

Summarizing the MADEIRA project research

*Middle atmosphere dynamics: exploiting infrasound
using a multidisciplinary approach at high latitudes*

Sven Peter Näsholm, NORSAR

& project participants Javier Amezcuia, Jelle D. Assink, Evgenia Belova, Erik Mårten Blixt, Quentin Brissaud, Mari Dahl Eggen, Patrick J. Espy, Robert Hibbins, Johan Kero, Tormod Kvaerna, Alexis Le Pichon, Yvan J. Orsolini, Ismael Vera Rodriguez, Antoine Turquet, and Ekaterina Vorobeva

Thursday 27 April 2023



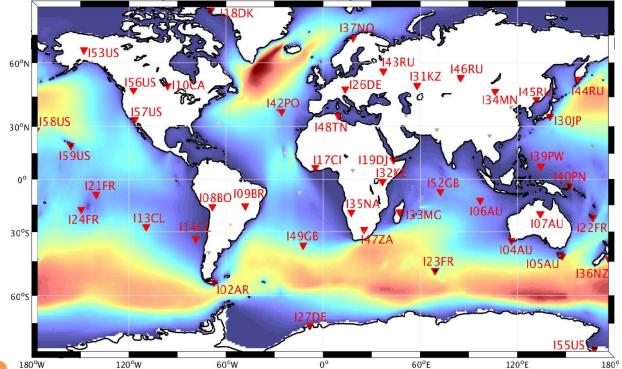
MADEIRA

Norwegian Research Council basic research programme, 2018 – 2023

EU Horizon 2020: ARISE2 –
*Atmospheric Dynamics
Research Infrastructure in
Europe* (2015 – 2018)

EU FP7: ARISE –
*Atmospheric Dynamics
Research Infrastructure in
Europe* (2012 – 2014)

**EXPLOSION & MICROBAROM INFRASOUND to
PROBE THE MIDDLE ATMOSPHERE**



2-minute pitch – slide 2 of 3

Unpredictability of Research

	Anticipated before project	MADEIRA result
Multi-station approaches for explosion datasets	Quite straightforward	Not done
Synergies: infrasound & meteor radar datasets	Quite straightforward	Not done
Probing gravity waves over long time-series	Feasible	Accomplished (see EGU23 pres. Vorobeva et al.)
Probing middle atmospheric tides	Feasible	Only started
Direct mapping between global infrasound & stratospheric vortex strength in m/s	Very ambitious	Proof-of-concept (see EGU23 pres. Eggen et al.)
Assimilation into atmospheric models	Extremely ambitions	Proof-of concept published



2-minute pitch – slide 3 of 3

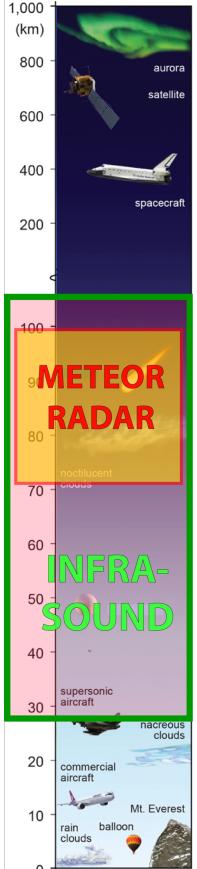


2-minute pitch

PICO screen additional slides →



One-pager designed in proposal elaboration phase



Constraints to wind & temperature

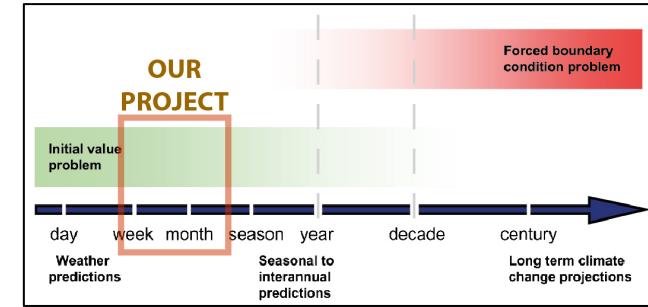
- 30–60 km: ground-based infrasound
- 70–100 km: ground-based meteor radar

Innovative approaches

- Multi-station & multi-source infrasound:
benefitting from fact that infrasound probes a path (not just point-wise)
- Constraints / assessments both to numerical weather prediction initial values & output ensembles

Paving the way for numerical weather prediction improvements

- Introduction of *high-top* models
⇒ enhanced predictions
- Potential for added model constraints when exploiting additional middle atmospheric dynamics data



Need a source: repeating explosions



- Finnish military ammunition destruction August, September
- ≈ 20 tons TNT yield

320 km → IS37 & ARCI arrays





Exploiting these explosions for probing



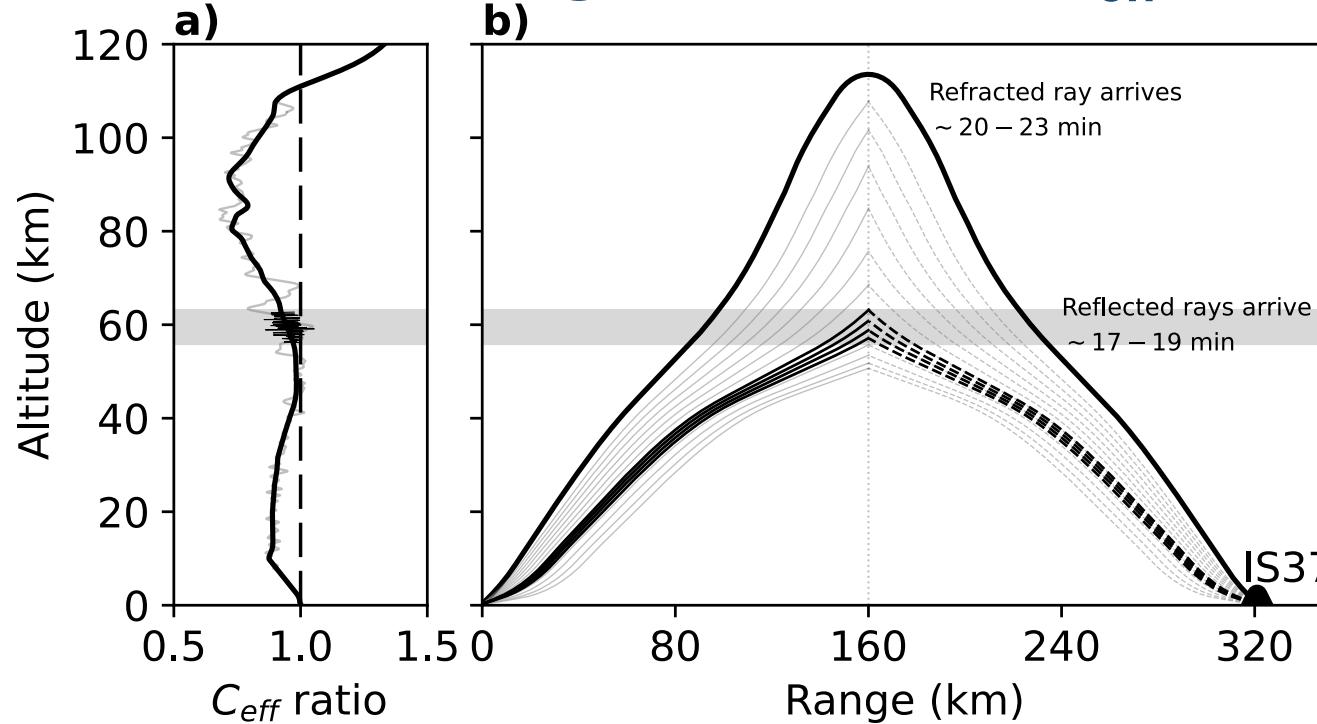
Probing small-scale structures, gravity (buoyancy) waves



Andøya Space, Norway, Facebook, March 2023

The Vorticity Experiment (VortEx) to better understand gravity waves and their interactions as they propagate from the mesosphere into the lower thermosphere. PI: G. Lehmacher, Clemson University, South Carolina

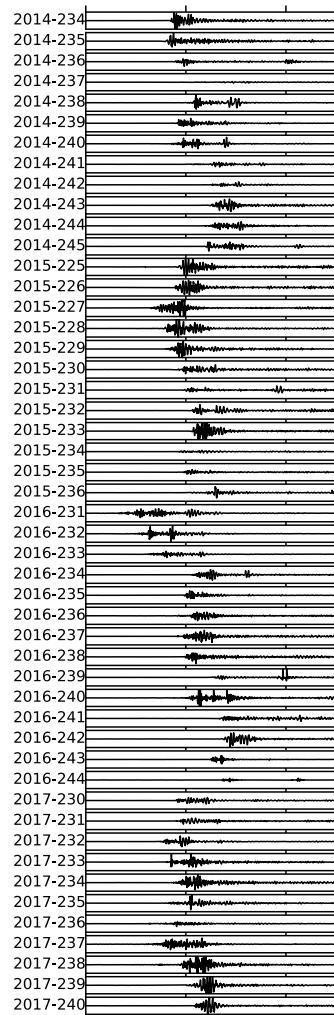
Utilize back-scattering sensitive to c_{eff} variations



Vorobeva, E., Assink, J., Chunchuzov, I., Renkwick, T., Espy, P., and Näsholm, S. P.: Using infrasound from explosions for probing internal gravity waves in the middle atmosphere, EGU General Assembly 2023, Vienna, Austria, 24–28 Apr 2023, EGU23-6993, <https://doi.org/10.5194/egusphere-egu23-6993>, 2023.

