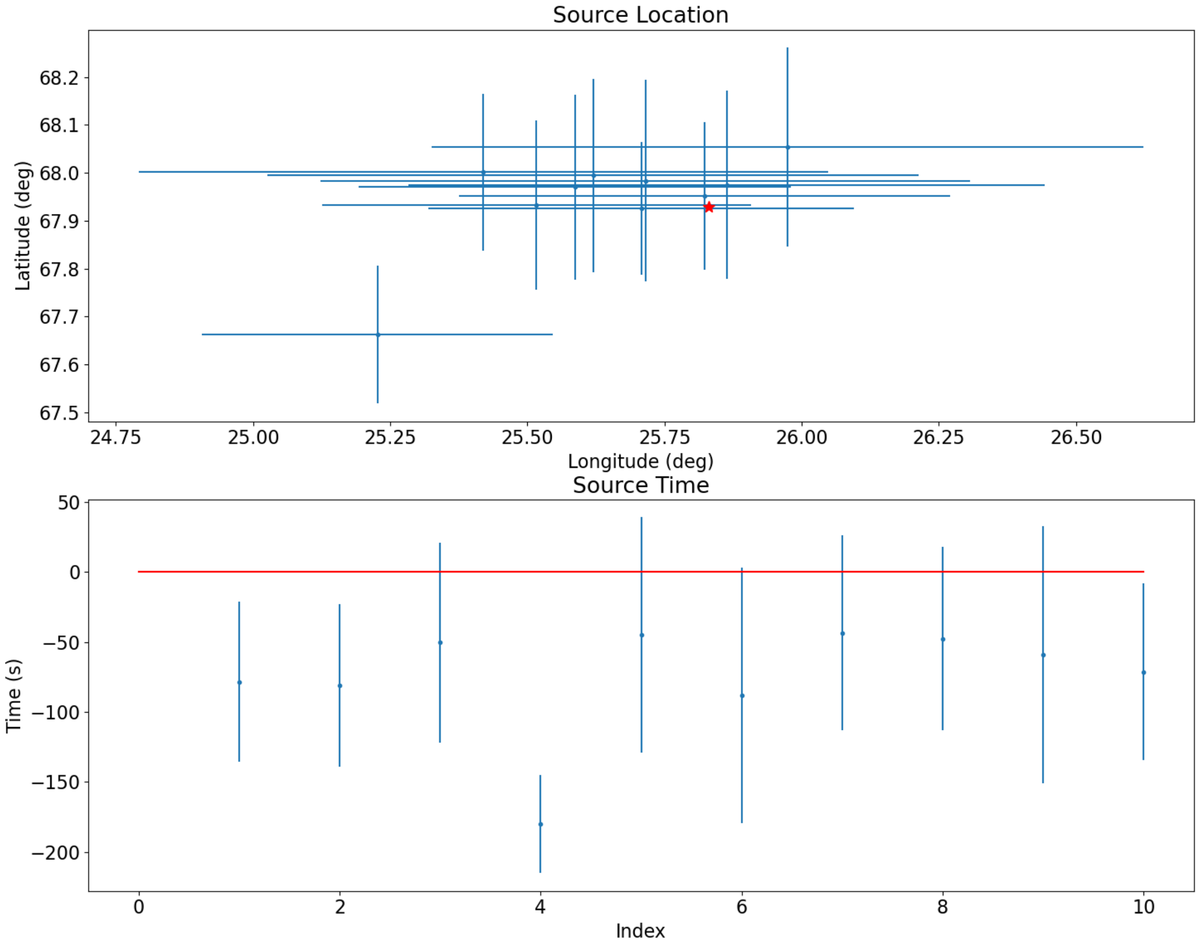


MSGWaM



Effects of GW on infrasound localization

- 10 different GW fields were estimated from the MSGWaM spectral outputs
- Each provides a source location and time estimate.
- Source locations and times (with errorbars representing 95% confidence intervals) with MSGWaM are generally in agreement with the ground truth.
- The gravity wave fields can have a substantial impact on the source location estimates (this was also observed with the waveforms).
- This demonstrates the importance of including a statistically robust estimate of the GW fields for infrasound propagation.



