Listening to the Earth using infrasound

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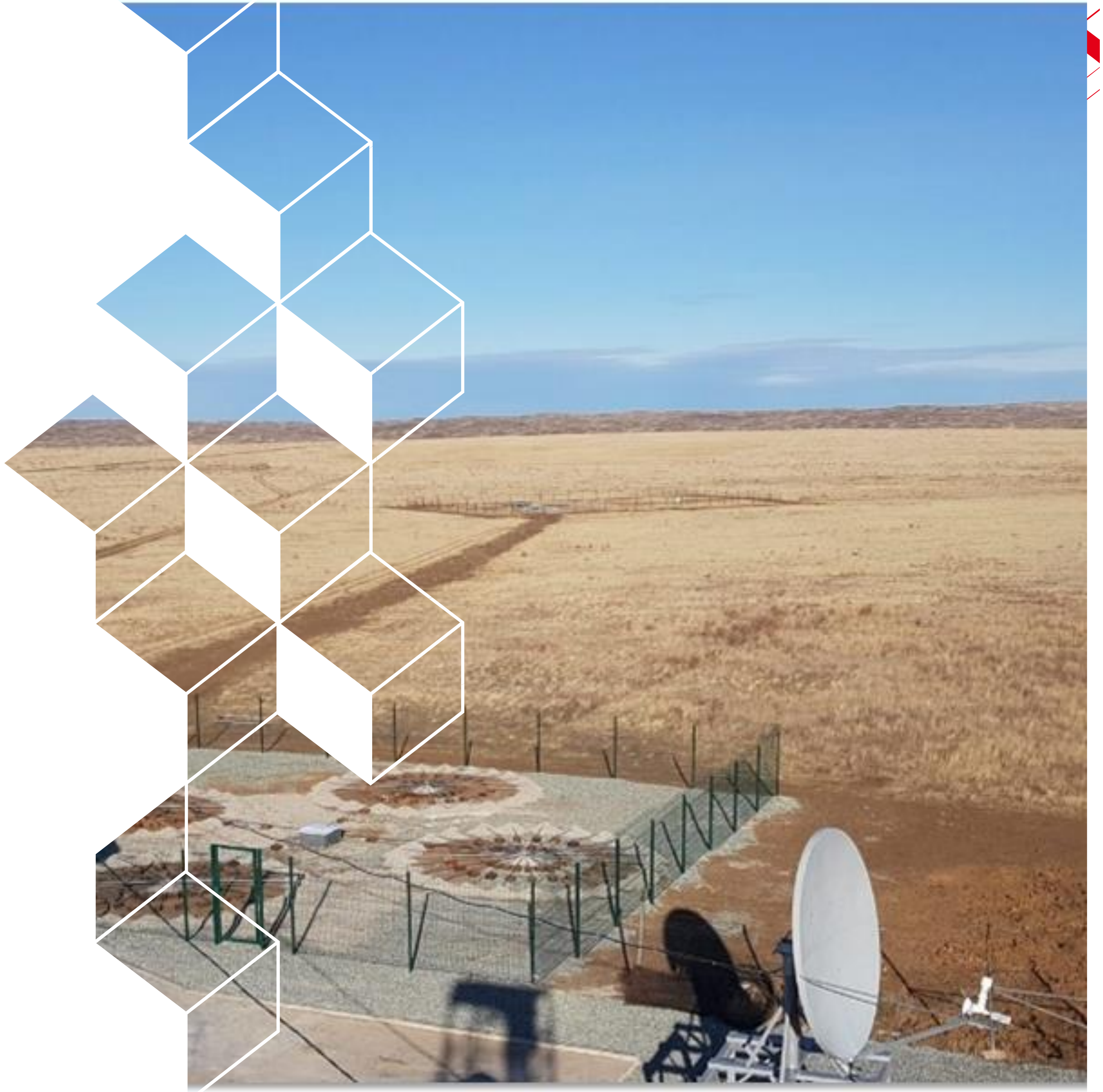
Outline

1. Historical overview
2. Infrasound propagation
3. Network performance modeling
4. From global to regional



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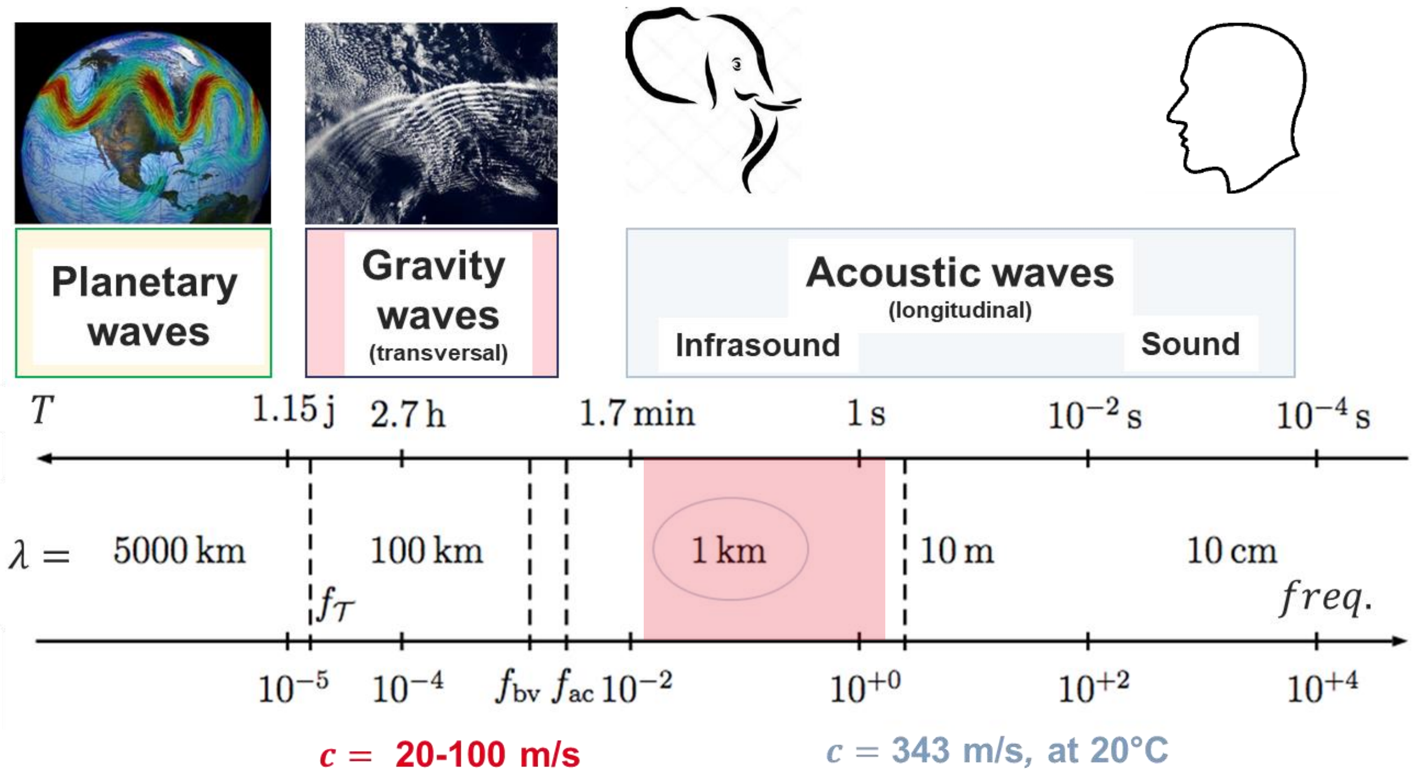
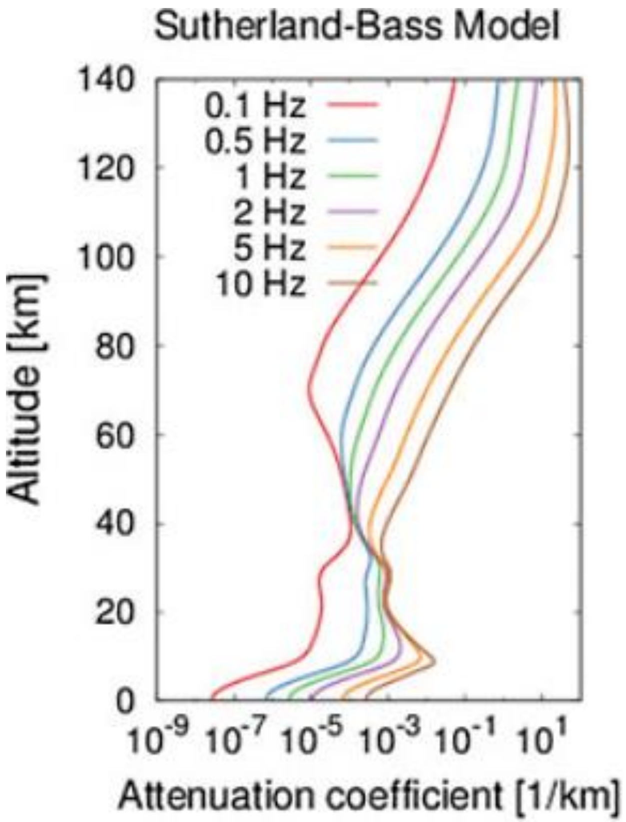
1. Historical overview

@ Shana ParkeHarrison

Infrasound,
and waves among other atmospheric waves

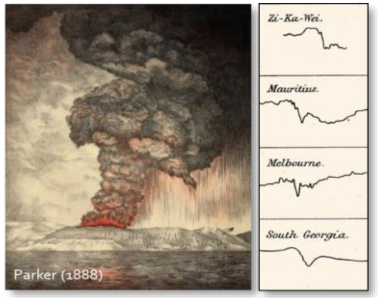




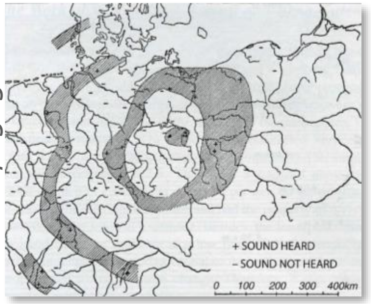
- **Attenuation at 1,000 km:**
  - / 10^7 at 3 Hz
  - / 1,000 at 0,01 Hz

Historical context...

Krakatoa, 1883



Accident, 1925



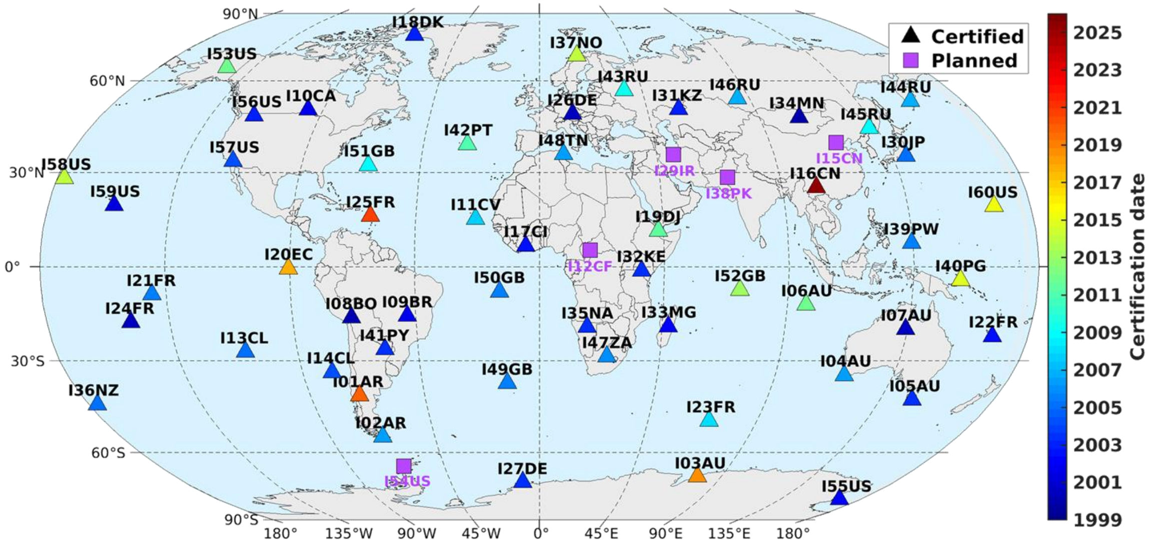
Ac. locator, 1940

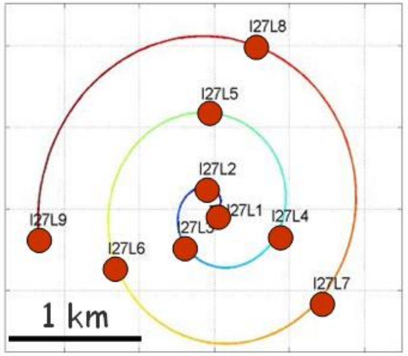
Pr. Rocard, 1956

MB3

Tonga, 2022

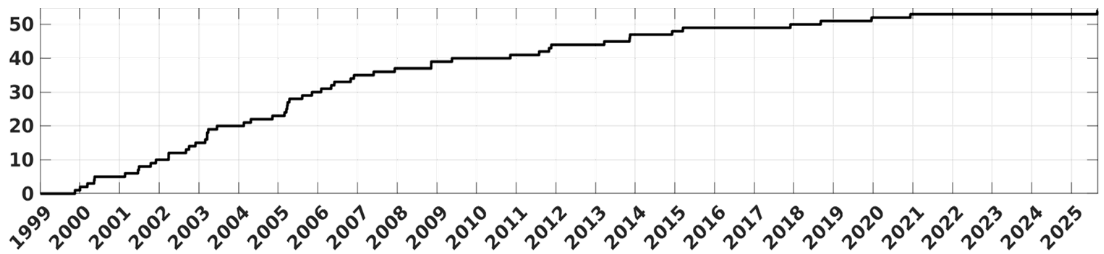
International Monitoring System (IMS)





- **Detection threshold < 1 kt**
- 60 infrasound arrays
- ~90% operating stations
- Array configuration:
  - 4-20 elements
  - ~1 km aperture

Number of certified stations



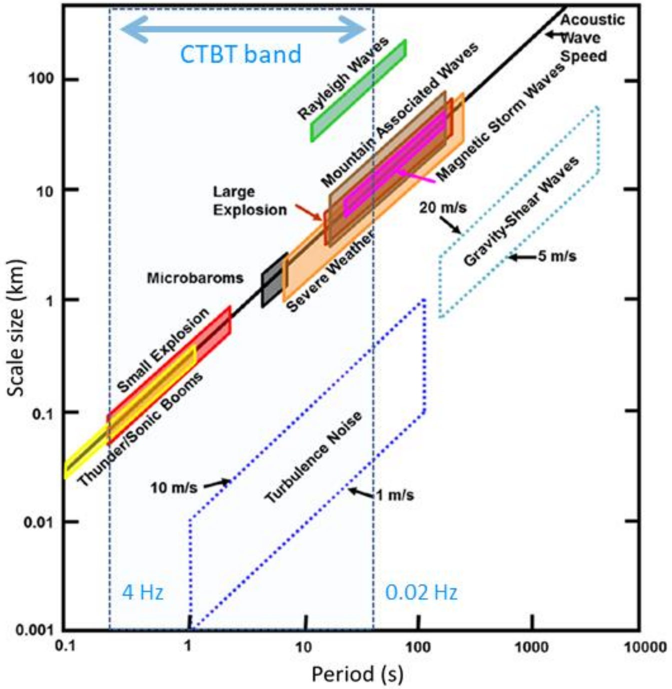
CTBTO - https://www.youtube.com/watch?v=GVWOA5pZG6o

A zoo of overlapping sources (0.05-5 Hz)

Les inspecteurs chargés de vérifier l'interdiction totale des essais nucléaires ne pourront guère descendre au-dessous de la kilotonne. Ils devront faire le tri entre ces explosions et les 8 000 secousses telluriques d'intensité comparable qui se produisent chaque année