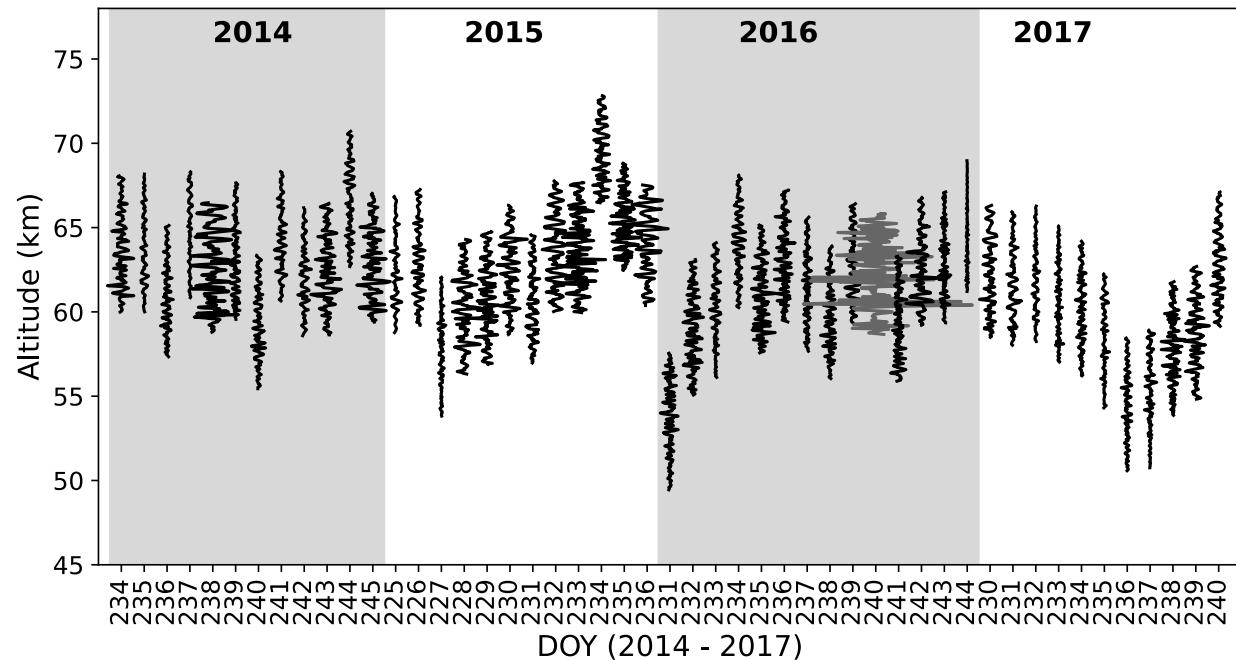
Vorobeva, E., Assink, J. D., Espy, P. J., Renkwick, T., Chunchuzov, I. P., & Näsholm, S. P. (2023). Probing gravity waves in the middle atmosphere using infrasound from explosions. ESSOAr preprint 10.22541/essoar.167751606.66986048/v1

17 18 19



Probing small-scale structures

Deconvolution-based approach



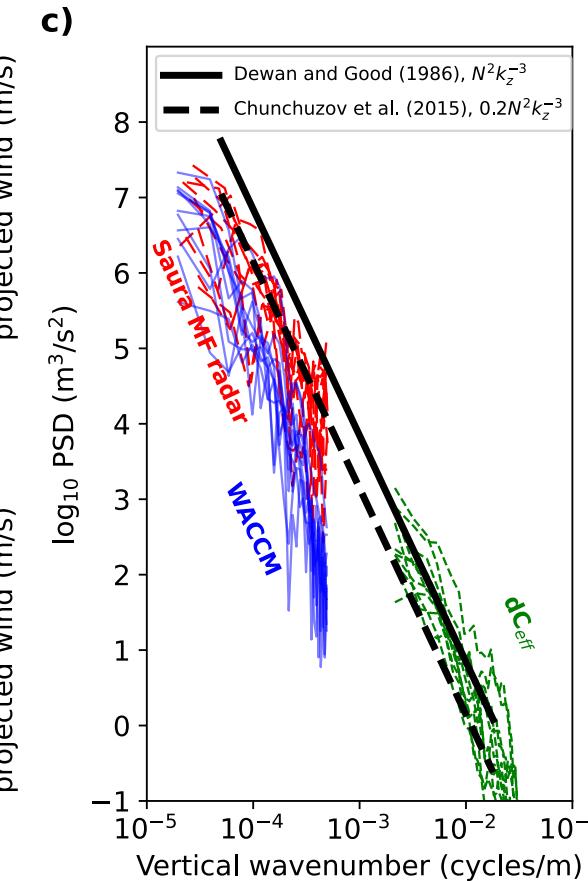
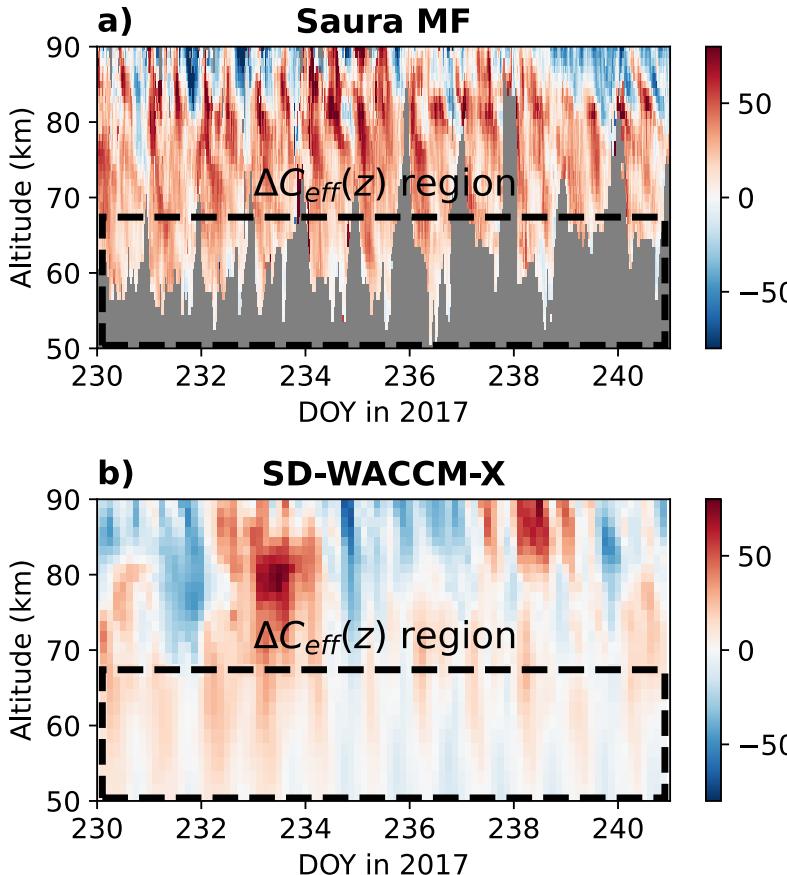
Vorobeva, E., Assink, J. D., Espy, P. J., Renkwick, T., Chunchuzov, I. P., & Näsholm, S. P. (2023). Probing gravity waves in the middle atmosphere using infrasound from explosions. ESSOAr preprint
[10.22541/essoar.167751606.66986048/v1](https://doi.org/10.22541/essoar.167751606.66986048/v1)

Variations in received time signal

⇒ Estimate vertical variations in effective soundspeed

⇒ Spectral characteristics in k_z

Atmospheric modelling relevance



Vorobeva, E., Assink, J. D., Espy, P. J., Renkwick, T., Chunchuzov, I. P., & Näsholm, S. P. (2023). Probing gravity waves in the middle atmosphere using infrasound from explosions. ESSOAr preprint 10.22541/essoar.167751606.66986048/v1

Sensing a spatial average of wind component

Estimating tropospheric and stratospheric winds using infrasound from explosions

Erik Mårten Blixt,^{1,a)} Sven Peter Näsholm,¹ Steven J. Gibbons,¹ Láslo G. Evers,^{2,b)} Andrew J. Charlton-Perez,³ Yvan J. Orsolini,⁴ and Tormod Kværna¹

¹*NORSAR, Gunnar Randers vei 15, 2027 Kjeller, Norway*

²*Delft University of Technology, Applied Geophysics & Petrophysics, Delft, Netherlands*