Conclusions

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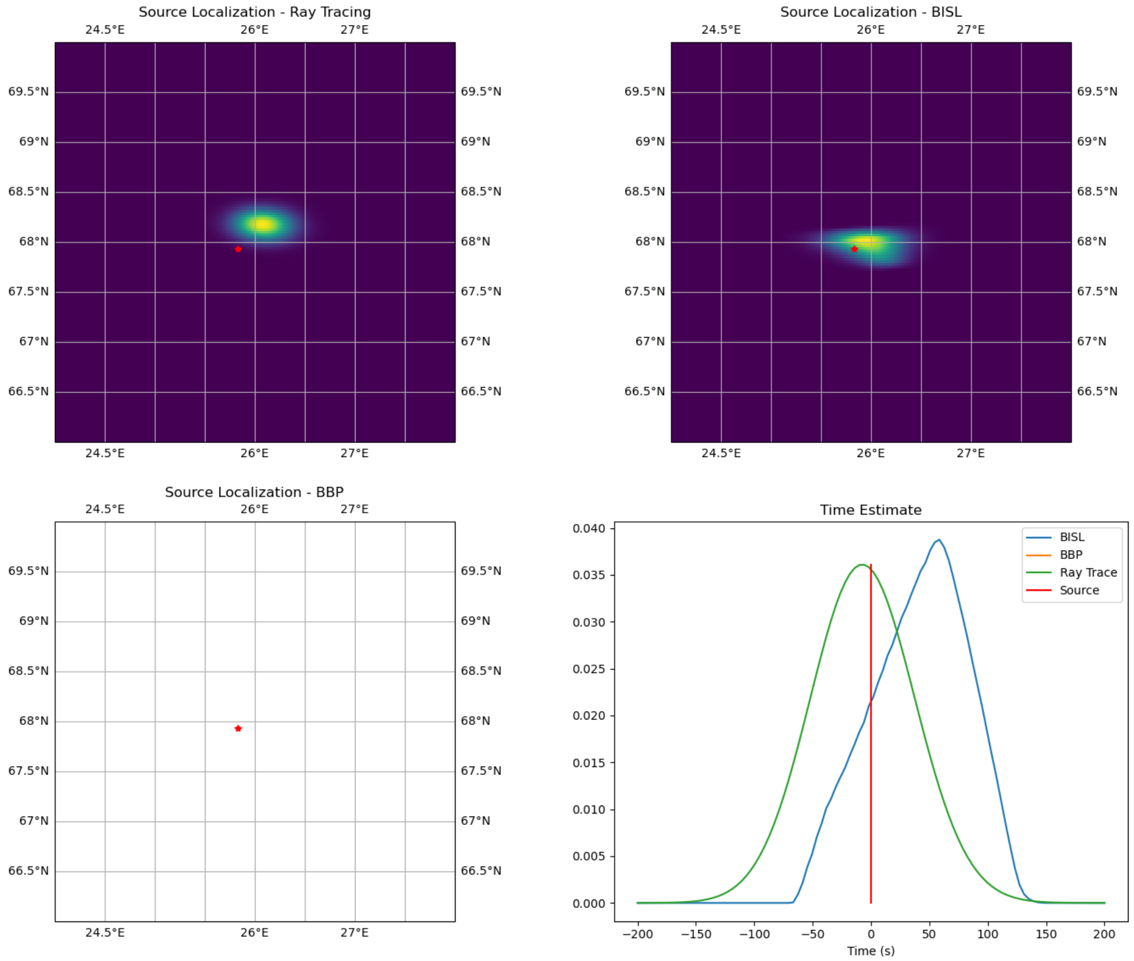
  - Currently at CEA, operational (IFS) model is used with a climatology for the Mesosphere and Lower Thermosphere (MLT).
  - UA-ICON provides these atmospheric parameters up to the MLT.
  - MSGWaM GW parameterizations provide improved background temperature profiles compared to default GW parameterizations (C*).
- Lidar comparisons during the summer of 2023 show good agreement with MSGWaM
- The Hukkakero reference event further demonstrates the importance of correct MLT model predictions
  - With GW perturbations, the stratospheric and mesospheric arrivals are better represented.
  - GW perturbations can have a significant impact on the source location, and therefore need to be properly accounted for.
- Further Lidar comparisons at different locations and during different seasons are necessary to further verify MSGWaM GW parameterisations.
- Validate MSGWaM vertical GW spectra using Lidar and radiosonde observations.