Les casse-tête de l'Agence atomique de Vienne

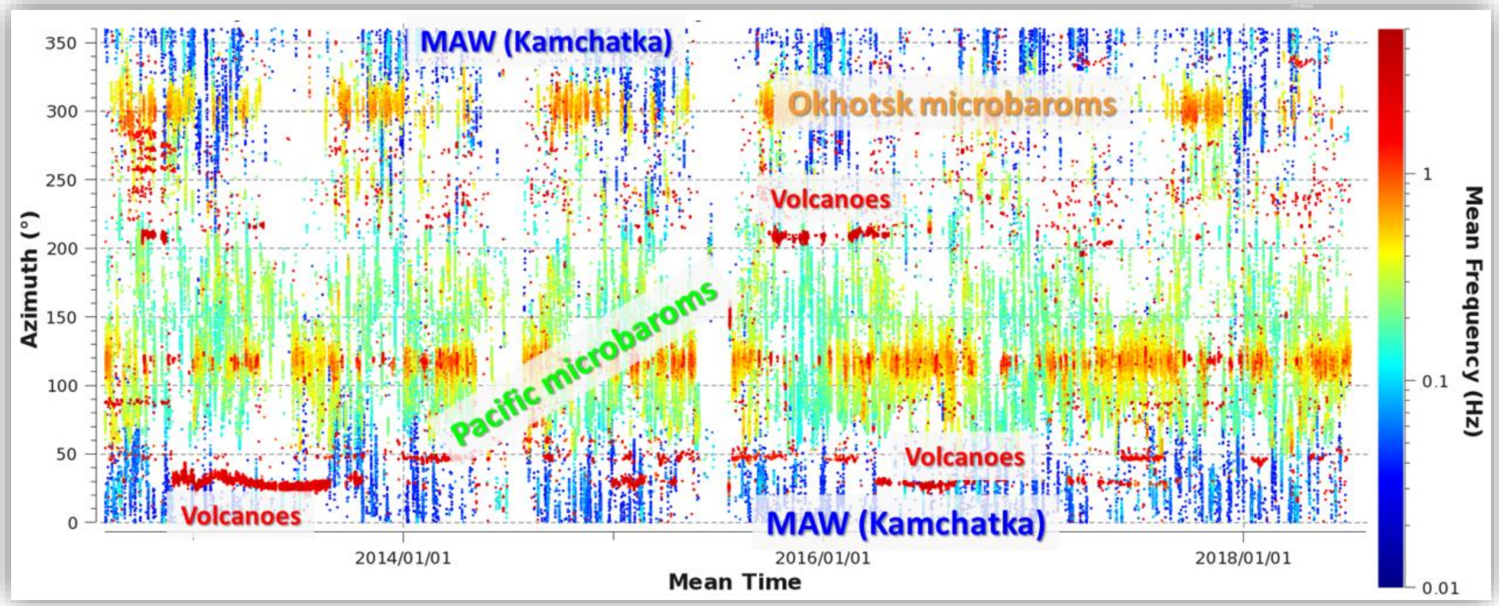
Le Monde, 8 Février 1996

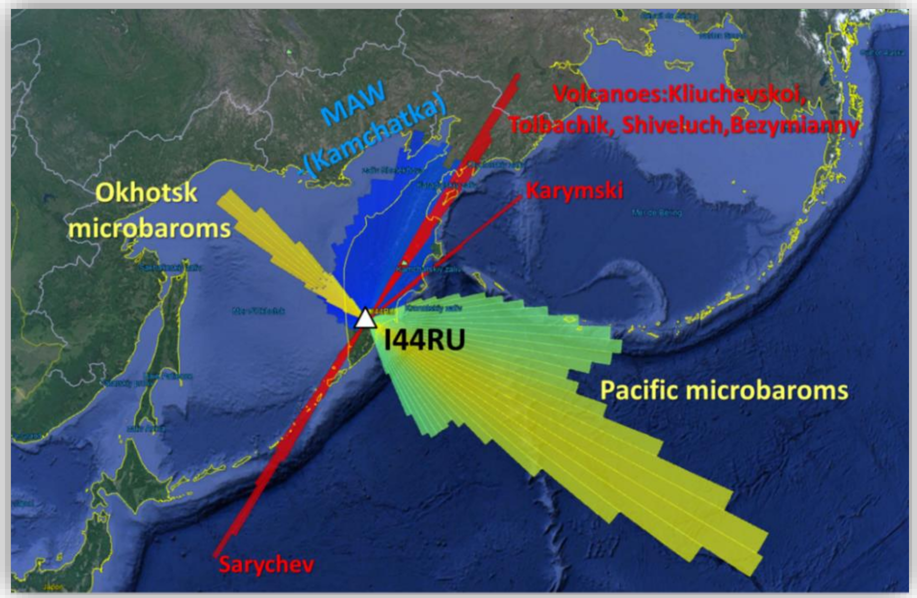


- Correlation / maximum likelihood methods (Cansi 1995, Poste 2023)
- Bandwidths logarithmically scaled
- Discriminate overlapping signals
- An opportunity to calibrate the network and promote civil and scientific applications

A zoo of overlapping sources (0.05-5 Hz)

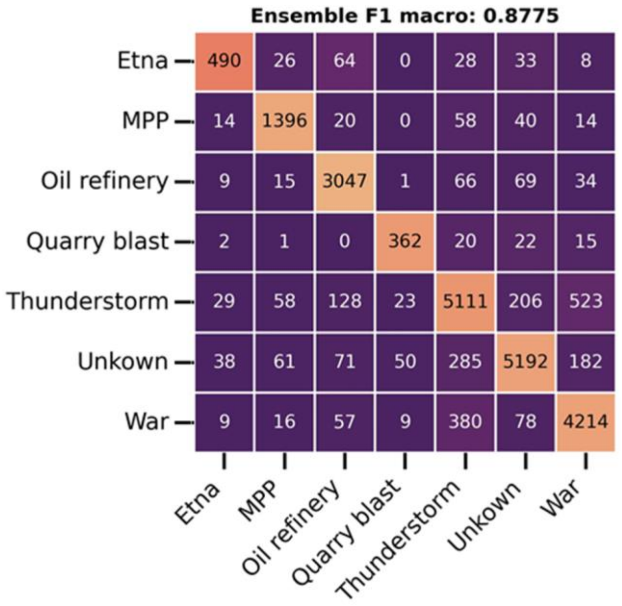
- Challenge: stations blinded by environmental coherent noise
- A real-time processing
- From detection to localization

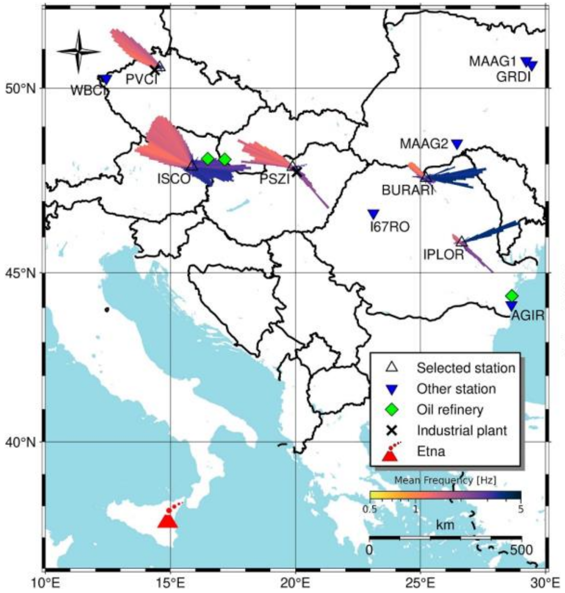


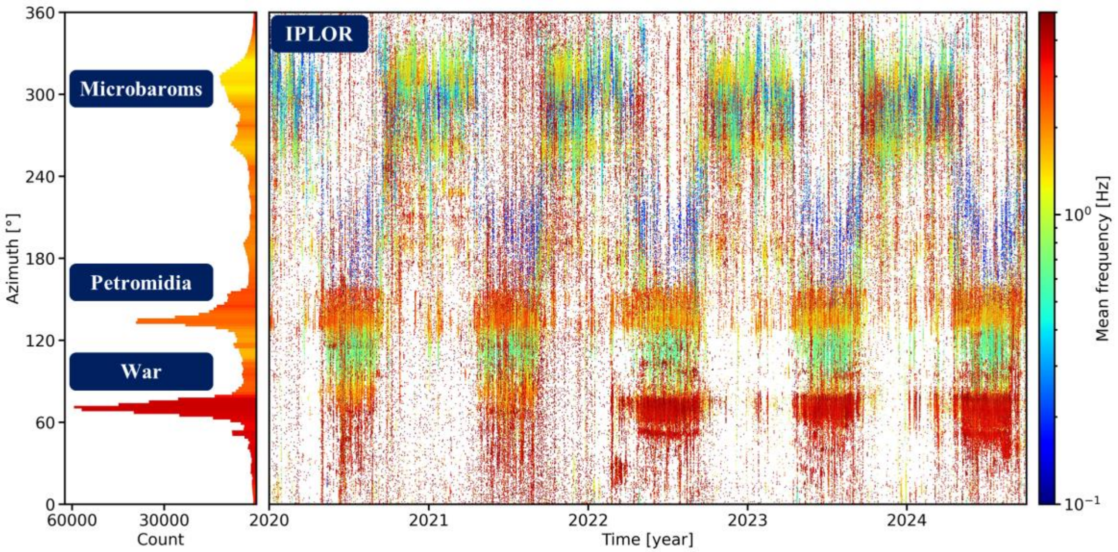


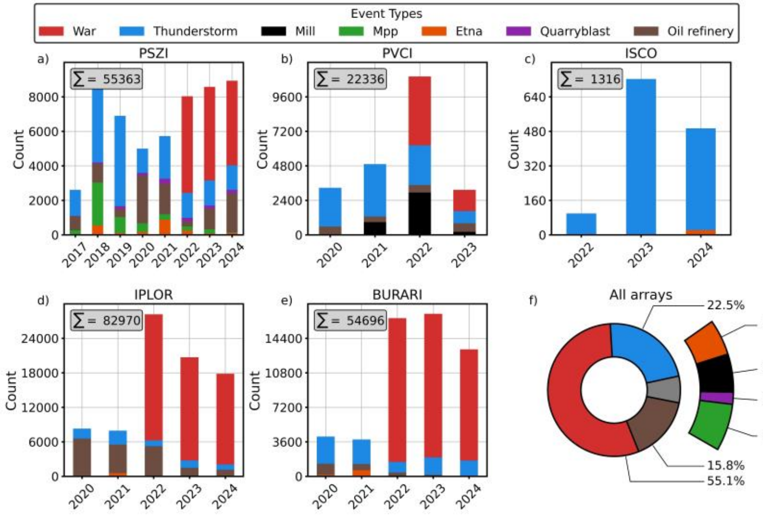
Rich observations from regional networks
Automatic discrimination using machine learning

- Features:
  - Tabular detection parameters fed into Random Forests
  - Convolutional Neural Networks (CNNs) trained on spectrograms (0.5-8 Hz)
- Ensemble classifier: 4 arrays used for training, validation and testing
  - 1 array used for transfer learning
  - Model accuracy (F1 score: 0.88)



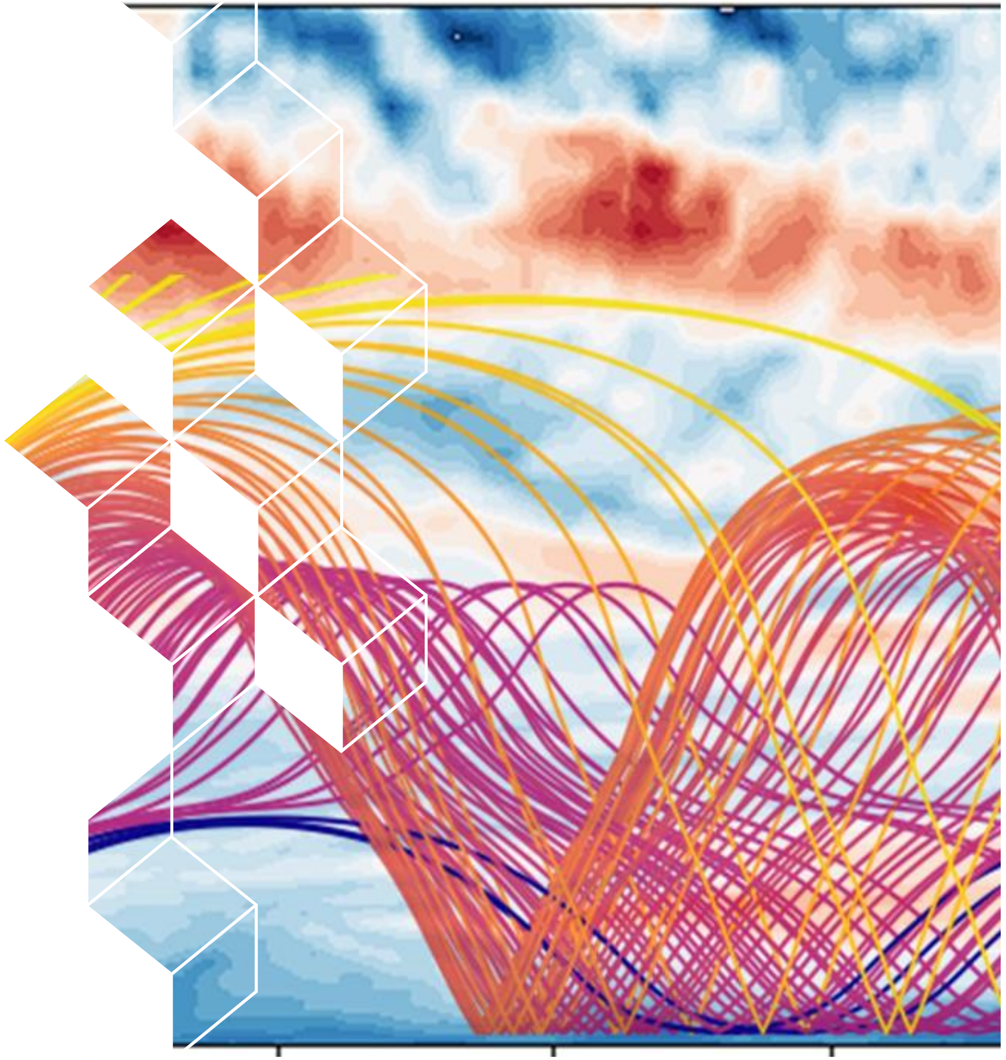






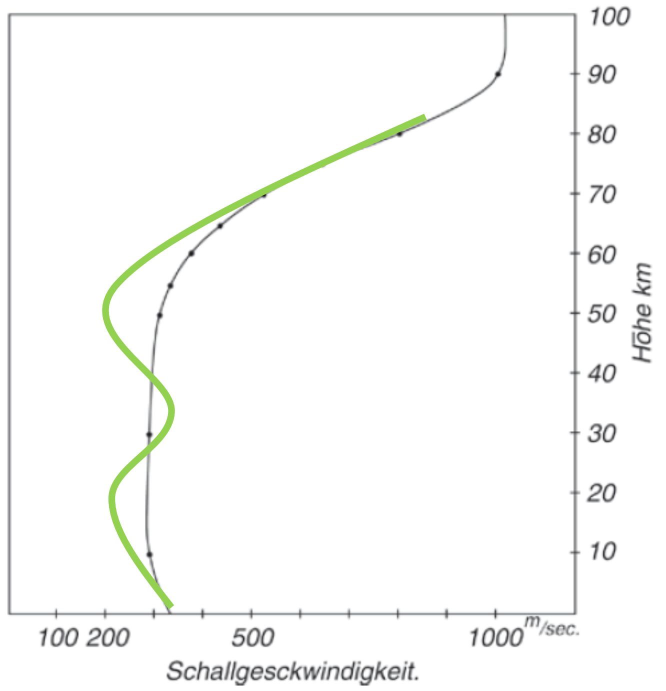
Pasztor et al., JGR 2025
DOI: 10.1029/2025JD044047

2. Infrasound propagation



The siege of Antwerp (Anvers)

October 1914: anomalous sound propagation



- First acoustic velocity profiles (Von dem Borne, 1910)
- Wind explains zones of silences (Lindemann 1922; Whipple 1923)

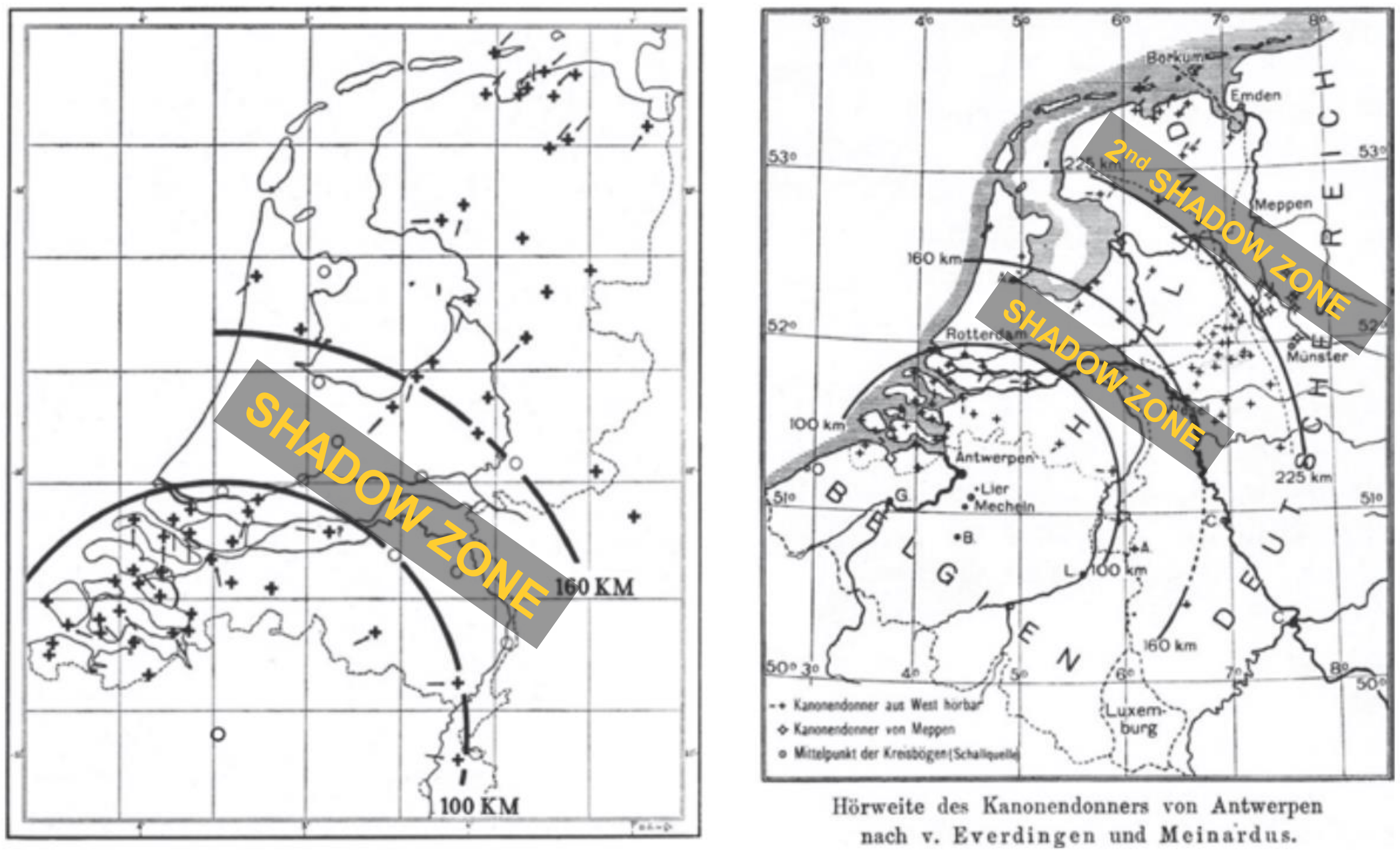
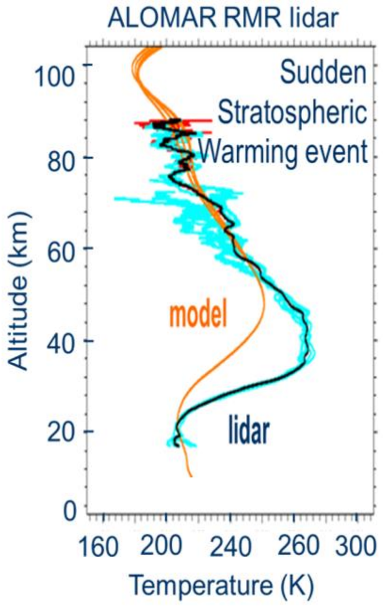