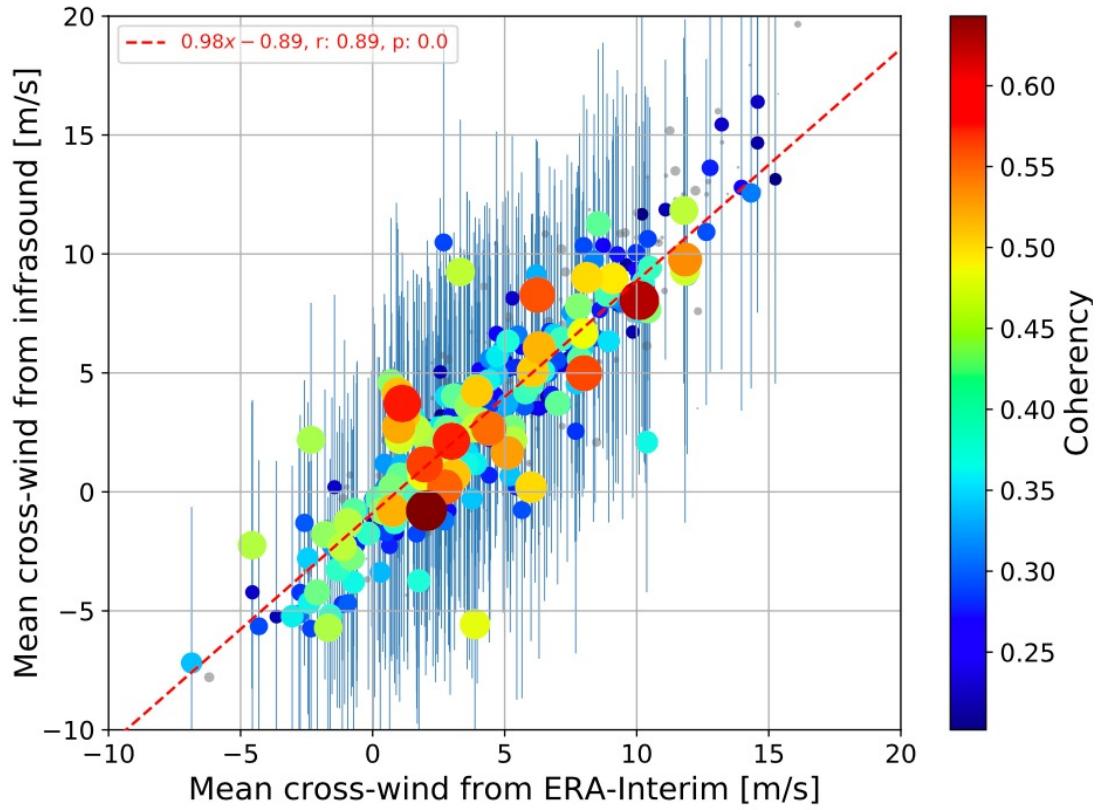
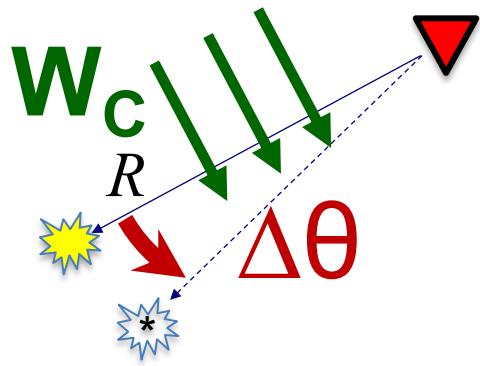
³*Department of Meteorology, University of Reading, Reading, United Kingdom*

⁴*Norwegian Institute for Air Research, Norway*

J. Acoust. Soc. Am. **146** (2), August 2019



Cross-wind



Atmospheric wind and temperature profiles inversion using infrasound: An ensemble model context

I. Vera Rodriguez,^{1,a)} S. P. Näsholm,^{1,b)} and A. Le Pichon^{2,c)}

¹*NORSAR, Kjeller, Norway*

²*CEA, DAM, DIF, F-91297 Arpajon, France*



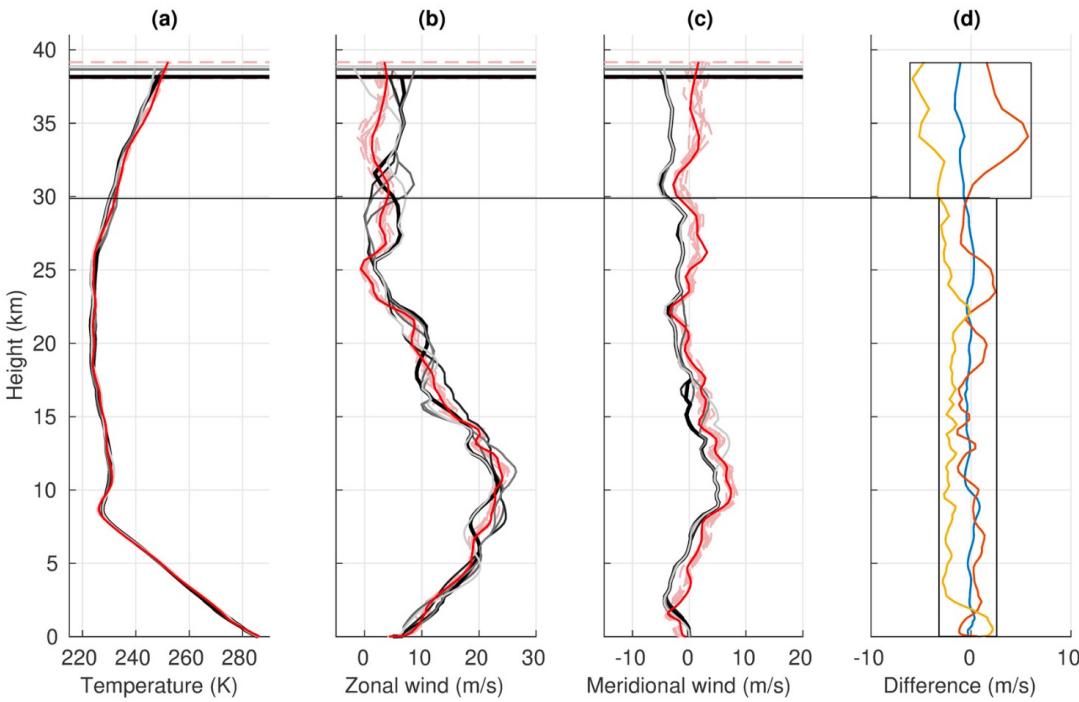


FIG. 6. (Color online) Inverted models for the inversion runs presented in Table I. Lighter gray colors are models with larger cost. The model with the lowest cost has a thicker black line. Red dashed-lines are the members of the ERA5-ensemble used to initialize the inversion in all cases. Similarly, the horizontal, red dashed-lines represent the initial reflection altitudes (39 km and 38 km for inversion runs #1–#3 and #4–#6, respectively). The thicker, solid red line is the ensemble member that lies closest to the best inversion result. Panels (a), (b), and (c) display the model parameters. Panel (d) shows the average of the cross differences between all inversion results and all ensemble members for adiabatic sound speed (blue), zonal wind (orange), and meridional wind (yellow).

Vera Rodriguez, Ismael, Sven Peter Näsholm, and Alexis Le Pichon. "Atmospheric wind and temperature profiles inversion using infrasound: An ensemble model context." *The Journal of the Acoustical Society of America* 148.5 (2020): 2923-2934.

First paper on assimilation of infrasound

into atmospheric models

Received: 13 September 2019

Revised: 16 April 2020

Accepted: 20 April 2020

DOI: 10.1002/qj.3809

Quarterly Journal of the
Royal Meteorological Society



RESEARCH ARTICLE

Assimilation of atmospheric infrasound data to constrain tropospheric and stratospheric winds

Javier Amezcua¹ | Sven Peter Näsholm² | Erik Mårten Blixt² | Andrew J. Charlton-Perez³

<https://doi.org/10.1002/qj.3809>

Traveltime & backazimuth deviation:

$$\bar{w}_c = -\frac{D}{T} \tan(\Delta\theta)$$

Ensemble Kalman filter:

$$y = Hx_{true} + \eta$$

Observation operator

Observation (data)