7. Bonus Slides: Source Localization

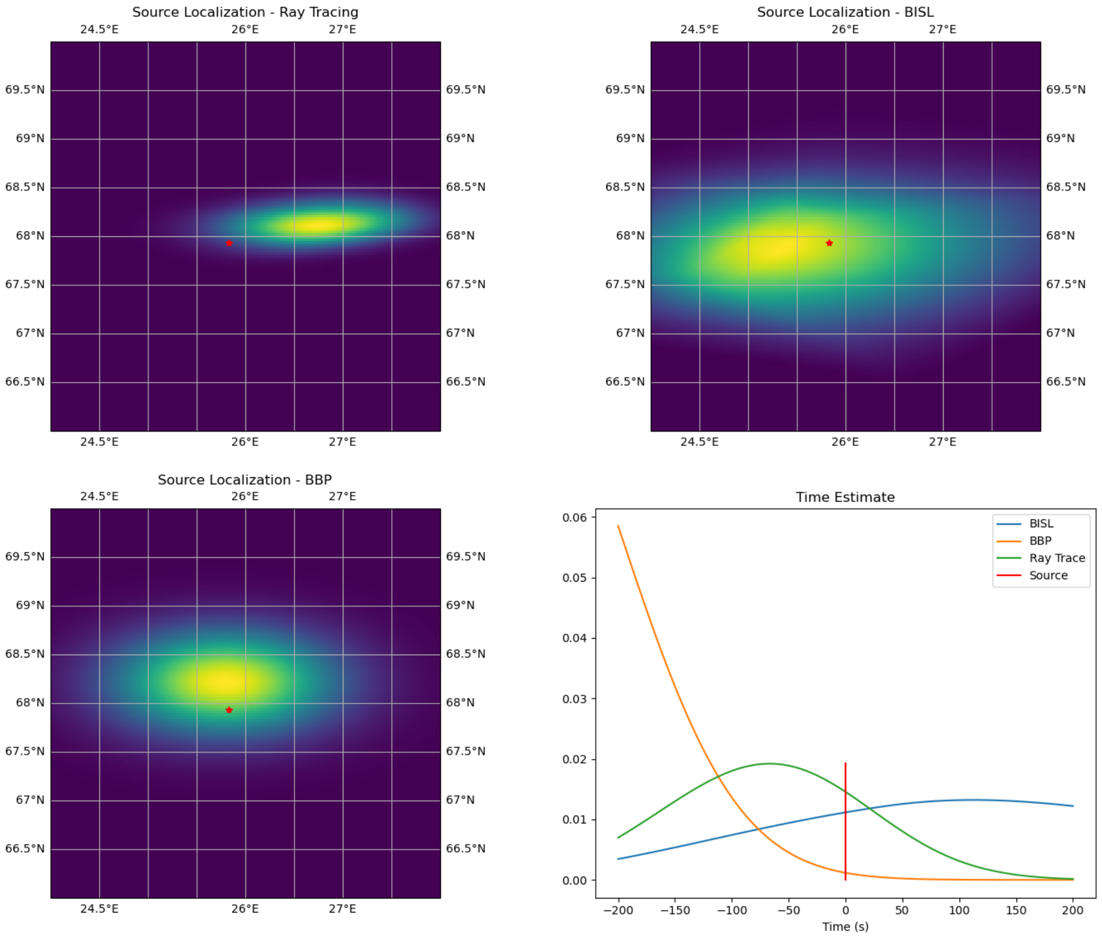
Sharing is encouraged