Fig. 1.11 Observations (*crosses*) from canon fires from the siege of Antwerp (*circle*) in the Netherlands (*left*) (Van Everdingen 1914) and Germany (*right frame*) (Meinardus 1915)

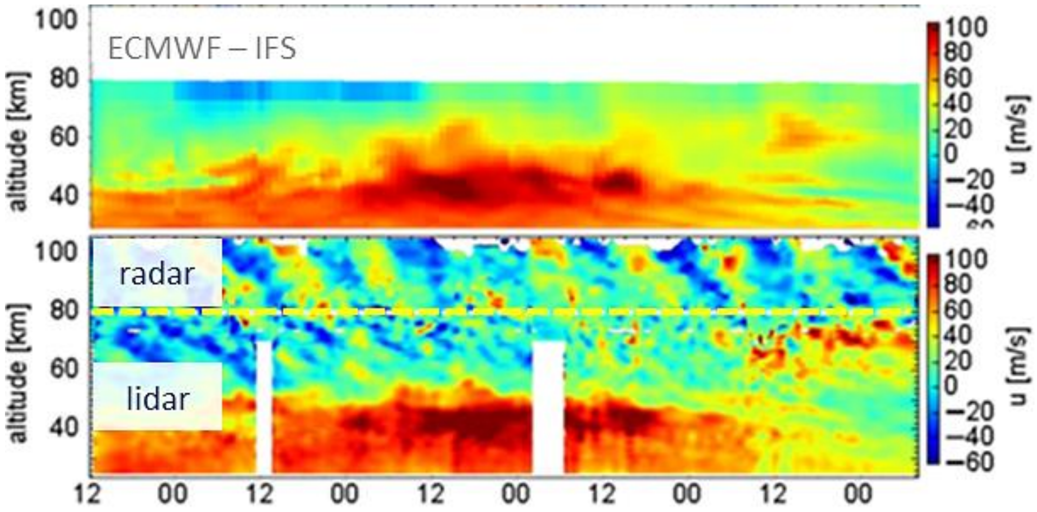
Towards an improved description of the atmosphere



Models	Vertical resolution	Horizontal resolution	Temporal resolution
Von dem Borne (~1880)	2-3 points – up to the stratosphere (balloons)	Local, single profiles	Ponctuals
HWM/MSIS (1970–1990)	~50 levels – up to the thermosphere	5°×5° (≈ 500 km)	Climatological (season/year)
IFS – ECMWF 2000–	91→137 levels 0-80 km	~9 km (TCo1279)	1-6 h
ICON 2020–	120 levels	~13 km	1-6 h
AIFS single/ensemble 2025–	Variable, from ERA5	0.25° (~25 km)	Minutes – 1 h

Ai

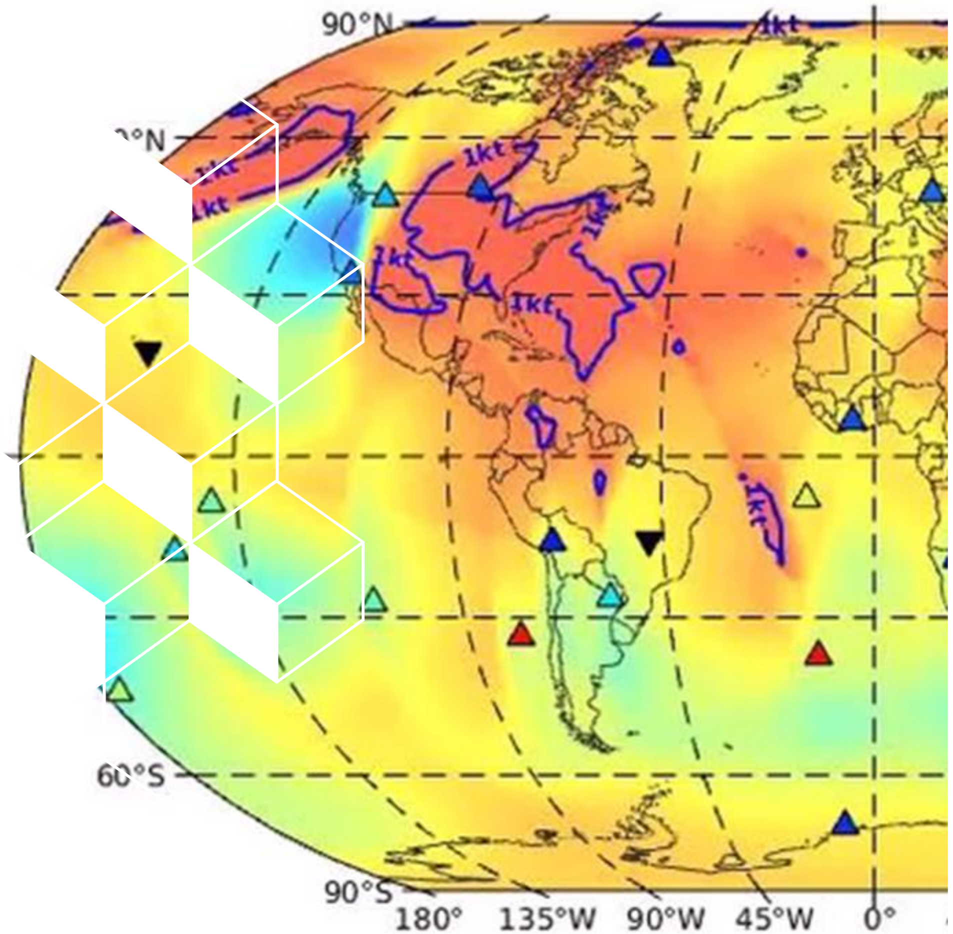
Aurora, FourCastNet, GraphCast, Pangu-Weather…



- Isolated sounding
- Climatology (HWM/MSIS)
- Operational products (ECMWF, IFS)
- High-top model (ICON NWP, MPIM/DWD)

➔ Still poorly resolved above ~40 km

3. Network performance modeling



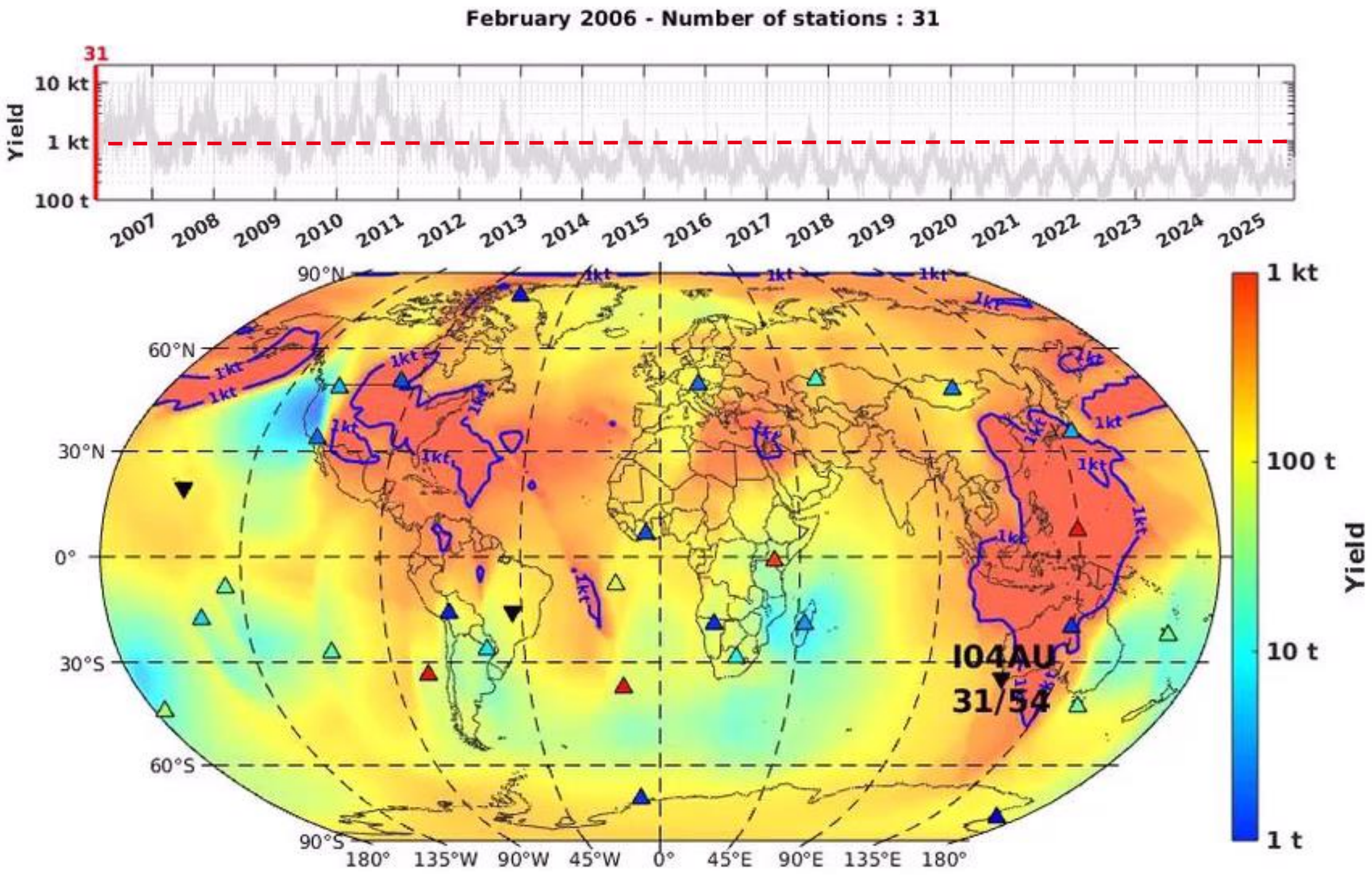
Network performance modeling
From empirical to statistical models

- Measured station noise
- Propagation-based probability distribution
- Attenuation relation accounting for geometrical spreading, dissipation and scattering
- Non-linear curve-fitting of simulated TLs [ceff x f]
- Tabulated parameters: $\alpha, a_s, d_s, R_s, \beta$ vs. effective sound speed ratio and frequency
- For [f x r x ceff]: μ_{TL} and σ_{TL}

➔ **Seuil à 3 stations <1 kt**

1 map = ~5x10^7 TL calculations!

From two decades to 45 s… (3 station coverage, 1h time step)



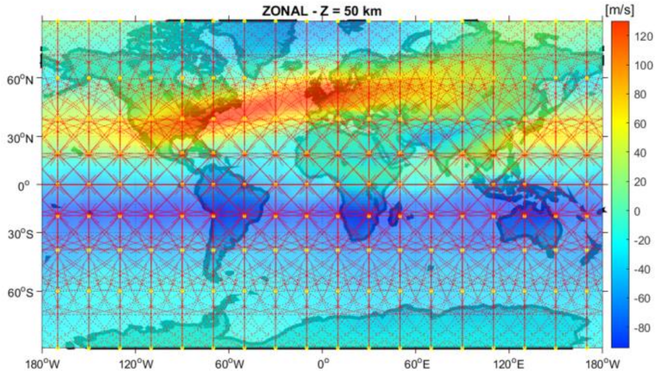
Le Pichon et al., JGR 2025

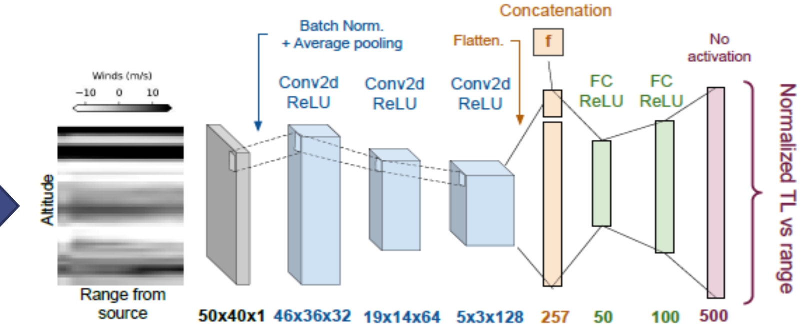
Network performance modeling

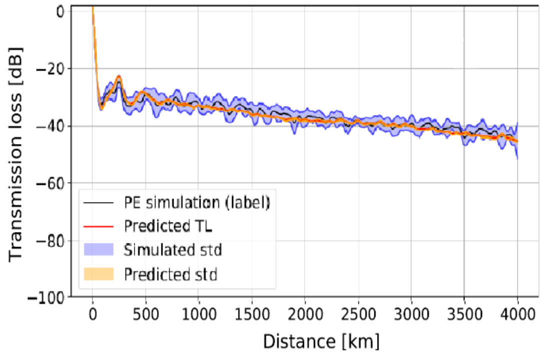
Deep learning surrogate model for near real-time application

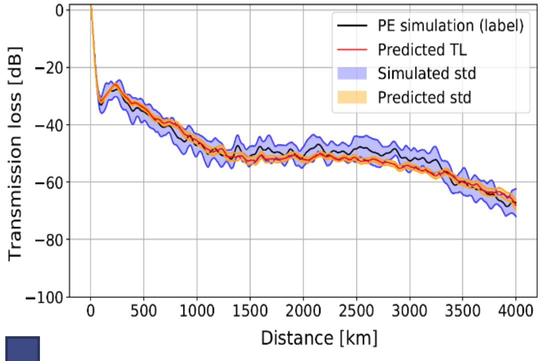
- Inputs: 2D realistic atmospheric slices
  - Whole Atmosphere Community Climate Model (Gettelman et al., 2019)
  - Massive simulations using parabolic equation solver (Waxler et al., 2021)
- Supervised Convolutional Recurrent Neural Network
  - Capture range-dependent features
  - Epistemic + data uncertainties (Gawlikowski et al., 2023)
- Outputs: ground-level transmission losses
  - Testing: ~ 5% average error
  - Generalization: ~ 10% average error

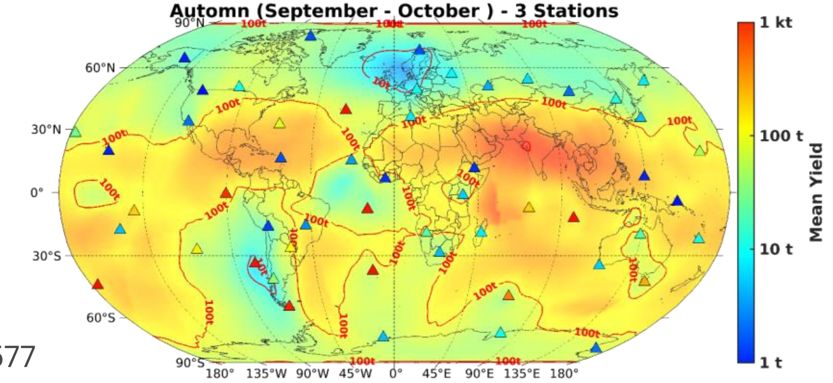
⇒ **Computation time reduction by 5 orders of magnitude**