Observation error with expectation = 0

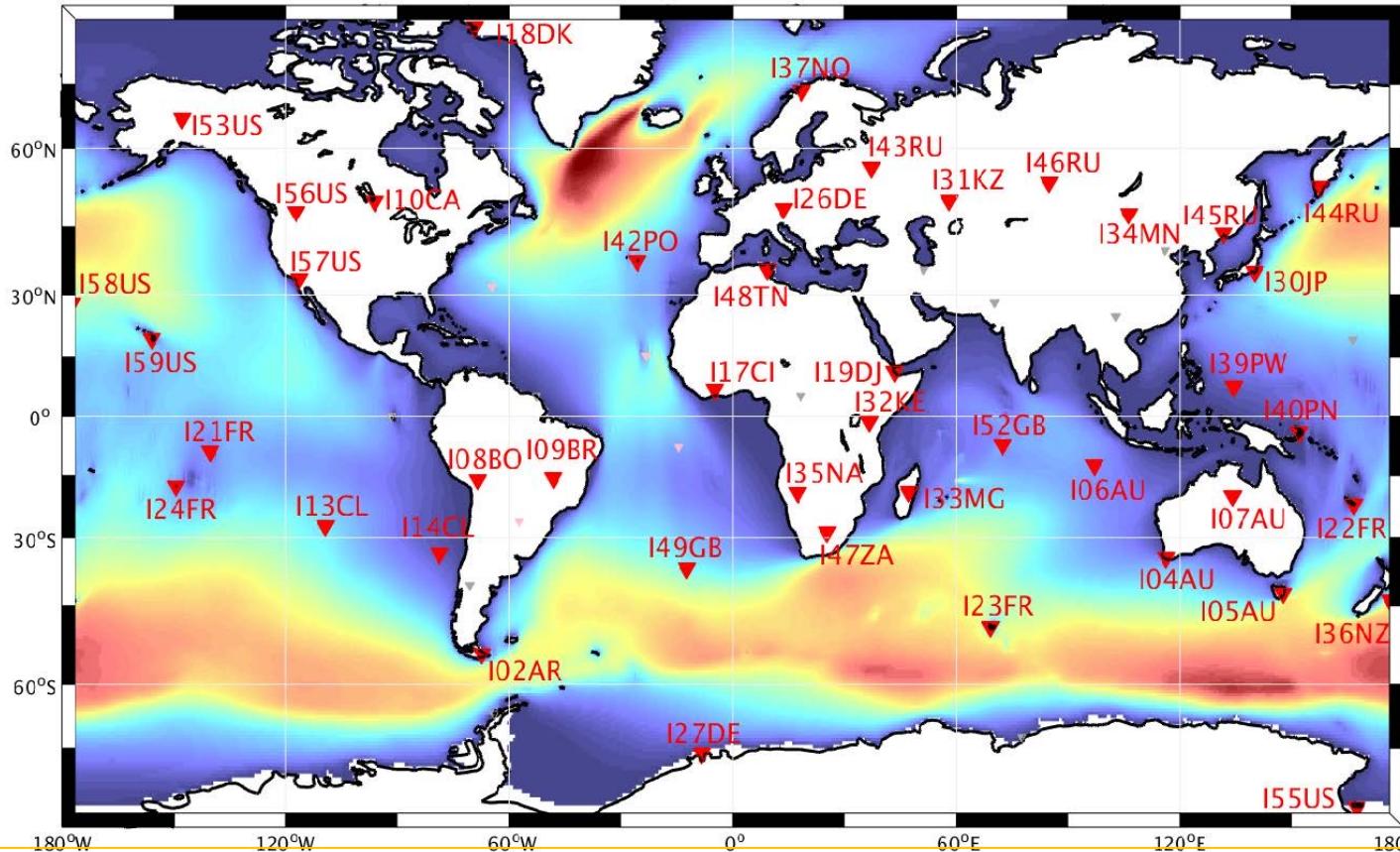


Atmospheric sensing from a quasi-continuous source

Microbarom source due to ocean swell



Ocean swell ⇒ microbarom infrasound



De Carlo, M., Hupe, P., Le Pichon, A., Ceranna, L., & Arduin, F. (2021, April). Validation of a general microbarom source model using global infrasound observations of the International Monitoring System. In *EGU General Assembly Conference Abstracts* (pp. EGU21-12043).



Benchmarking microbarom radiation and propagation model against infrasound recordings: a vespagram-based approach

Ekaterina Vorobeva^{1,2}, Marine De Carlo^{3,4}, Alexis Le Pichon³, Patrick Joseph Espy¹, and Sven Peter Näsholm^{2,5}

¹Department of Physics, Norwegian University of Science and Technology, Trondheim, Norway

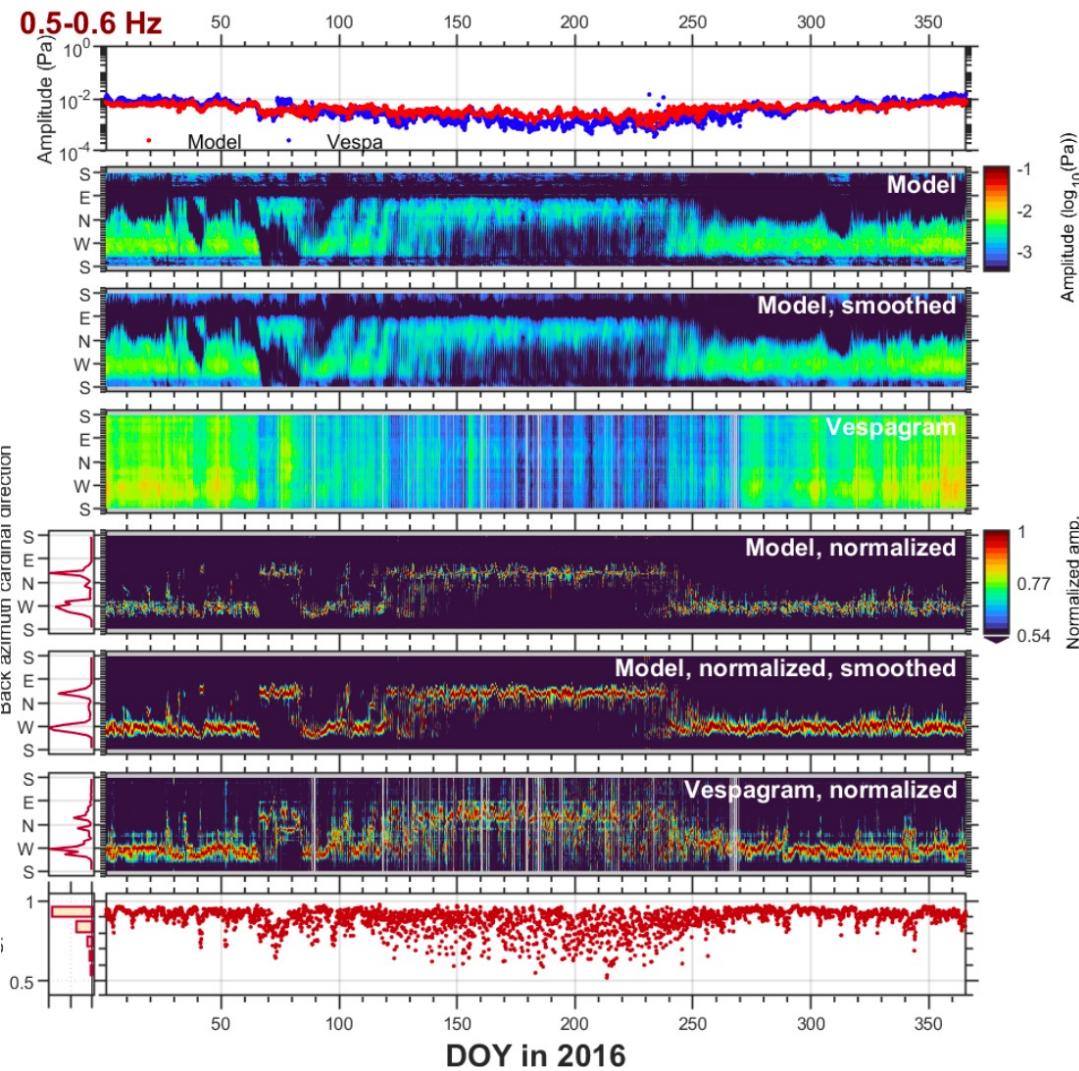
²NORSAR, Kjeller, Norway

³The French Alternative Energies and Atomic Energy Commission (CEA) – DAM, DIF, 91297 Arpajon, France

⁴Laboratoire d’Océanographie Physique et Spatiale (LOPS), Univ. Brest, CNRS, IRD, Ifremer, IUEM, Brest, France

⁵Department of Informatics, University of Oslo, Oslo, Norway





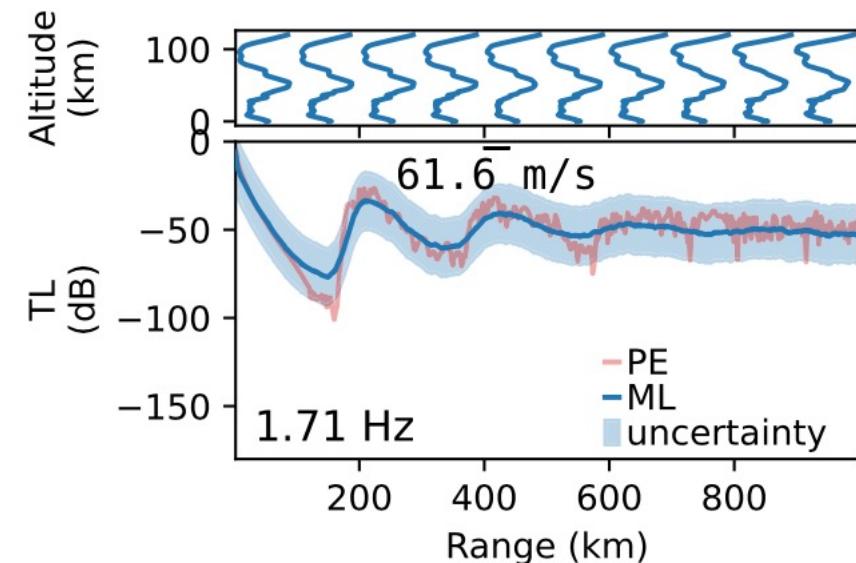
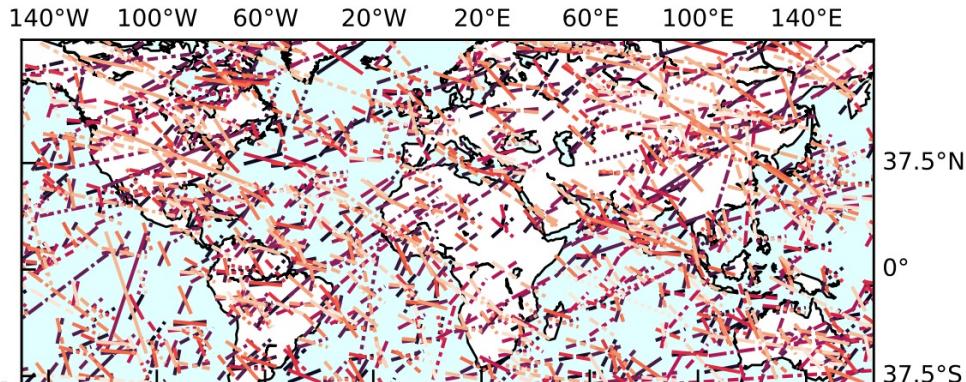
Predicting infrasound transmission loss using deep learning

Quentin Brissaud ,¹ Sven Peter Näsholm ,^{1,2} Antoine Turquet¹ and Alexis Le Pichon³

¹*NORSAR, Solutions Department, Gunnar Randers vei 15, 2007 Kjeller, Norway. E-mail: quentin@norsar.no*

²*Department of Informatics, University of Oslo, P.O. Box 1080, NO-0316 Oslo, Norway*