Hukkakero – Effects of shadow zone

Shadow Zone Stations

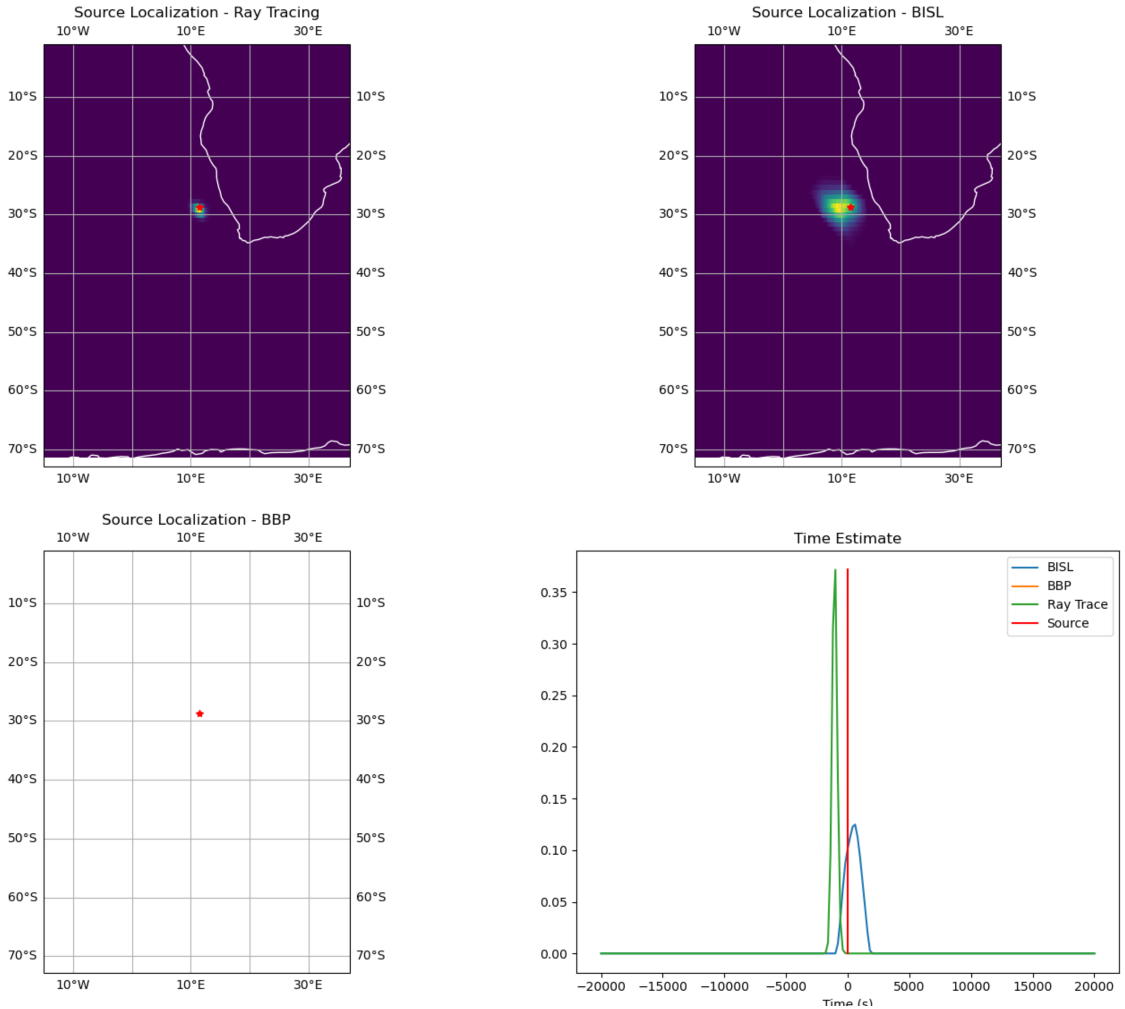