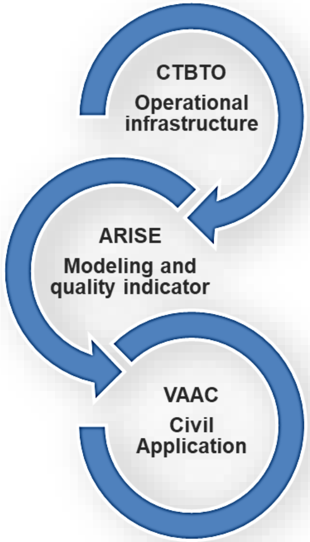


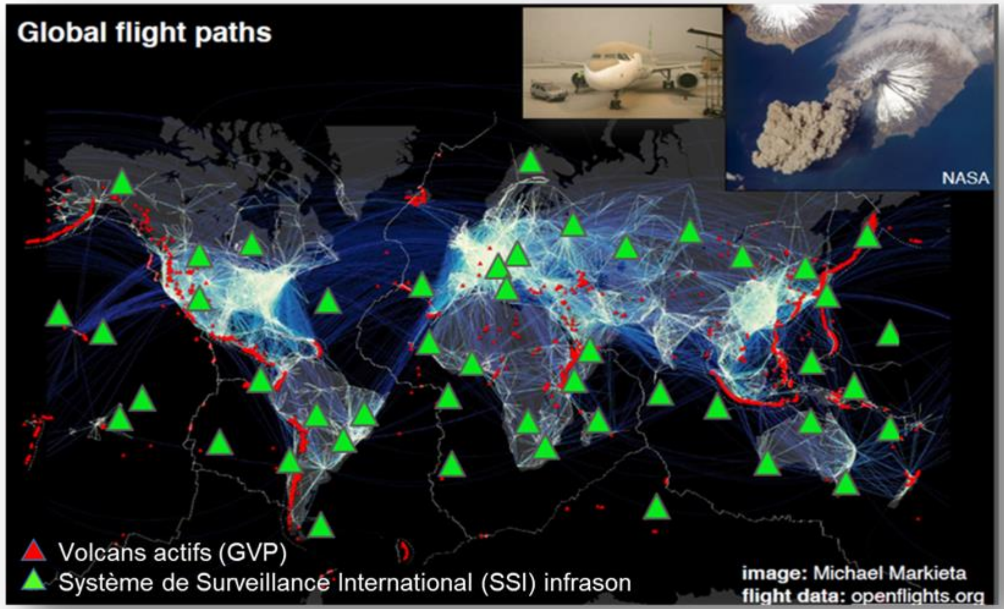


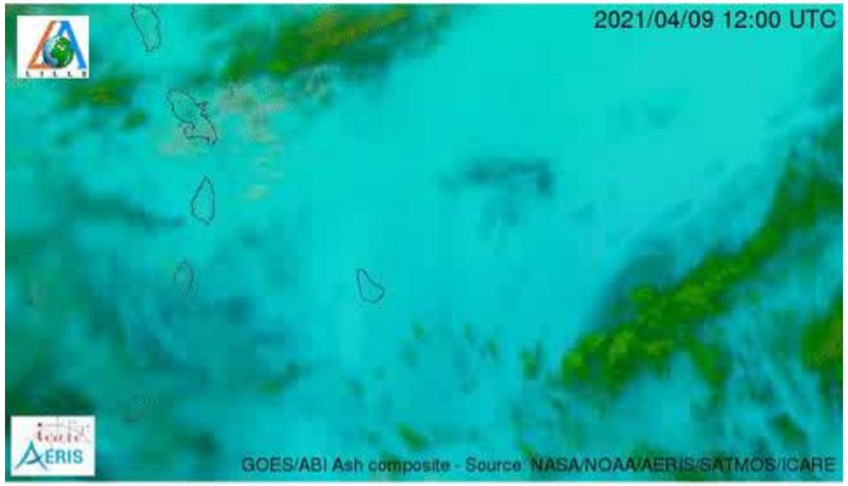


Cameijo et al., JGR 2025
DOI: 10.1029/2025JD043577

Automatic detection, location, and characterization of volcanic eruption

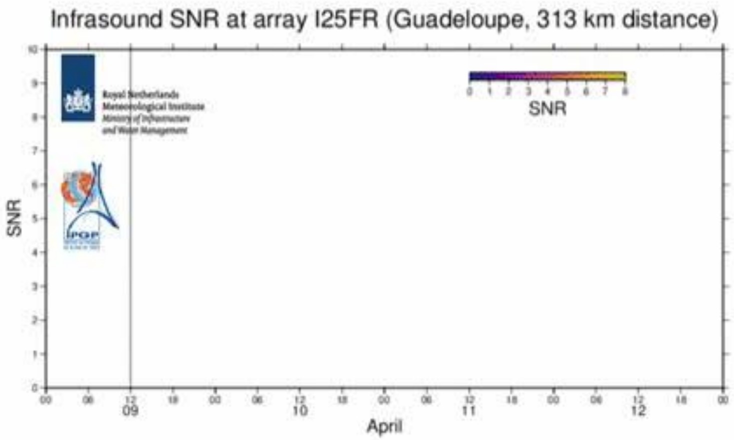






Source: NASA/NOAA/AERIS/SATMOS/ICARE

Marie Boichu, Jacques Descloitre (Univ. Lille, LOA / AERIS / ICARE – marie.boichu@univ-lille.fr).



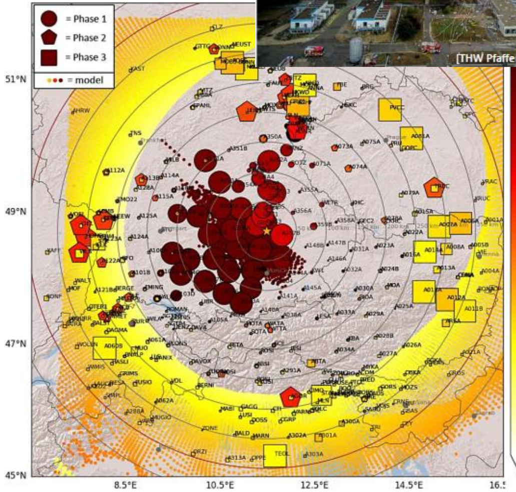
From prototype to real-time system

- ARISE (2012-2018): Volcanic Information System (VIS)
- Geo-Inquire (2022-2026): *European Catalogues for Geohazard Analysis Infrastructure*
  - Post-doc 2024-25 OPGC-LMV/CNRS (Research Fellowship, UCA)
  - August 2025 — VIS Workshop, Univ. of Firenze, Italy / UCA, France
  - Web service: HOTVOLC, SNOV/EPOS-France
  - Integration in the EPOS ERIC VOLC-TCS portal

4. From global to regional

Improving detection capability using dense seismo-acoustic network

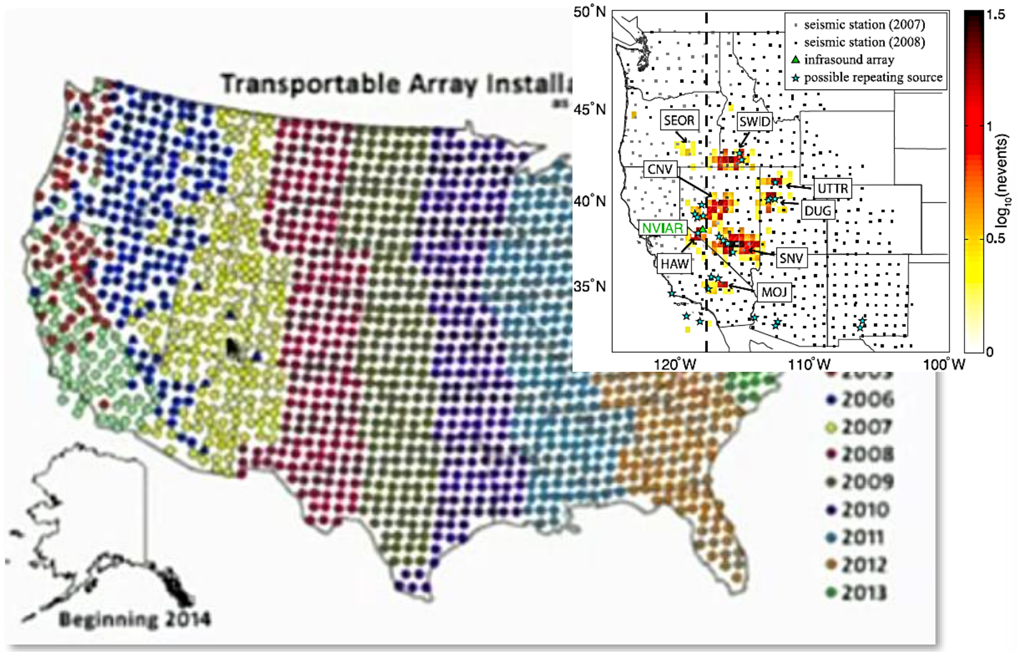
Fuchs, 2019

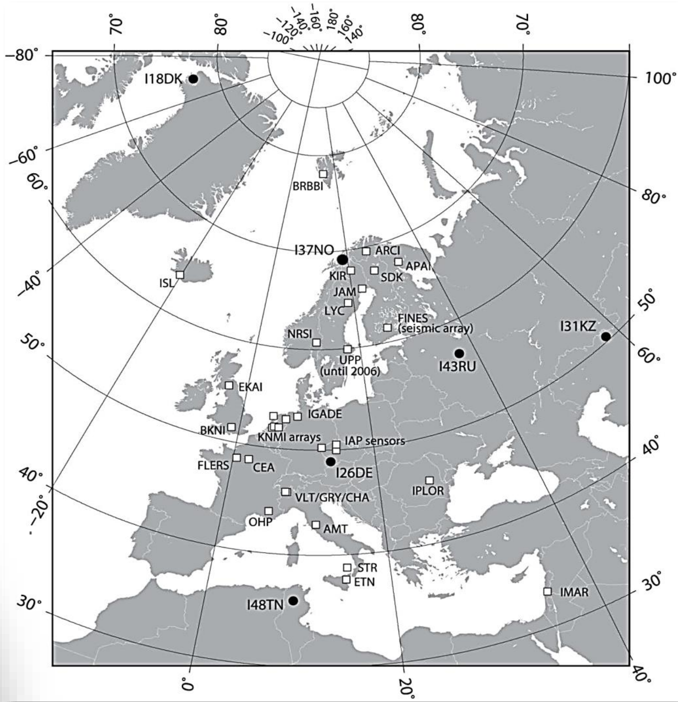


- Illuminating anthropogenic activities (accidental explosions) with the transportable USArray network
- Fine spatial mapping of stratospheric waveguides
- Investigate the effects of small-scale atmospheric disturbances on infrasound propagation (e.g. parameterization of gravity waves)

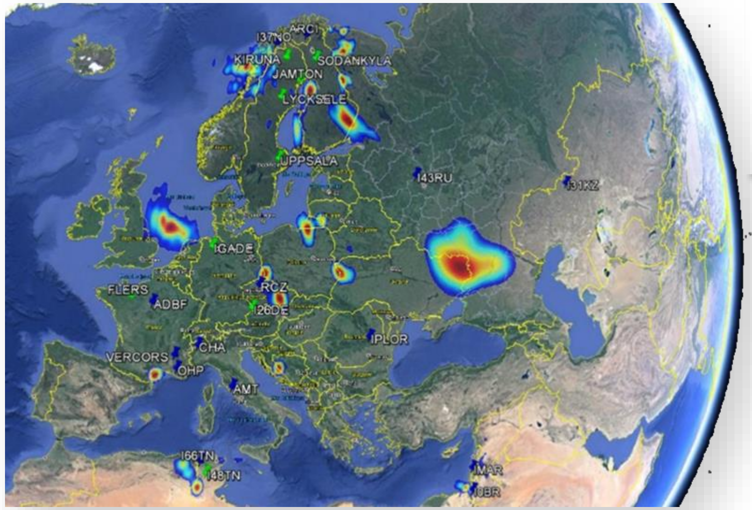
Hedlin, 2014

Walker, 2011





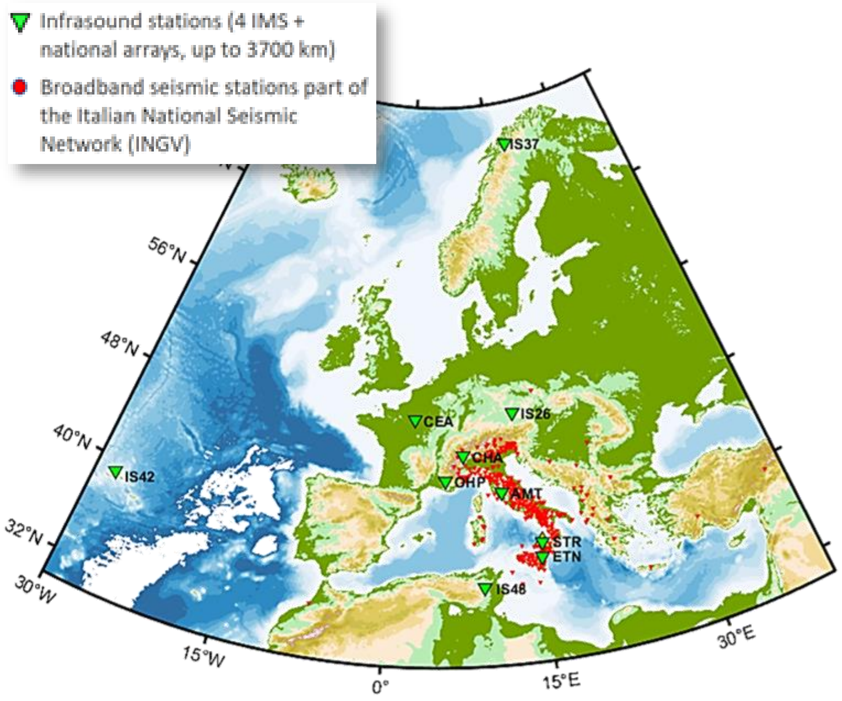
The European Arctic: A laboratory for seismoacoustic studies. Gibbons, 2017

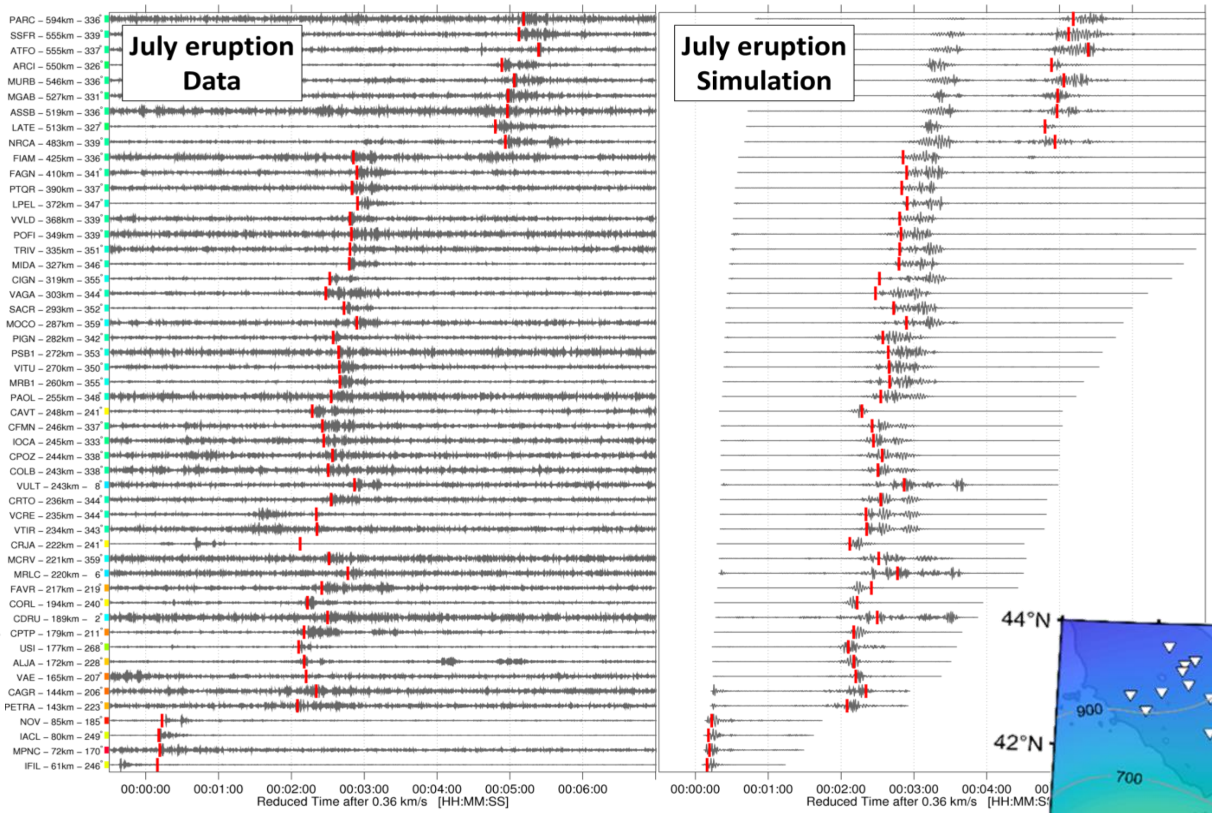


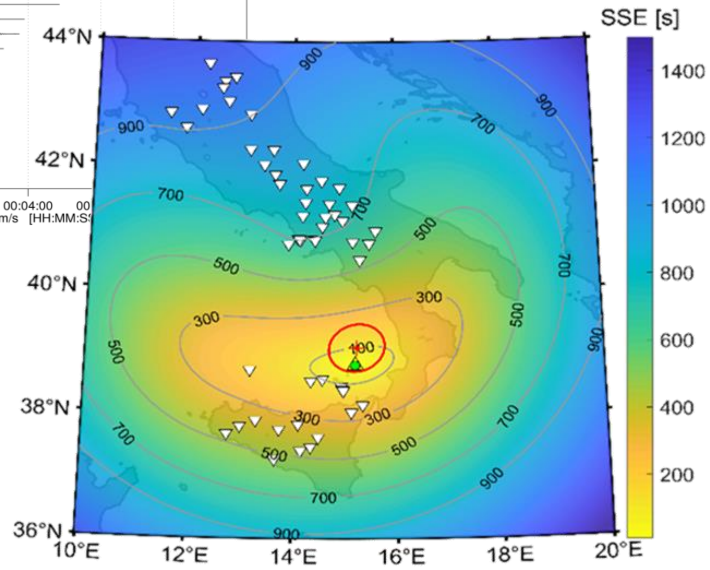
- Since 2012: 24 stations
- Decrease of the detection threshold by one order of magnitude