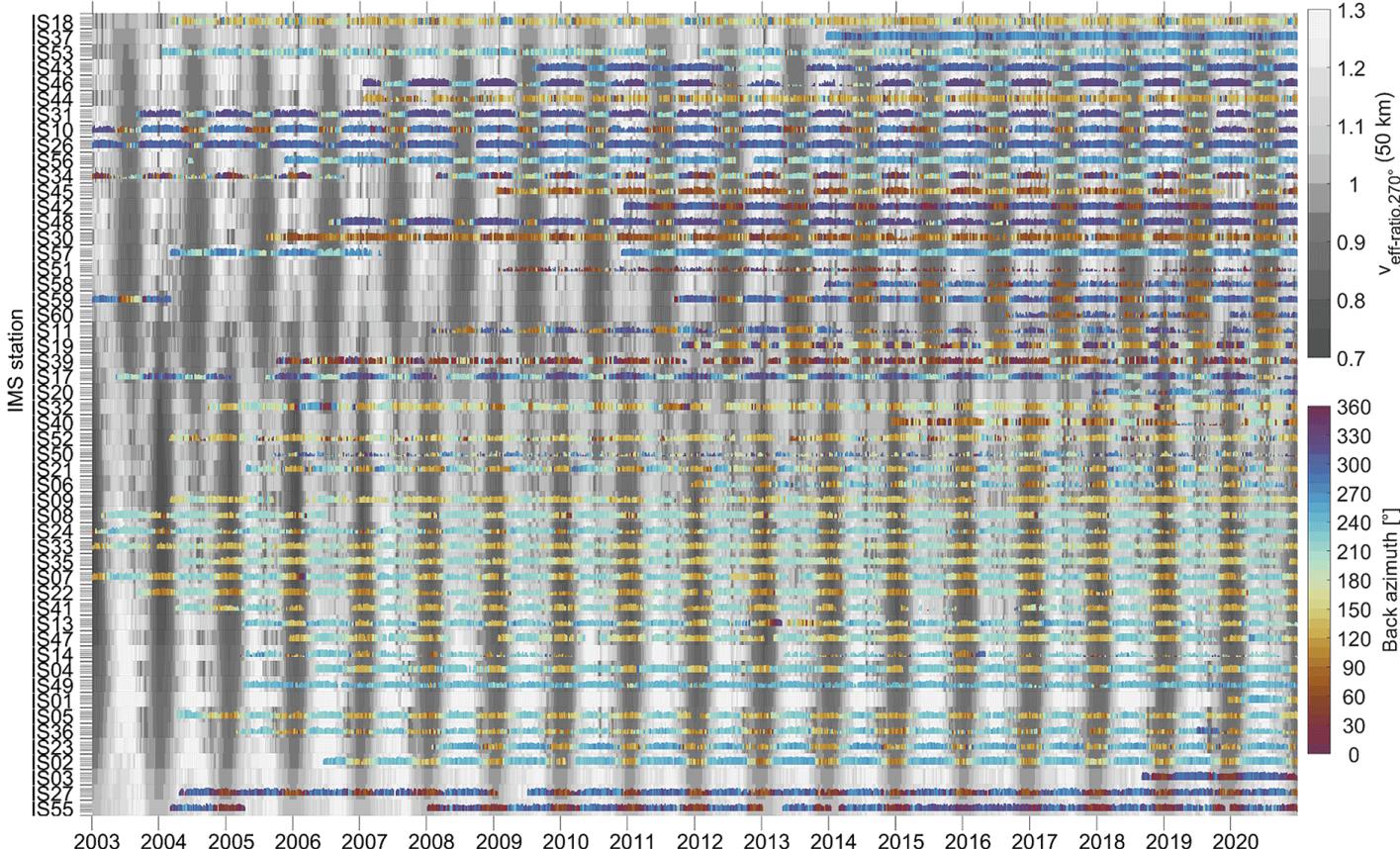
³*CEA, DAM, DIF, F-91297 Arpajon, France*



Mapping microbarom data to stratospheric polar vortex diagnostics

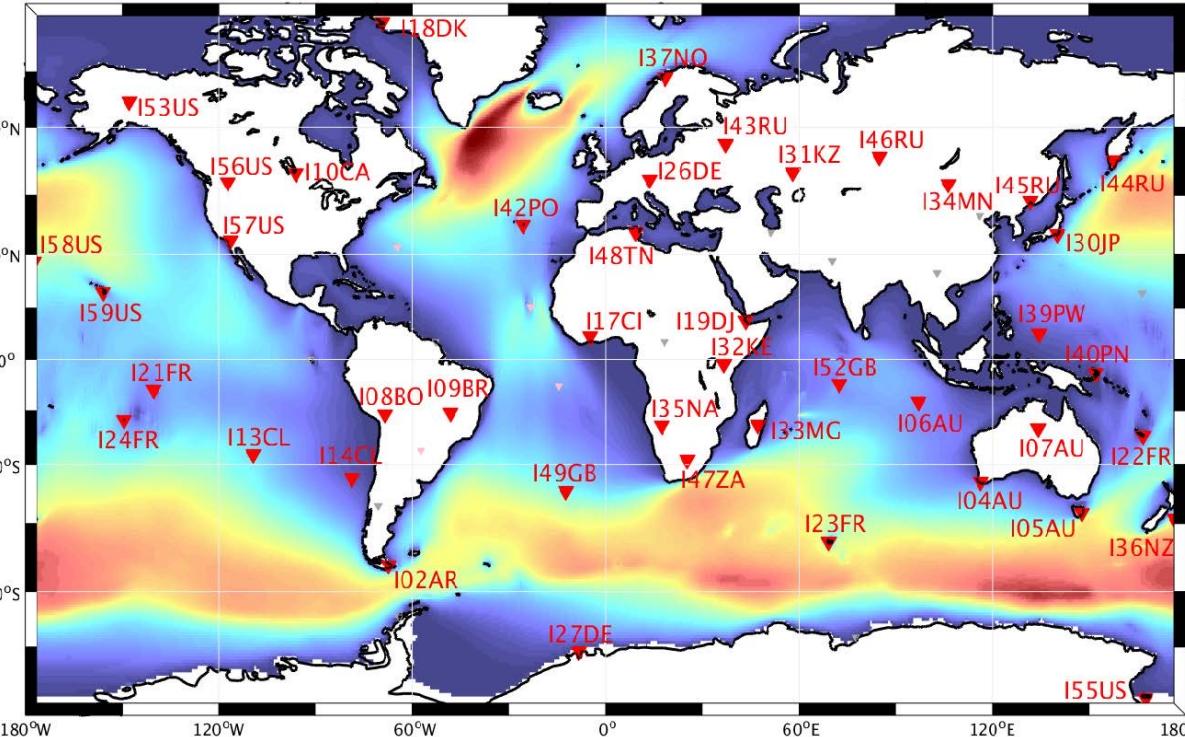
INSPIRATION
FROM EARLIER
ANALYSES
LIKE THIS →

- Global fingerprint of stratospheric dynamics
- Multi-decadal database of processed infrasound open



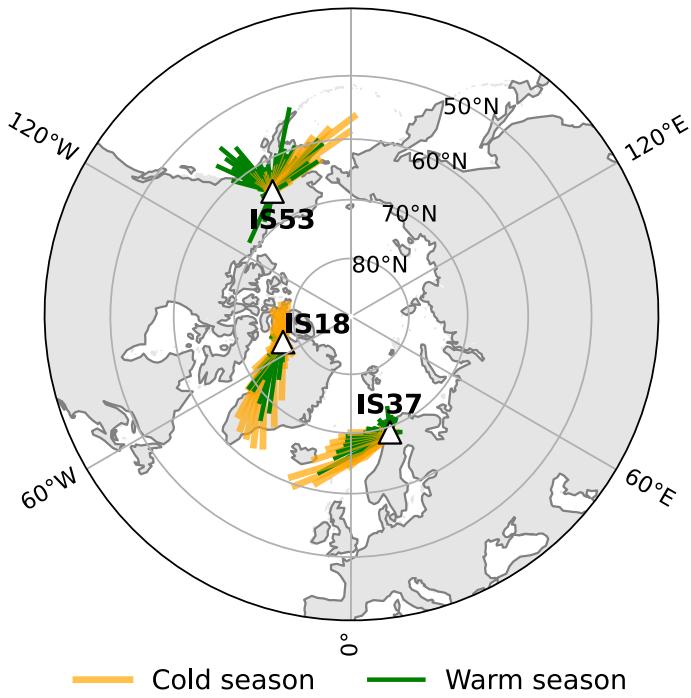
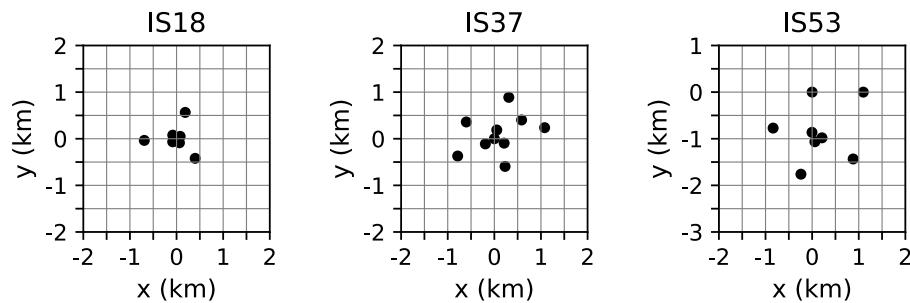
Stratospheric polar vortex probing from high-latitude infrasound