Non-Shadow Zone Stations

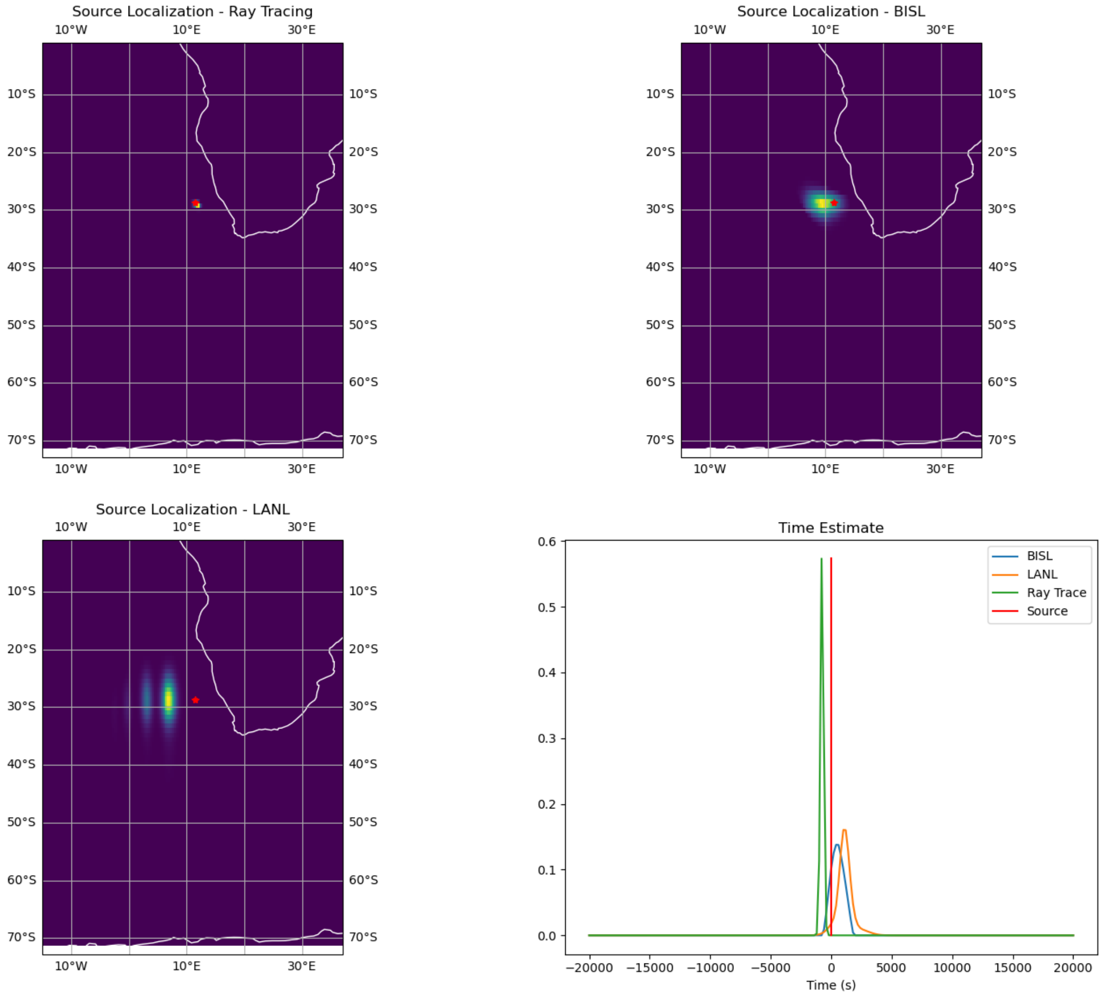


South Atlantic Fireball

6 Stations