Rich observations from regional networks

2019 paroxysmal Stromboli eruptions







- Normal mode simulations (0.5-2 Hz)
- Atmospheric model: ECMWF IFS
- Location error: ~1.5 km with INGV stations (~30 km with 6 IMS stations)
- Origin time: Δt<3 s

Le Pichon et al., Scientific Report
DOI: 10.1038/s41598-021-93942-x

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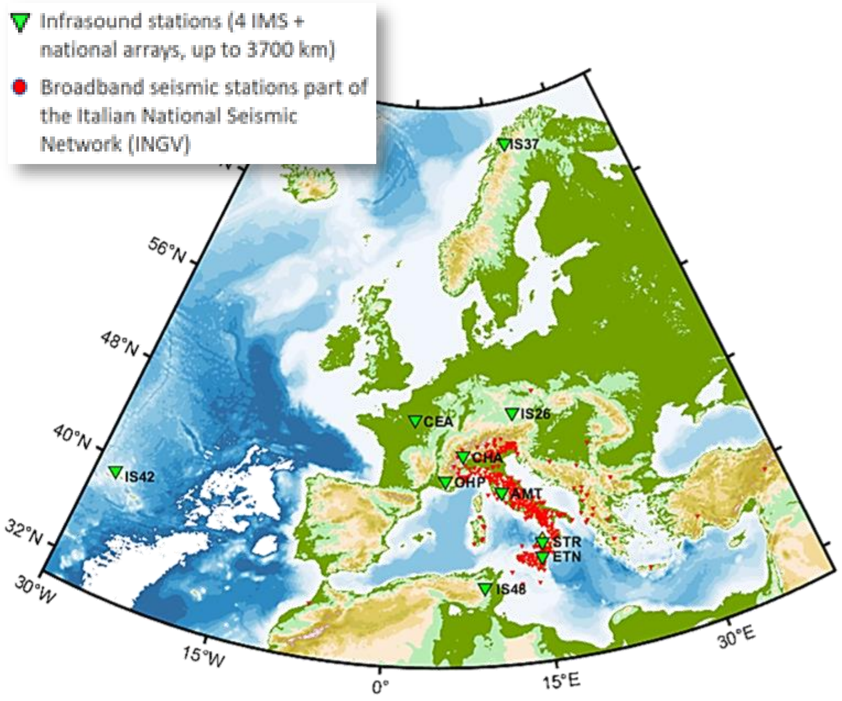
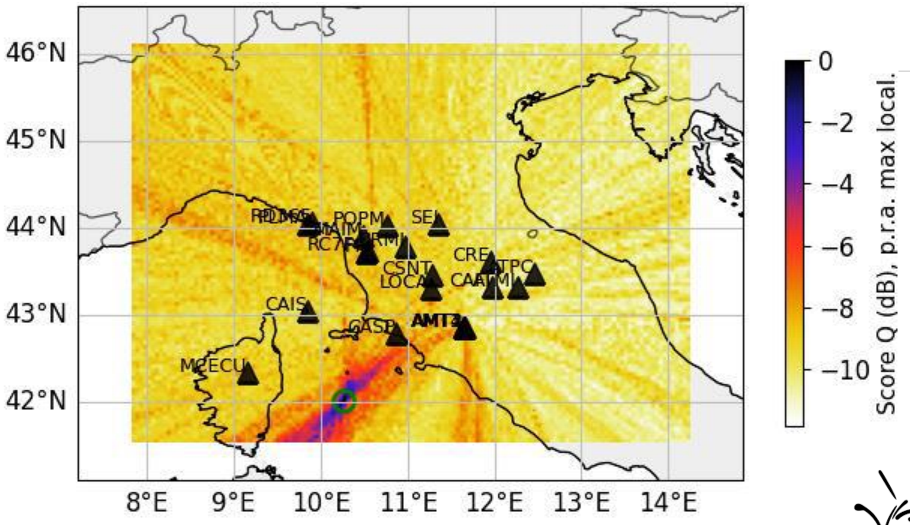
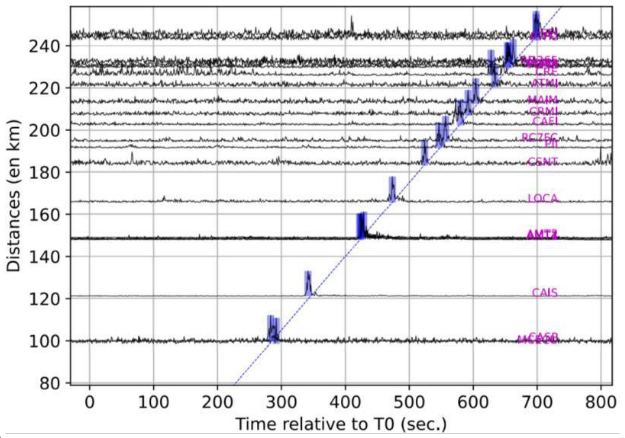


Meteor entry: South of Elba island 20/06/2024





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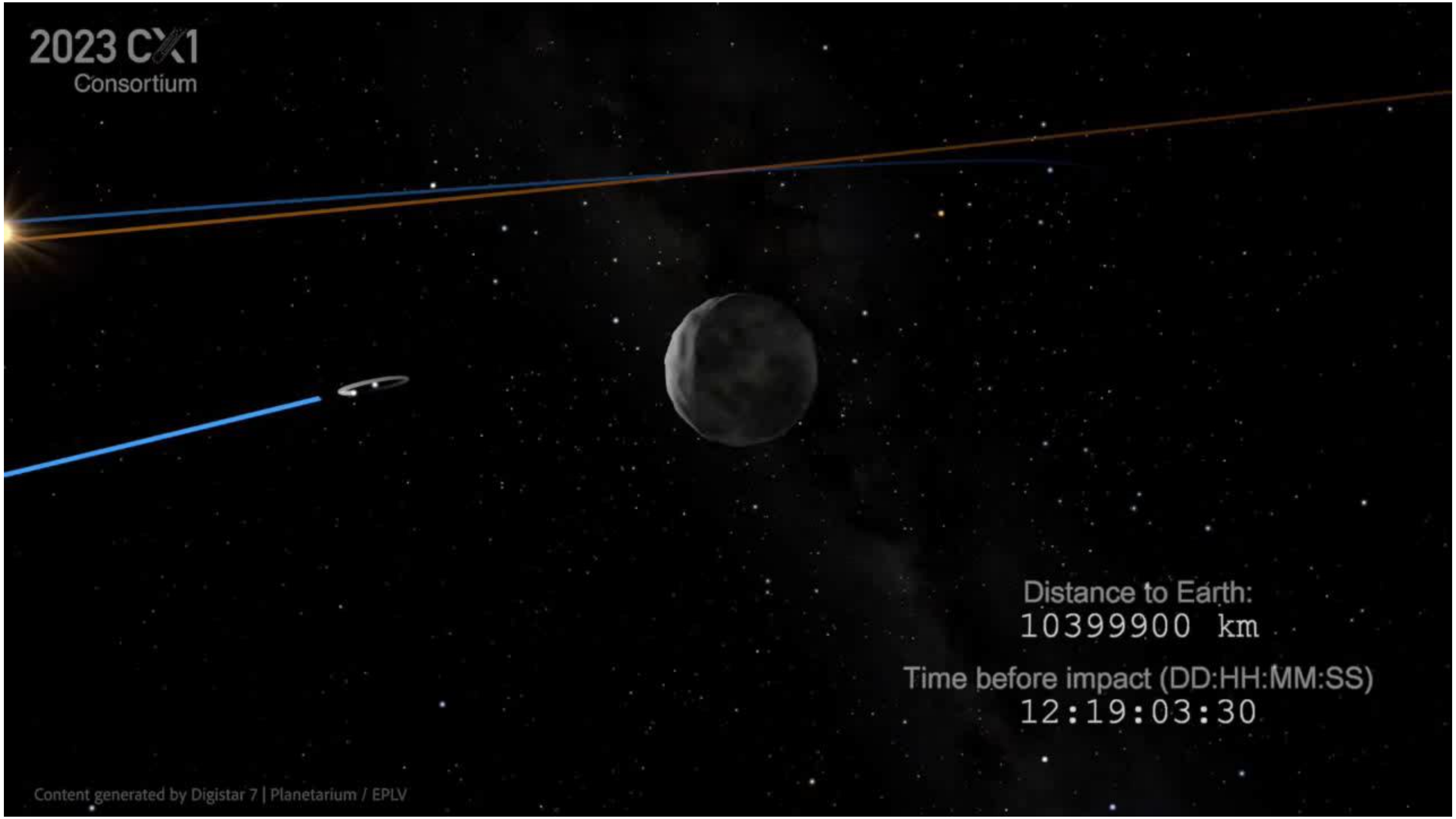
POSTER – « Identification et localisation de phénomènes atmosphériques grâce à un réseau sismique dense »
G. Mazet-Roux et al.

Le Pichon et al., Scientific Report
DOI: 10.1038/s41598-021-93942-x

Rich observations from regional networks

Eyes and ears to listen to the sky



Vigie Ciel
FRIPON

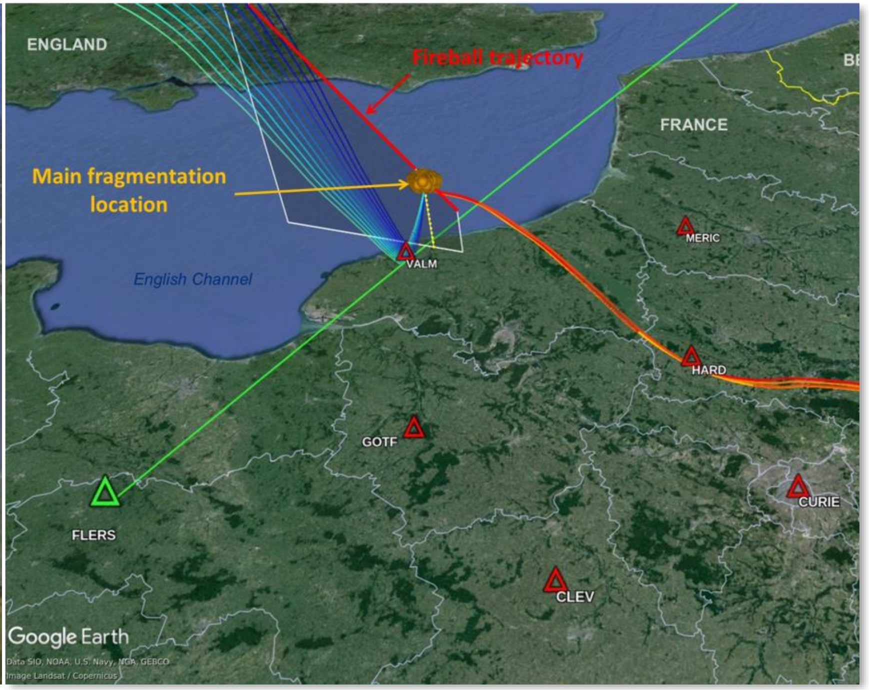
FRIPON
Fireball Recovery and InterPlanetary Observation Network

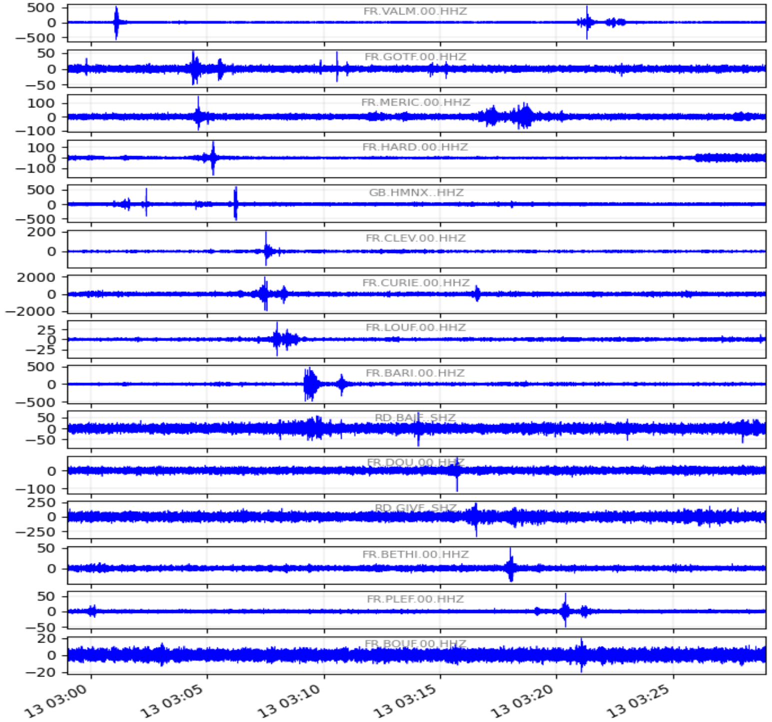
Auriane et al.,
Nature Astronomy, 2025

https://www.vigie-ciel.org/le-projet-fripon/
https://www.youtube.com/watch?v=l0Yb0cfU4uw

Characterization of asteroid 2023 CX1

A unique case study for planetary defense





Courtesy of J. Vergne

- 7th asteroid ever detected prior to impact (ESA and NASA)
- FRIPON/Vigie-Ciel network mobilized the public
- An orbit with unmatched precision
- 98% of kinetic energy deposited as a point source at ~28 km altitude

FRIPON
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Auriane et al., Nature Astronomy
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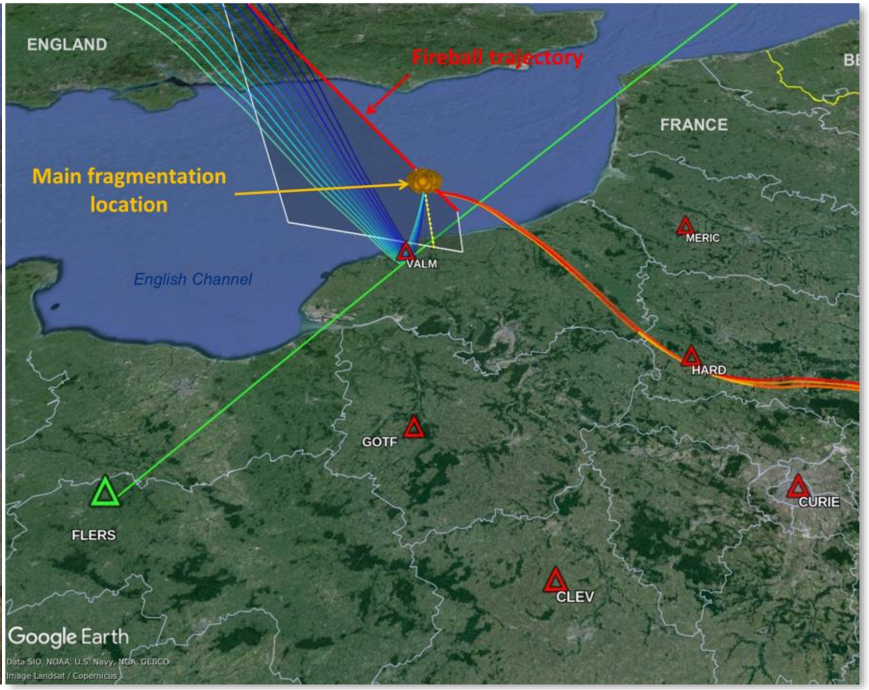

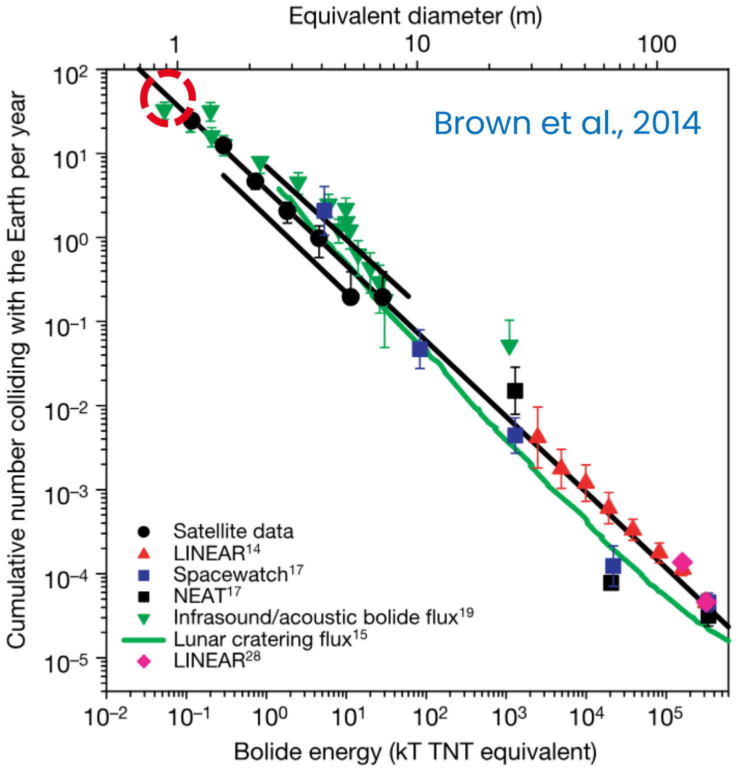

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Auriane et al., Nature Astronomy
DOI: 10.1038/s41598-021-93942-x