Paper in preparation



- ERA-5 1hPa polar cap average zonal wind: ground-truth
- 5 years infrasound to train a specialized neural net
 - ⇒ Direct mapping between infrasound data & stratospheric winds
 - ⇒ Can be implemented in real-time

Eggen, M. D. and Vorobeva, E. and Midtfjord, A. D. and Benth, F. E. and Hupe, P. and Brissaud, Q. and Orsolini, Y. and Le Pichon, A and Listowski, C and Näsholm, S.P. *In preparation. See also separate EGU presentation*

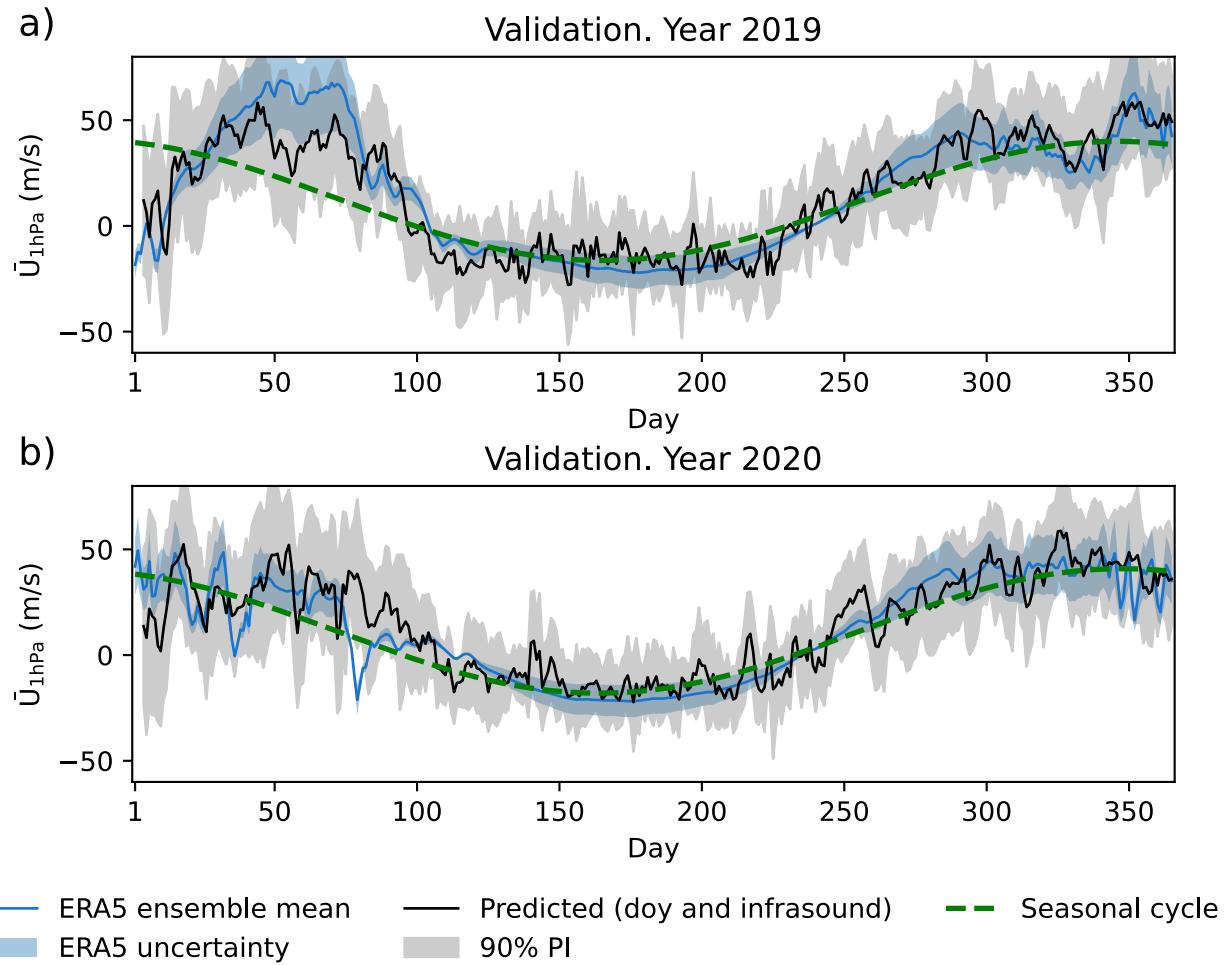


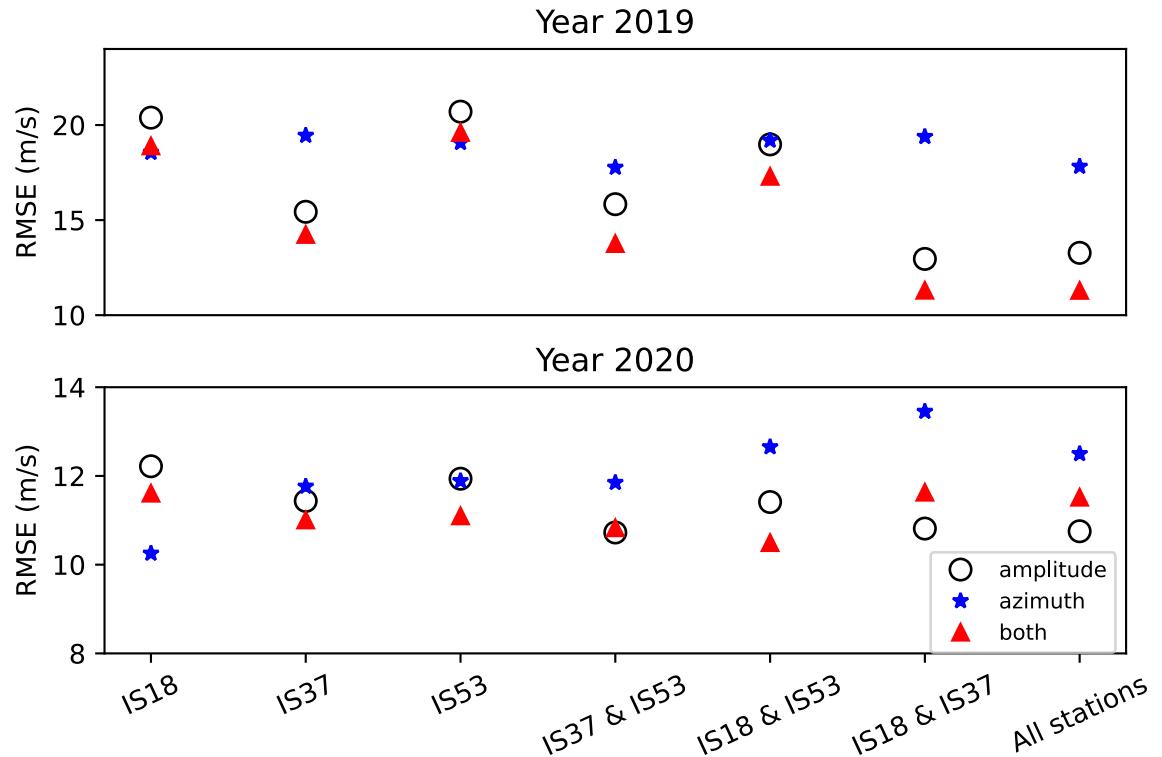
Eggen, M. D. and Vorobeva, E. and
 Midtfjord, A. D. and Benth, F. E. and Hupe,
 P. and Brissaud, Q. and Orsolini, Y. and Le
 Pichon, A and Listowski, C and Näsholm,
 S.P. *EGU*

Directly mapping
infrasound recordings to
upper stratospheric zonal
wind zonal mean
in m/s

*Relevant to stratospheric
diagnostics*

Eggen, M. D. and Vorobeva, E. and
Midtfjord, A. D. and Benth, F. E. and Hupe,
P. and Brissaud, Q. and Orsolini, Y. and Le
Pichon, A and Listowski, C and Näsholm,
S.P. *EGU*





Eggen, M. D. and Vorobeva, E. and
Midtfjord, A. D. and Benth, F. E. and Hupe,
P. and Brissaud, Q. and Orsolini, Y. and Le
Pichon, A and Listowski, C and Näsholm,
S.P. *EGU*

MADEIRA general aspects



Approach & reflections

- Used *Journal paper subprojects* as frameworks for collaboration
Funder gave great flexibility regarding WPs and Milestones from proposal
- Extensive guest research program greatly reduced due to Corona
- Exensive project internal workshop and visit program cancelled due to Corona:
Only one all-consortium meeting: the kick-off!
 - Maybe these are not needed?
 - Maybe at the cost of less integration of some partners?
 - Would have made PhD candidate life much easier if visits with partners were possible from the start

Thank you!

Research Council of Norway

FRIPRO/FRINATEK, Contract 274377:

Middle Atmosphere Dynamics:

Exploiting Infrasound Using a Multidisciplinary Approach at High Latitudes (MADEIRA)

So many friendly and creative colleagues !