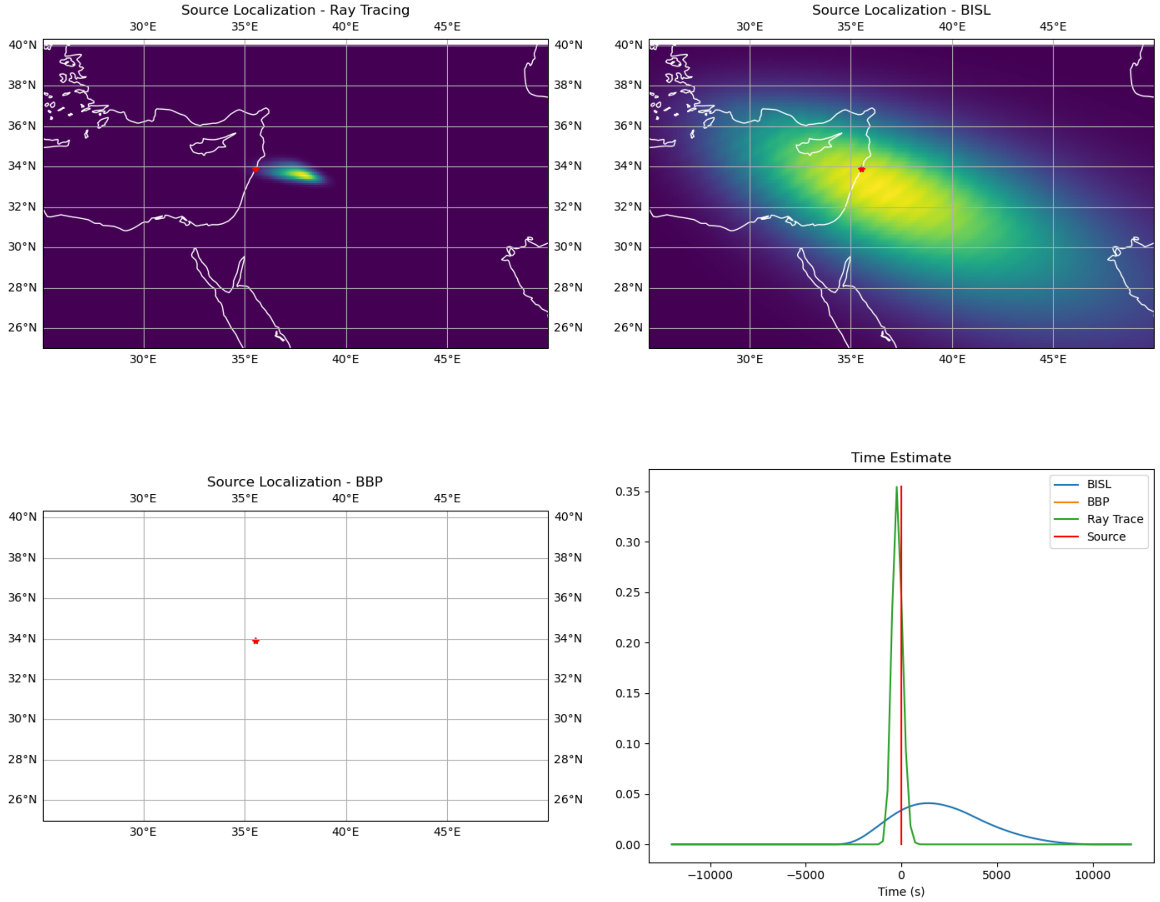


5 Stations



Beirut – Atmosphere Sensitivity

IFS



WACCM