Summary

A global coverage of infrasound

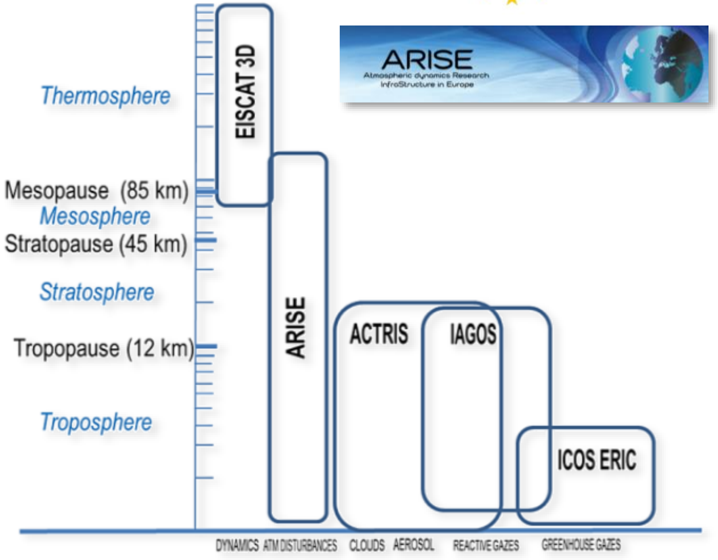
- Larger and much more sensitive than any previously operated network
- Benchmark to assess/optimize operational procedures

Advances in operational monitoring methods

- Confidence in the quality of the measurements
- Methods for high-resolution processing and numerical modeling
- Advances in Bayesian approaches and machine learning methods for propagation modeling and discrimination

Developing multi-disciplinary approaches

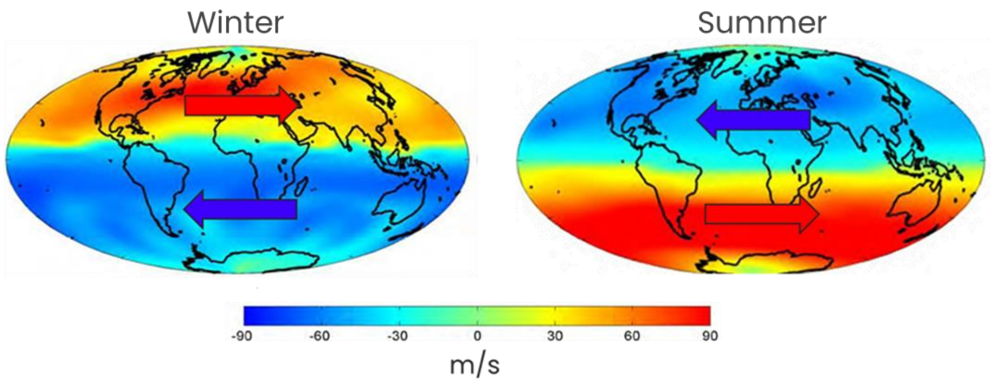
- Additional observational constraints of the middle atmosphere dynamics
- Reliable information for volcanic hazard warning systems
- Assessing meteor impact hazard
- Seismo-acoustic synergy being explored (RLBP – M. Bonnin ; H. Iacobucci)…



POSTER – « Révéler l'inaudible : apport des mesures infrasons sur les sites multi-instrumentés du RLBP»
H. Iacobucci et al.

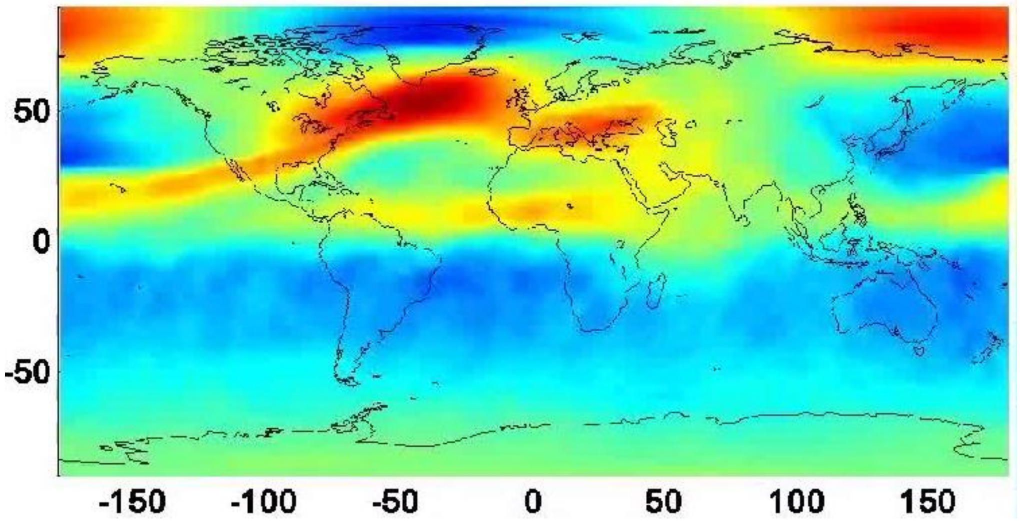
Infrasound waveguides in the middle atmosphere

Zonal wind at 50 km

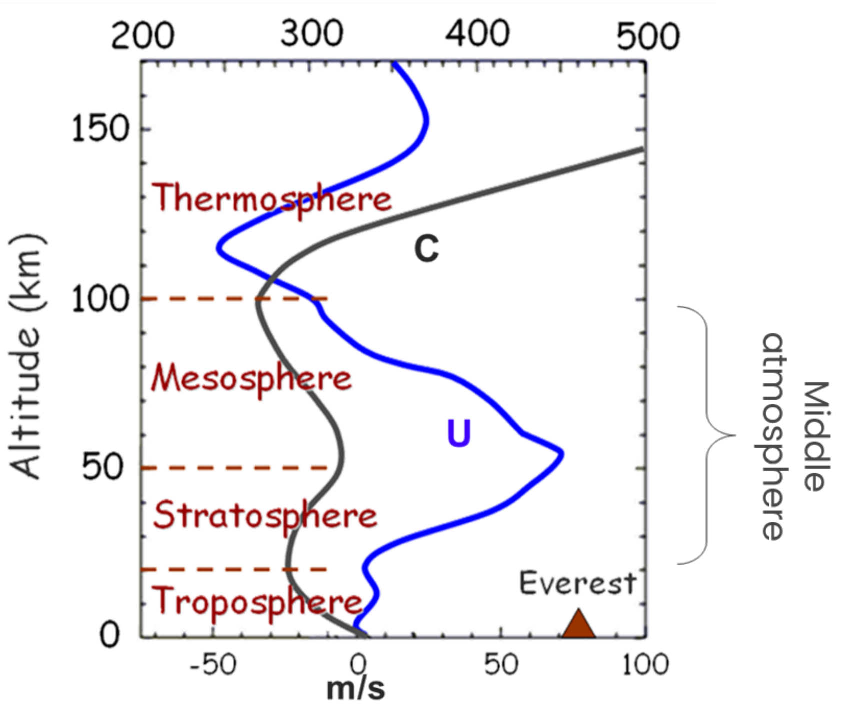


HWM93
MSIS90

ECMWF 2023, zonal wind @50 km



ECMWF
IFS 2023



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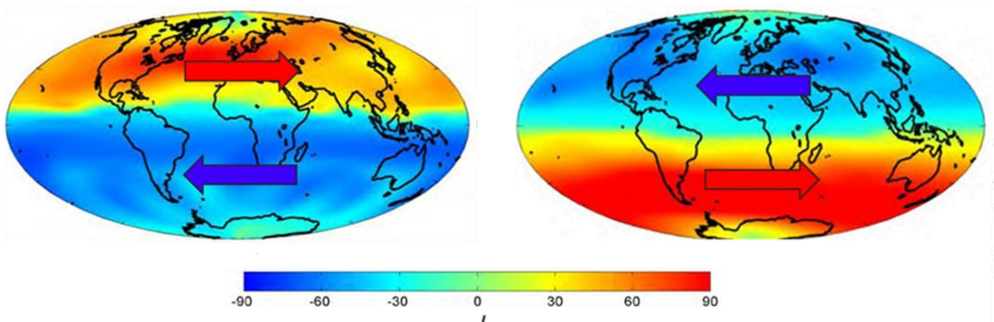
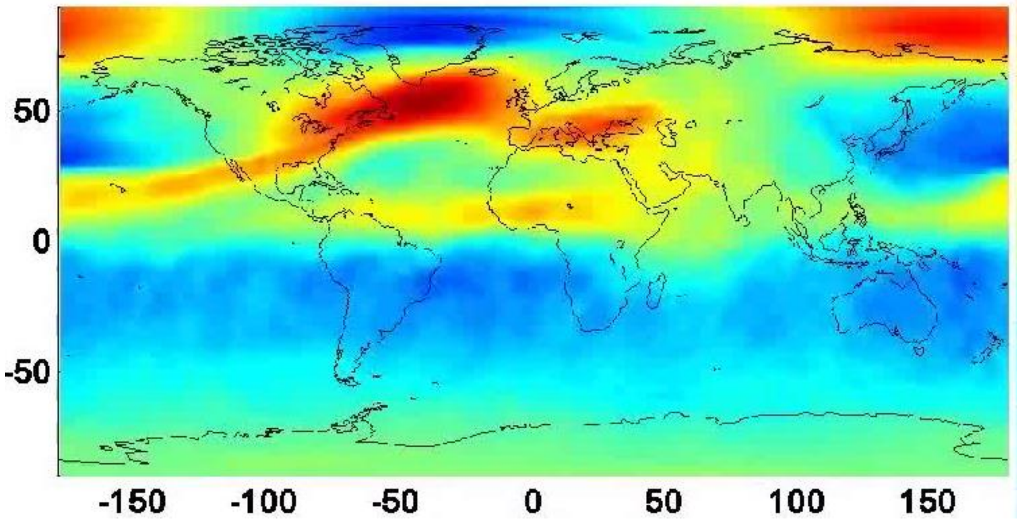
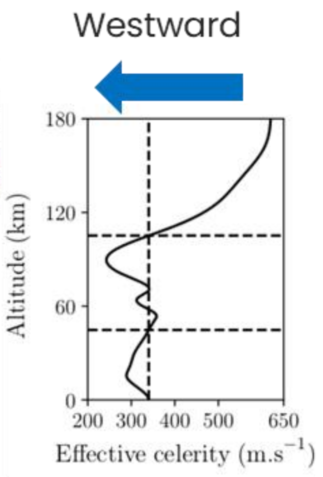
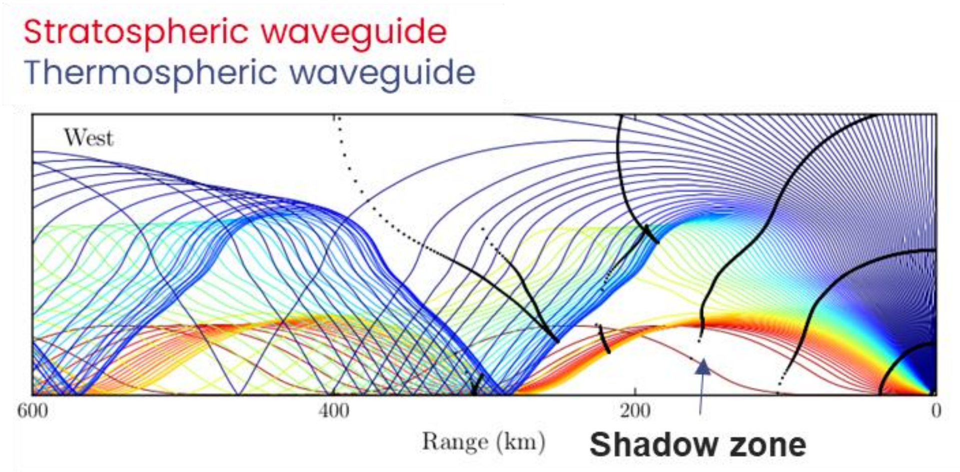
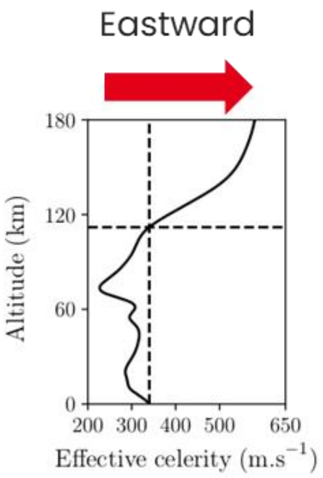


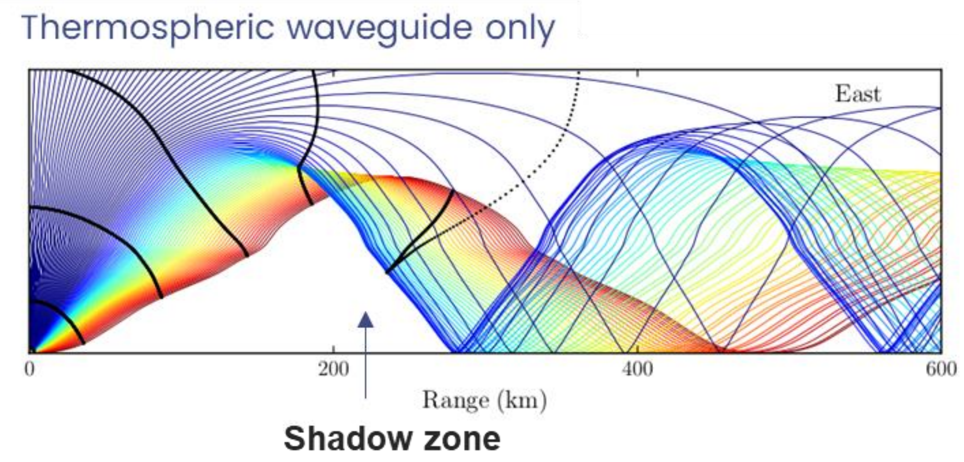
ECMWF 2023, zonal wind @50 km



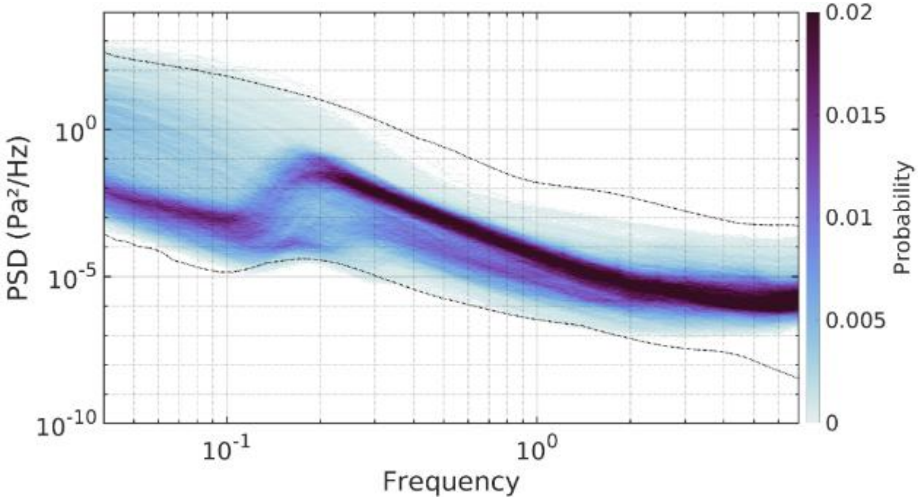


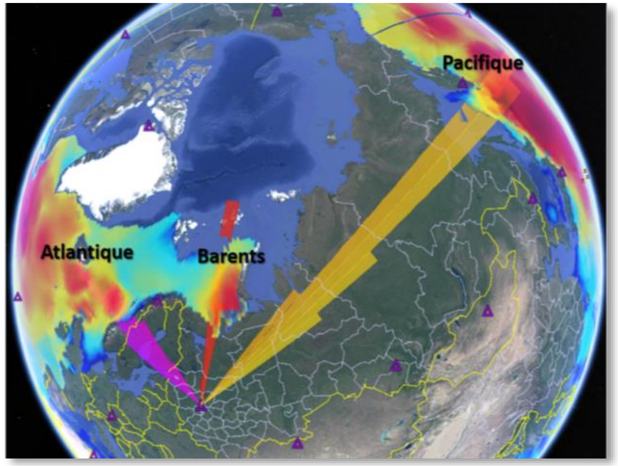




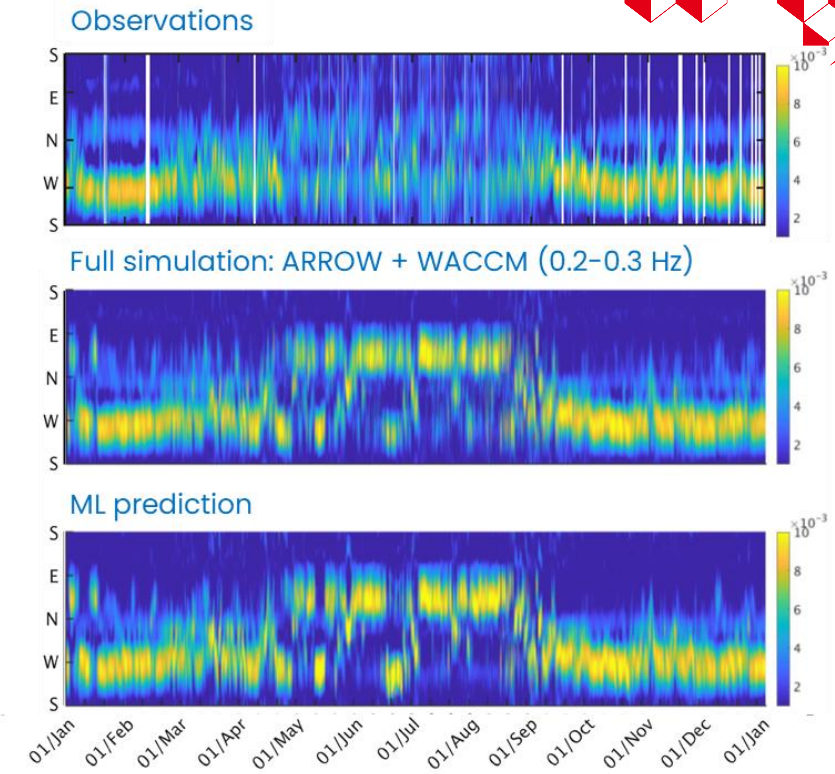


Improving atmospheric model
Ocean noise as a calibration source

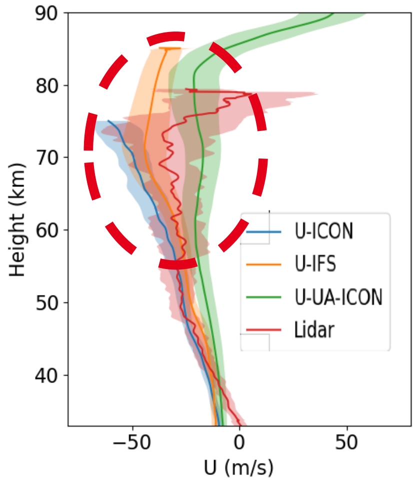




ARROW, DOI: 10.13155/99652
https://sextant.ifremer.fr/Donnees/Catalogue#



- Microbaroms: a continuous and global source of coherent noise (5-6 s)
- Characterizing the oceanic noise as recorded by dense seismo-acoustic network (Smirnov, 2021)
- Operational global source model (De Carlo, 2021)
- Towards a proof of concept for microbarom assimilation
  - Implementation of a ML meta model (CRNN) for infrasound propagation (Cameijo et al., 2025)
  - Auto-differentiation of the observation operator
  - Gradient based sensitivity studies