Javier Amezcuia

Jelle Assink

Evgenia Belova

Fred Espen Benth

Mårten Blixt

Quentin Brissaud

Andrew Charlton-Perez

Marine De Carlo

Mari Dahl Eggen

Patrick Espy

Edouard Forestier

Steven Gibbons

Rob Hibbins

Patrick Hupe

Kamran Iranpour

Johan Kero

Tormod Kvaerna

Alexis Le Pichon

Steffen Mæland

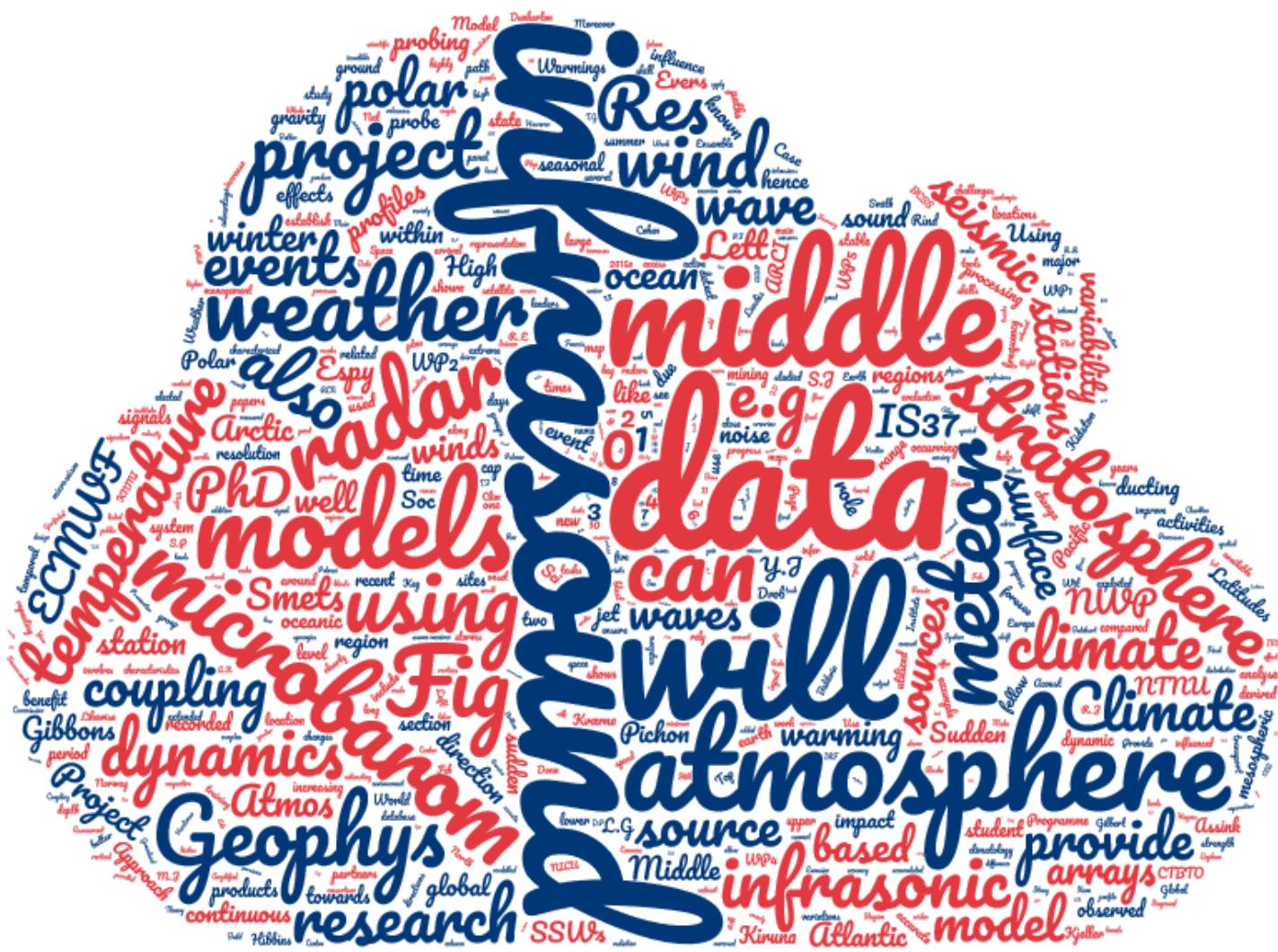
Yvan Orsolini

Kristina Rognlien Dahl

Ismael Vera Rodriguez

Antoine Turquet

Ekaterina Vorobeva



Scientific works and public outreach, sorted by year

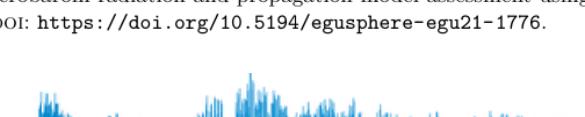
- [1] Näsholm, S. P.; Blixt, E. M.; Gibbons, S. J.; Stettner, F. B.; Kvaerna, T. "Interpreting explosive acoustic arrivals at the ARCES seismic array in the context of atmospheric cross-winds". *49th Nordic Seismology Seminar* (Sept. 26, 2018). Kjeller, Norway, 2018. Conference talk.
- [2] Blixt, E. M.; Näsholm, S. P.; Gibbons, S. J.; Stettner, F. B.; Kvaerna, T. "Cross-wind effects on infrasound propagation". *CTBTO Infrasound Technology Workshop* (Nov. 7, 2018). Vienna, Austria, 2018. Conference talk.
- [3] Gibbons, S. J.; Näsholm S. P. Blixt, E. M.; Kvaerna, T. "Measuring infrasonic wavefronts over large aperture sensor arrays". *CTBTO Infrasound Technology Workshop* (Nov. 6, 2018). Vienna, Austria, 2018. Conference talk.
- [4] Näsholm, S. P. "Observations of microbarom-generated infrasound in Northern Norway during three different sudden stratospheric warmings". *International Space Science Institute Bern (ISSI), International Team or Experts Workshop: Synergy between Satellite and Ground-Based Observations for the Study of Middle Atmosphere Dynamics* (Mar. 5, 2019). Bern, Switzerland, 2019. Conference talk.
- [5] Blanc, E.; Hauchecorne, A.; Keckhut, P.; Le Pichon, A.; Baumgarten, G.; Stober, G.; Espy, P.; Hibbins, R.; Näsholm, S. P.; Charlton-Perez, A.; Marlton, G.; Marchetti, E.; Brachet, N.; Mialle, P.; Ceranna, L.; Pilger, C.; Hupe, P.; Rapp, M.; Kaifler, B.; Kero, J.; Belova, E.; Lastovicka, J.; Gausa, M.; Cammas, J. P. "Atmospheric dynamics from near ground to near Earth space: The ARISE project". *European Geosciences Union General Assembly Conference Abstracts* (Apr. 10, 2019). Vienna, Austria, 2019. Conference poster.
- [6] Blixt, E. M.; Charlton-Perez, A. J.; Evers, L. G.; Gibbons, S. J.; Kvaerna, T.; Näsholm, S. P.; Stettner, F. B. "Cross-wind effects on infrasound waves partially reflected at stratospheric altitudes". *European Geosciences Union General Assembly Conference Abstracts* (Apr. 10, 2019). Vienna, Austria, 2019. Conference talk.
- [7] De Carlo, M.; Le Pichon, A.; Ardhuin, F.; Näsholm, S. P.; Smets, P. "Evaluating microbaroms source models in finite ocean depth: comparison with IMS station observations". *European Geosciences Union General Assembly Conference Abstracts* (Apr. 10, 2019). Vienna, Austria, 2019. Conference poster.
- [8] Le Pichon, A.; De Carlo, M.; Vergoz, J.; Näsholm, S. P.; Espy, P.; Hibbins, R.; Kero, J. "Characterizing middle atmosphere variability using ocean ambient noise as recorded by a regional infrasound network". *European Geosciences Union General Assembly Conference Abstracts* (Apr. 10, 2019). Vienna, Austria, 2019. Conference poster.
- [9] Dinescu, R.; Ghica, D.; Schweitzer, J.; Näsholm, S. P.; Popa, M.; Ionescu, C. "Monitoring man-made hazards using data recorded with the Romanian seismic and infrasonic arrays". *European Geosciences Union General Assembly Conference Abstracts* (Apr. 10, 2019). Vienna, Austria, 2019. Conference poster.
- [10] Näsholm, S. P.; Assink, J. D.; Blixt, E. M.; De Carlo, M.; Evers, L. G.; Gibbons, S. J.; Kero, J.; Le Pichon, A.; Orsolini, Y.; den Ouden, O. F. C.; Smets, P. S. M. "Observations of microbarom-generated infrasound in Northern Norway during three different sudden stratospheric warmings". *European Geosciences Union General Assembly Conference Abstracts* (Apr. 14, 2019). Vienna, Austria, 2019. Conference talk.
- [11] Blanc, E.; Le Pichon, A.; Pilger, C.; Hupe, P.; Ceranna, L.; Marchetti, E.; Brachet, N.; Mialle, P.; Hereil, P.; Näsholm, S. P.; Charlton-Perez, A.; Marlton, G. "ARISE project: infrasound monitoring for civil applications". *CTBTO: Science and Technology Conference* (June 25, 2019). Vienna, Austria, 2019. Conference poster.