Letournel et al., JGR,
DOI: 10.1029/2024JD042034

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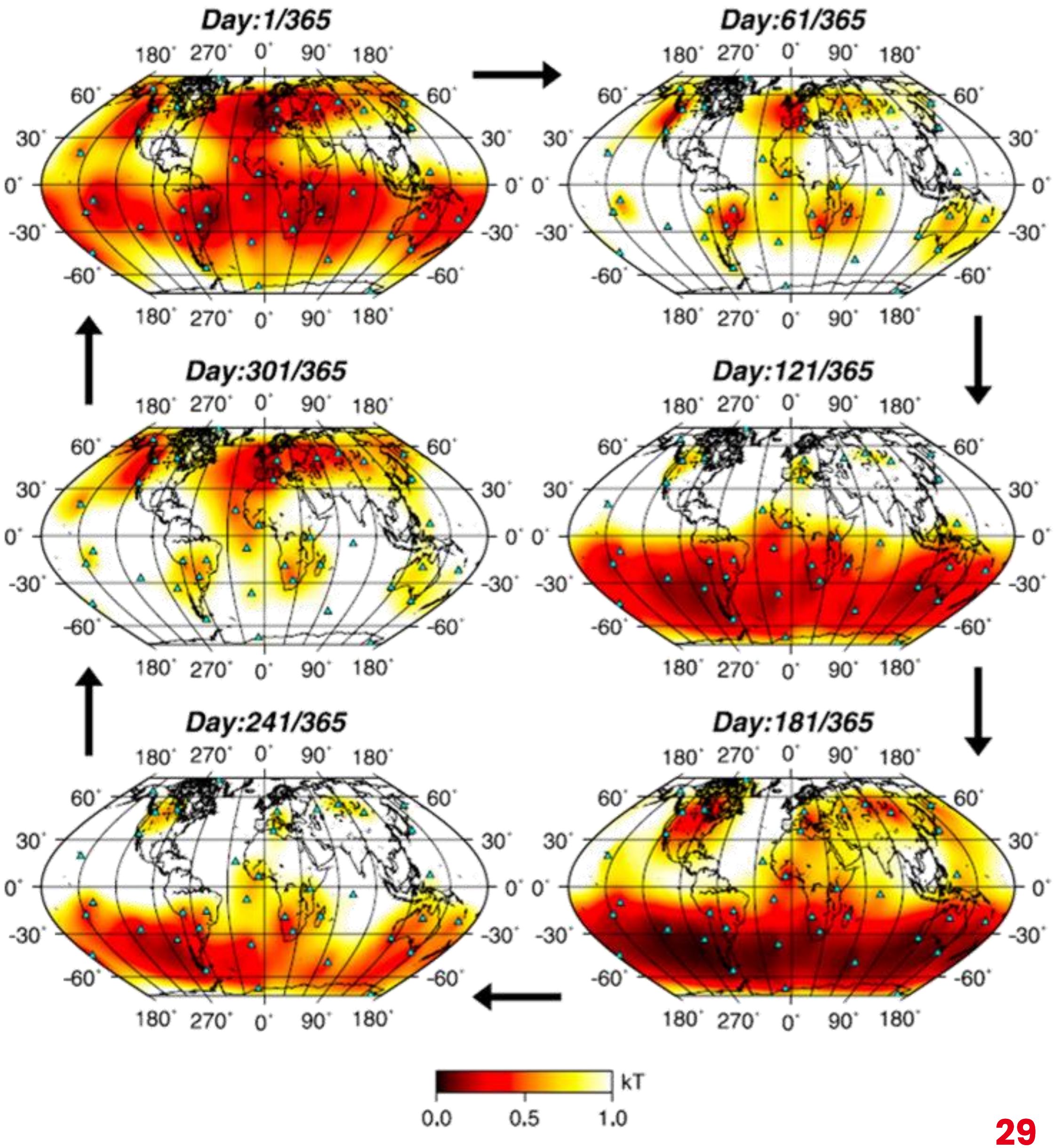
Network performance modeling

From empirical to statistical models

- **Context**
  - Highly variable detection capability
  - Empirical yield-scaling relation (Green, 2010)
    - Frequency dependent, up to 1,000 km
    - Idealized atmospheric scenarios (climatology)
    - Uniform background noise
- **Challenge**
  - Incorporate realistic atmospheric specifications
  - Realistic station noise
  - Simulation based attenuation relation

➔ Near-real time assessment of the spatio-temporal variability of the network performance



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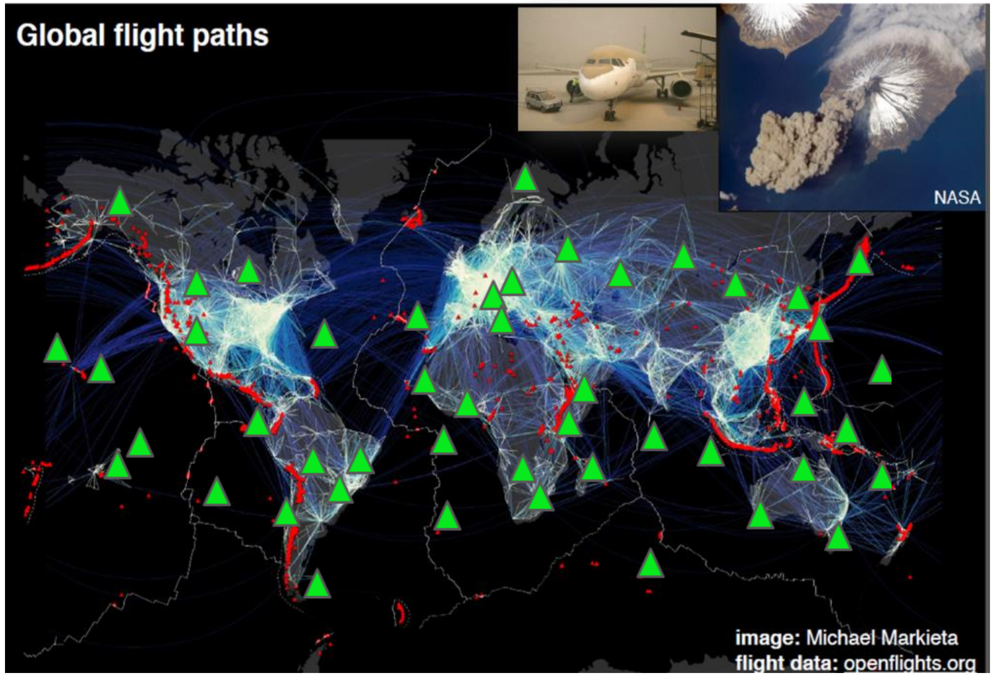
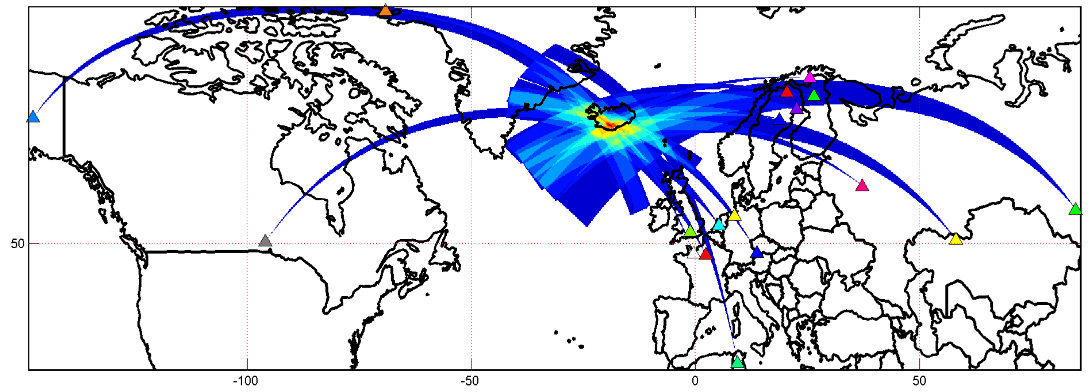
Remote infrasound monitoring of volcanic eruptions

- Serious hazards to aircraft in flight near to the ash plume
- Volcanic source terms are critical to model the ash dispersion
- Many of the world’s volcanoes lack dedicated monitoring instruments; detection relies on satellite imagery (cloud covererage)
- Infrasound may supplement other monitoring techniques (volcanic and seismological observatories, pilot report, remote sensing)



Eyjafjallajökull eruption, Island, 2010

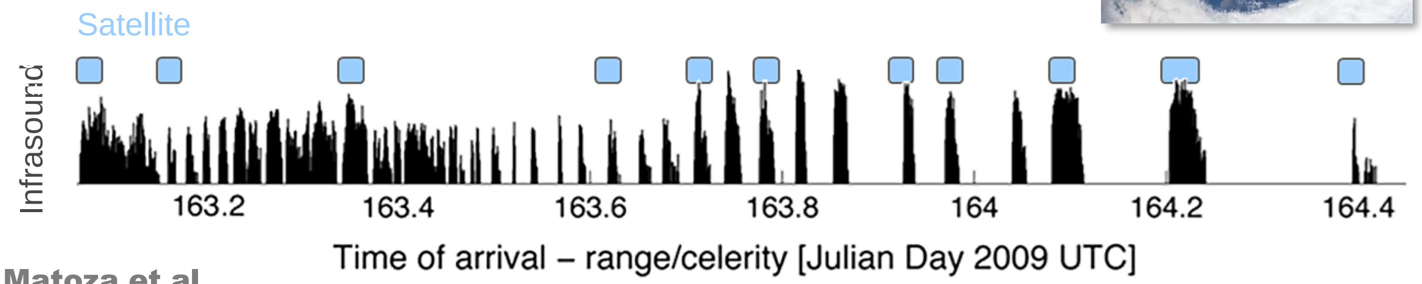


Matoza et al., 2012

IMS infrasound network:

- ✓ ~90% complete, global coverage
- ✓ multi-year continuous high-quality recordings,
- ✓ median distance from any volcano to the nearest array:980 km

Sarychev Peak eruption, Kuril Islands, 2009



Matoza et al., 2011

A high-performance global monitoring network
Long-range detection of meteorite

- Bering bolide, 18 december 2018
- Energy: 173 kt (NASA fireball report)
- Detections on 18 IMS stations (15,000 km)
- Incorporating unresolved small scale structures in the atmospheric model
- Propagation simulations (celerity models, azimuthal deviation)

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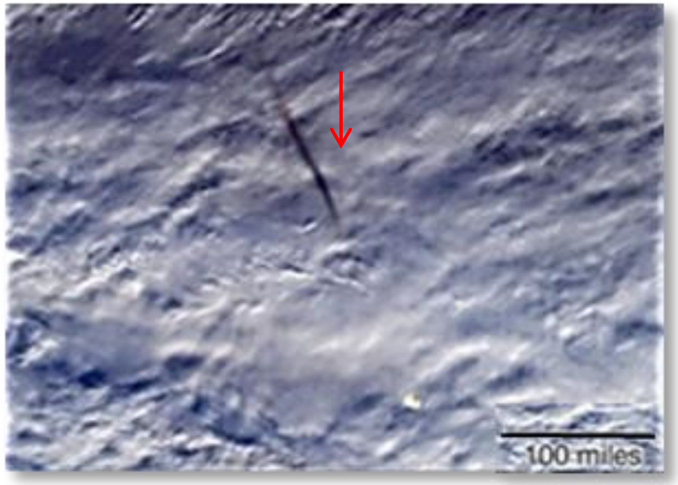
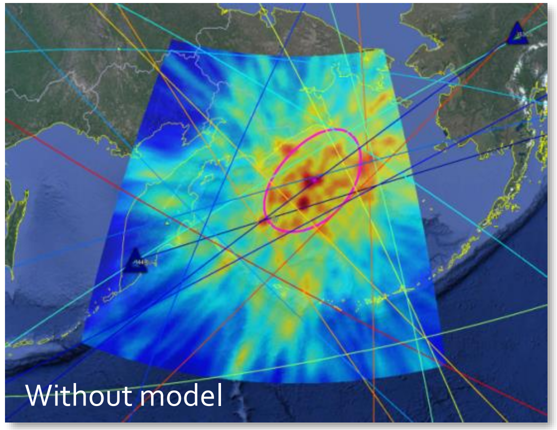
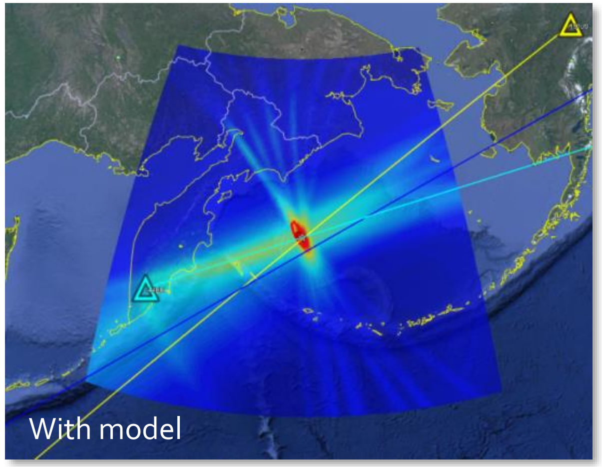
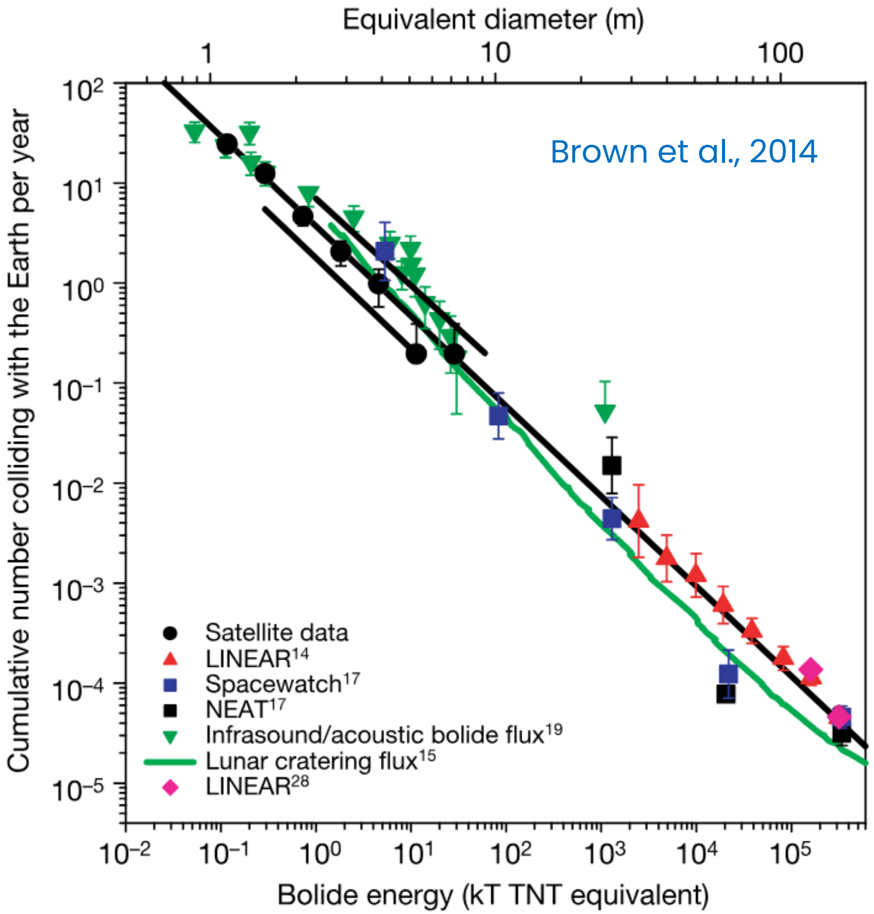


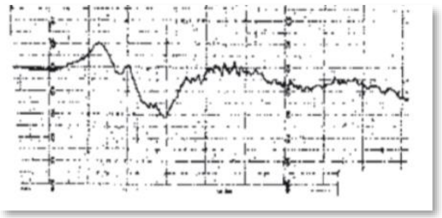
Errors 380 km / 24 min



Errors: 20 km / 20 s



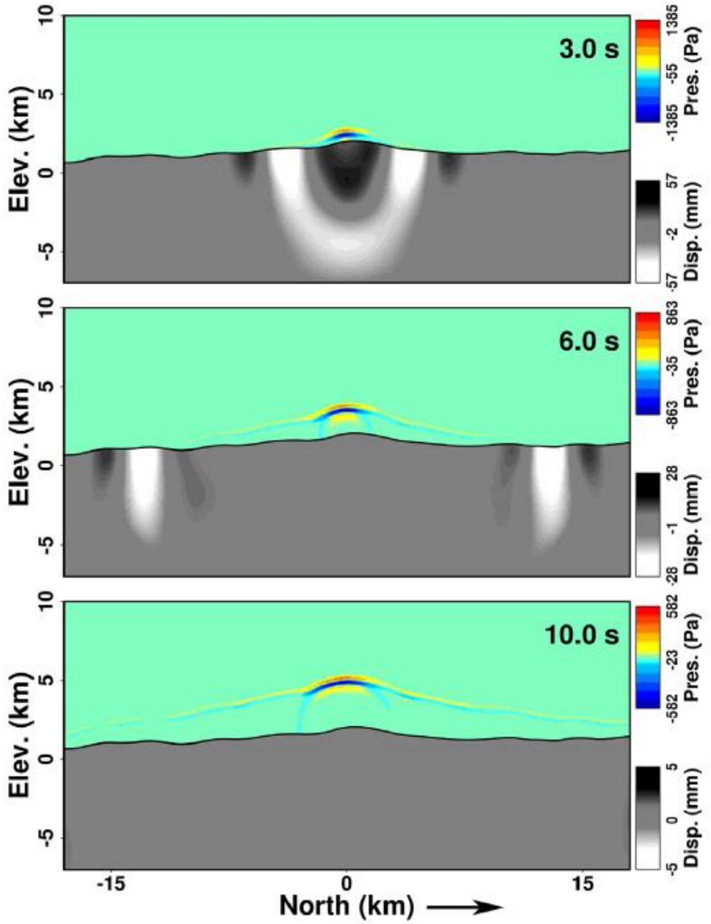




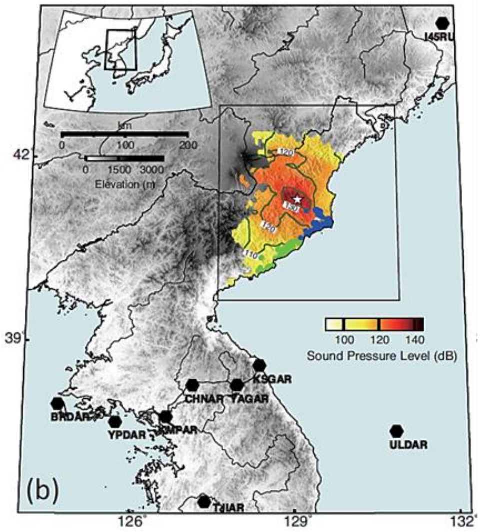
Bolt, 1964

Seismo-acoustic coupling
North Korean nuclear test: 3 sept. 2017
Che et al. (2021)

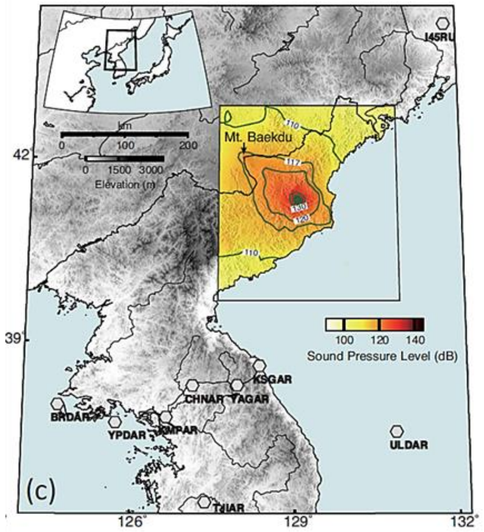
ELAc (Petersson, 2018)



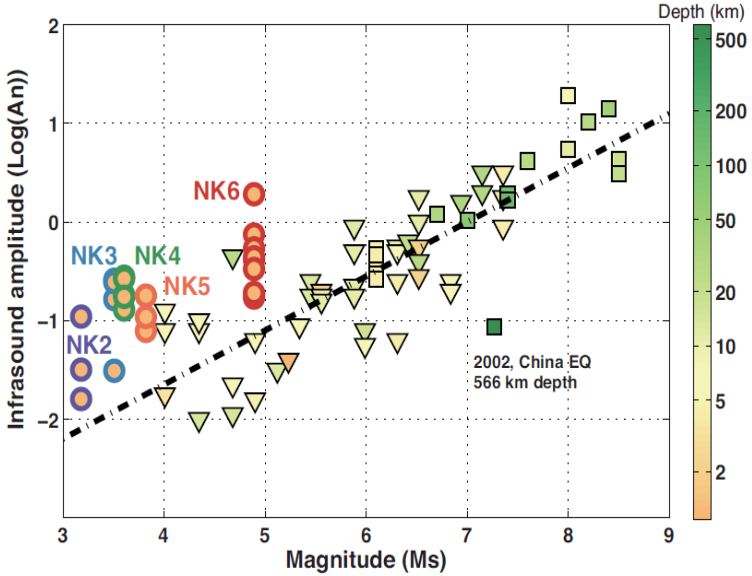
IS back-propagation



ELAc (Petersson, 2018)



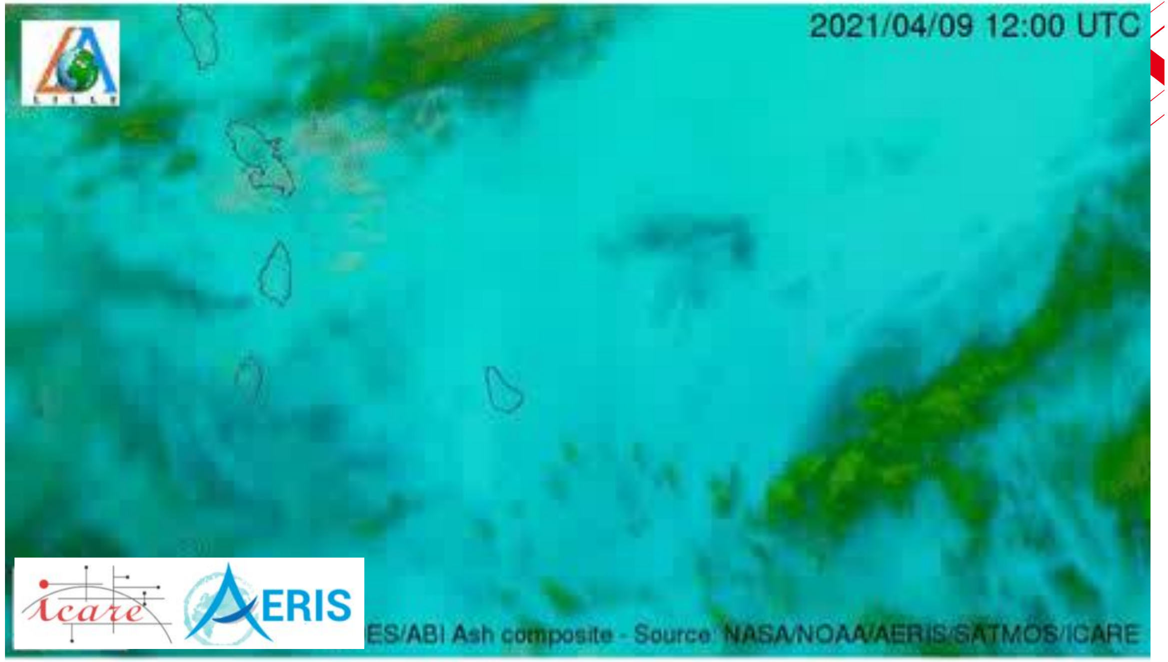
Tests NK vs. earthqaukes



- Full 3-D seismo-acoustic simulations predict the propagation of acoustic waves in a heterogeneous medium.
- Back-projecting infrasound records yields locations of the ground-to-air coupling areas surrounding the epicentre.
- Simulations capture the excitation of epicentral and diffracted acoustic phases.
- New quantitative constraints to enhance confidence in source discrimination for nuclear monitoring research.

Monitoring volcanic eruptions April 2021: La Soufrière St Vincent Island

- Pyroclastic flows and heavy ash in the lower stratosphere
- Infrasound detections at IS25 (Guadeloupe, 313 km)
- Good correlation between IS and satellite data
- IS detection provides the time sequence of the puffs



Source: NASA/NOAA/AERIS/SATMOS/ICARE

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Source, IPGP (R. Grandin)
KNMI (J. Assink),
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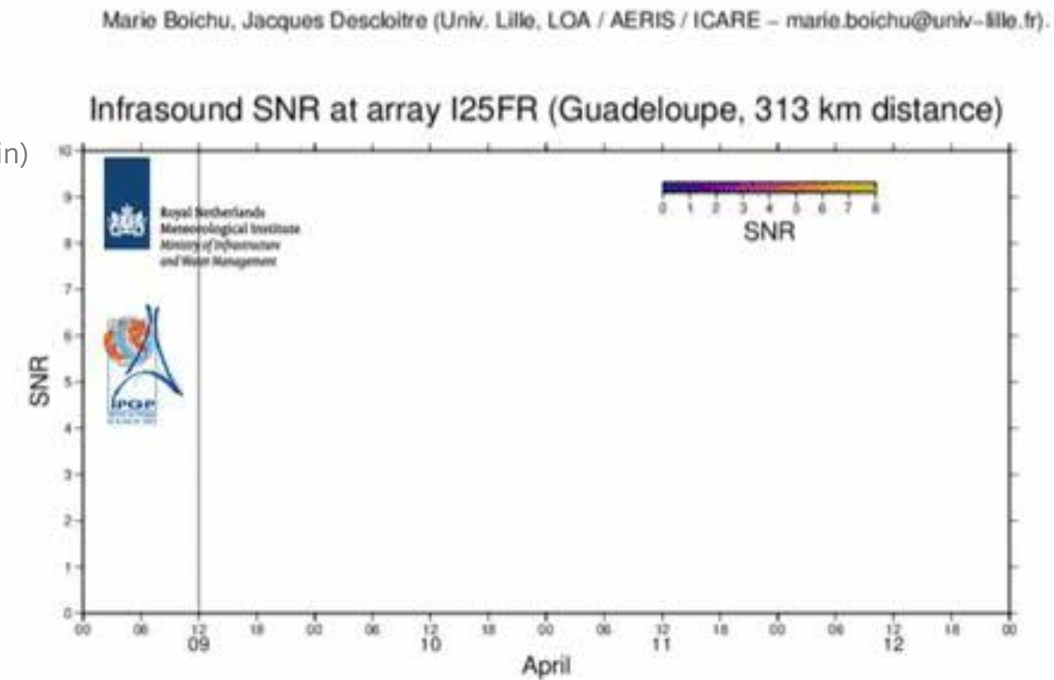
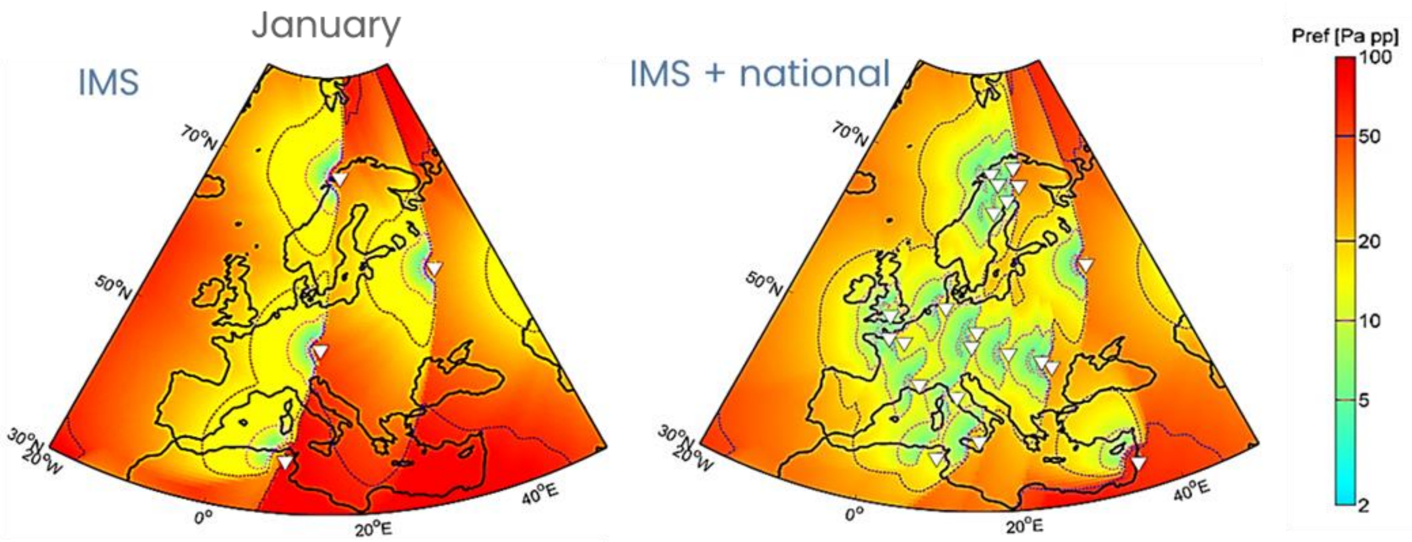
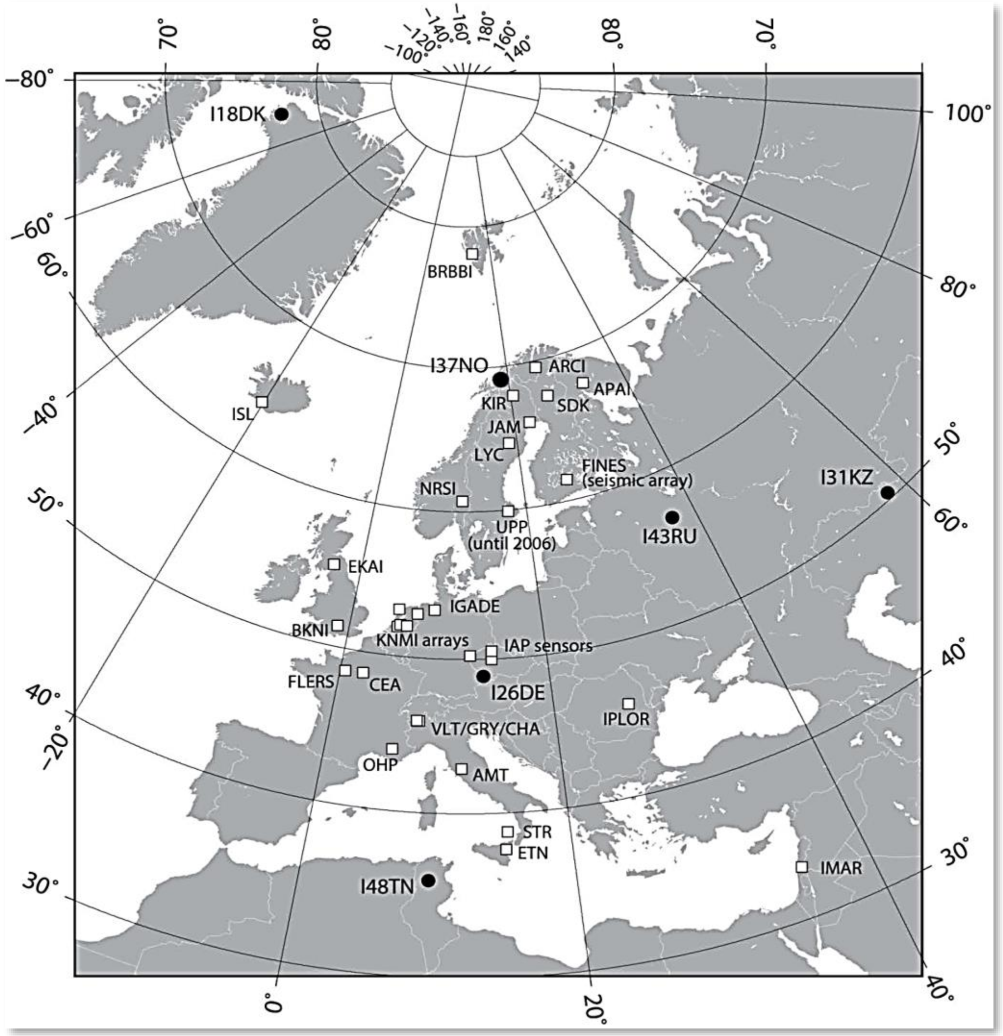


Rich observations from regional networks

- Since 2012: significant improvement in network detection capability:
  ➔ 24 stations; decrease of the detection threshold by one order of magnitude
- The European Arctic: a unique observatory for seismo-acoustic studies (Pilger, 2018)
- Characterization of the environmental coherent noise (open-pit mines, military activity…)





1 - Rich observations from regional networks
Probing gravity waves in the middle atmosphere

- The European Arctic: a unique observatory for seismo-acoustic studies
- Characterization of the environmental coherent noise (open-pit mines, military activity…)
- Probing the atmosphere
  Vorobeva, JGR 2023, DOI: 10.1029/2023JD038725