- [12] Blixt, E. M.; Näsholm, S. P.; Gibbons, S.; Kvaerna, T. "Estimating tropospheric and stratospheric large-scale wind components using infrasound from explosions". *CTBT: Science and Technology Conference* (June 25, 2019). Vienna, Austria, 2019. Conference poster.
- [13] Millet, C.; Ribstein, B.; Näsholm, S. P. "Learning about small-scale atmospheric structures through recurrent infrasound events". *CTBT: Science and Technology Conference* (June 26, 2019). Vienna, Austria, 2019. Conference poster.
- [14] Blixt, E. M.; Näsholm, S. P.; Gibbons, S. J.; Evers, L. G.; Charlton-Perez, A. J.; Orsolini, Y. J.; Kvaerna, T. "Estimating tropospheric and stratospheric winds using infrasound from explosions". *The Journal of Acoustical Society of America* 146.2 (2019), pp. 973–982. DOI: <https://doi.org/10.1121/1.5120183>.
- [15] Näsholm, S. P. "Exploiting low-frequency acoustic waves to probe middle atmospheric dynamics". *The Centre for Earth Evolution and Dynamics seminars* (Sept. 5, 2019). University of Oslo, Oslo, Norway, 2019. Invited talk.
- [16] De Carlo, M.; Le Pichon, A.; Vergoz, J.; Ardhuin, F.; Näsholm, S. P.; Ceranna, L.; Hupe, P.; Pilger, C. "Characterizing coherent ambient noise in the North Atlantic and Barents sea regions". *CTBTO Infrasound Technology Workshop* (Nov. 14, 2019). Aqaba, Jordan, 2019. Conference talk.
- [17] Le Pichon, A.; De Carlo, M.; Näsholm, S. P.; Kero, J.; Ceranna, L.; Hupe, P.; Ardhuin, F. "Characterizing ocean ambient noise using a regional infrasound network: a sensitivity analysis". *American Geophysical Union fall meeting* (Dec. 12, 2019). San Francisco, United states, 2019. Conference poster.
- [18] Näsholm, S. P. "Probing middle atmospheric winds using infrasound recorded at ground-based arrays". *The 43rd Scandinavian Symposium on Physical Acoustics* (Jan. 27, 2020). Geilo, Norway, 2020. Conference talk.
- [19] Amezcuia, J.; Näsholm, S. P.; Blixt, M.; Charlton-Perez, A. "Assimilation of Atmospheric Infrasound Data to Constrain Winds using an EnKF". *International Conference on Ensemble Methods in Modelling and Data Assimilation (EMMDA)* (Feb. 24, 2020). New Delhi, India, 2020.
- [20] Näsholm, S. P.; Vorobeva, E.; Le Pichon, A.; Orsolini, Y. J.; Turquet, A. L.; Hibbins, R. E.; Espy, P. J.; De Carlo, M.; Assink, J. D.; Rodriguez, I. V. "Semi-diurnal tidal signatures in microbarom infrasound array measurements". *European Geosciences Union General Assembly* (May 8, 2020). Vienna, Austria, 2020. DOI: 10.5194/egusphere-egu2020-19035. URL: <https://doi.org/10.5194/egusphere-egu2020-19035>. Conference online presentation.
- [21] Amezcuia, J.; Näsholm, S. P.; Blixt, M.; Charlton-Perez, A. "Assimilation of atmospheric infrasound data to constrain tropospheric and stratospheric winds". *European Geosciences Union General Assembly* (May 8, 2020). Vienna, Austria, 2020. DOI: 10.5194/egusphere-egu2020-8244. URL: <https://doi.org/10.5194/egusphere-egu2020-8244>. Conference online presentation, solicited by the session chairs.
- [22] Belova, E.; Kero, J.; Näsholm, S. P.; Vorobeva, E.; Godin, O. A.; Barabash, V. "Polar Mesosphere Winter Echoes and their relation to infrasound". *European Geosciences Union General Assembly* (May 8, 2020). Vienna, Austria, 2020. DOI: 10.5194/egusphere-egu2020-5055. URL: <https://doi.org/10.5194/egusphere-egu2020-5055>. Conference online presentation.
- [23] Vera Rodriguez, I.; Näsholm, S. P.; Turquet, A. L.; Evers, L. G. "Climatology reflected by infrasound travel-times sampling the stratosphere in its transition between summer and winter". *European Geosciences Union General Assembly* (May 8, 2020). Vienna, Austria, 2020. DOI: 10.5194/egusphere-egu2020-20269. URL: <https://doi.org/10.5194/egusphere-egu2020-20269>. Conference online presentation.
- [24] Vorobeva, E.; Näsholm, S. P.; Espy, P.; Orsolini, Y.; Hibbins, R. "Wind estimates in the mesosphere - lower thermosphere retrieved from infrasound data". *European Geosciences Union General Assembly* (May 8, 2020). Vienna, Austria, 2020. DOI: 10.5194/egusphere-egu2020-10128. URL: <https://doi.org/10.5194/egusphere-egu2020-10128>. Conference online presentation.



- [25] Amezcuia, J.; Näsholm, S. P.; Blixt, E. M.; Charlton-Perez, A. J. "Assimilation of atmospheric infrasound data to constrain tropospheric and stratospheric winds". *Quarterly Journal of the Royal Meteorological Society* 146.731 (2020), pp. 2634–2653. DOI: 10.1002/qj.3809. URL: <https://doi.org/10.1002/qj.3809>.
- [26] Näsholm, S. P. "Probing middle atmospheric winds using infrasound recorded at ground infrasound recorded at ground-based arrays". *Signal Forum talk series* (June 2, 2020). Kongsgberg Maritime, Horten, Norway, 2020. Invited seminar talk.
- [27] Roper, J. "Sound bites". *Meteorological Technology International* (September 2020). Popular scientific paper, interviewing S. P. Näsholm, pp. 25–30. URL: <https://www.meteorologicaltechnologyinternational.com>.
- [28] Vera Rodriguez, I.; Näsholm, S. P.; Le Pichon, A. "Atmospheric model calibration using infrasound waves from explosions". *University of Reading Data Assimilation Centre (DARC) Seminar Series* (Oct. 21, 2020). Reading, UK (over videolink), 2020. Invited seminar talk held by Vera Rodriguez.
- [29] Torgersen, E. *Værmeldingen kan bli bedre ved å overvåke infralyd fra stratosfæren*. Research news site "Titan," interviewing S. P. Näsholm. Also co-published in *Teknisk Ukeblad*. 2020. URL: <https://titan.uio.no/fysikk-informatikk/2020/vaermeldingen-kan-bli-bedre-ved-a-overvake-infralyd-fra-stratosfaeren>.
- [30] Vera Rodriguez, I.; Näsholm, S. P.; Le Pichon, A. "Atmospheric wind and temperature profile inversion using infrasound: an ensemble model context". *The Journal of the Acoustical Society of America* 148.5 (2020), pp. 2923–2934. DOI: <https://doi.org/10.1121/10.0002482>.
- [31] Vorobeva, E.; De Carlo, M.; Näsholm, S. P.; Le Pichon, A. "Vespagram-based approach for benchmarking microbarom models and observations". *A.M. Obukhov Institute of Atmospheric Physics. Turbulence, Atmosphere and Climate Dynamics Workshop 2020* (Nov. 10, 2020). Moscow, Russian Federation, 2020. Conference poster.
- [32] Turquet, A.; Kero, J.; Brissaud, Q.; Näsholm, S. P.; Kvaerna, T.; Le Pichon, A. "In-depth seismo-acoustic analysis of mining-induced Mw 4.9 Kiruna earthquake". *American Geophysical Union fall meeting* (Dec. 7, 2020). Online everywhere, 2020. Conference poster.
- [33] Zhang, J.; Limpasuvan, V.; Orsolini, Y. J.; Espy, P. J.; Hibbins, R. E. "Climatological Westward-Propagating Semidiurnal Tides and Their Composite Response to Sudden Stratospheric Warmings in SuperDARN and SD-WACCM-X". *Journal of Geophysical Research: Atmospheres* 126.3 (2021), e2020JD032895. DOI: <https://doi.org/10.1029/2020JD032895>.
- [34] Eggen, M. D.; Dahl, K.; Näsholm, S. P.; Mæland, S. "Stochastic modelling of stratospheric temperature". *European Geosciences Union General Assembly* (Apr. 27, 2021). Vienna, Austria, 2021. DOI: <https://doi.org/10.5194/egusphere-egu21-239>. Conference online presentation.
- [35] Turquet, A.; Brissaud, Q.; Näsholm, S. P.; Kero, J.; Kvaerna, T.; Listowski, C.; Le Pichon, A. "Near and far-field seismo-acoustic analysis of mb 4.9 mining induced earthquake nearby Kiruna, Sweden". *European Geosciences Union General Assembly* (Apr. 26, 2021). Vienna, Austria, 2021. DOI: <https://doi.org/10.5194/egusphere-egu21-8343>. Conference online presentation, highlighted by the conveners.
- [36] Rodriguez, I. V.; Näsholm, S. P.; Brissaud, Q.; Turquet, A.; Le Pichon, A. "Estimation of infrasound-consistent wind and temperature atmospheric profiles from model ensembles in North Scandinavia". *European Geosciences Union General Assembly* (Apr. 26, 2021). Vienna, Austria, 2021. DOI: <https://doi.org/10.5194/egusphere-egu21-1384>. Conference online presentation.
- [37] Vorobeva, E.; De Carlo, M.; Espy, P.; Näsholm, S. P. "Vespagram-based approach for microbarom radiation and propagation model assessment using infrasound recordings". *European Geosciences Union General Assembly* (Apr. 26, 2021). Vienna, Austria, 2021. DOI: <https://doi.org/10.5194/egusphere-egu21-1776>. Conference online presentation, solicited by the session chairs.



- [38] Yankovsky, V.; Vorobeva, E.; Manuilova, R.; Mironova, I. "Model of Daytime Oxygen Emissions in the Mesopause Region and Above: New Results". *European Geosciences Union General Assembly* (Apr. 29, 2021). Vienna, Austria, 2021. DOI: <https://doi.org/10.5194/egusphere-egu21-2656>. Conference online presentation.
- [39] ★ Vorobeva, E.; De Carlo, M.; Le Pichon, A.; Espy, P. J.; Näsholm, S. P. "Benchmarking microbarom radiation and propagation model against infrasound recordings: a vespagram-based approach". *Annales Geophysicae* 39.3 (2021), pp. 515–531. DOI: [10.5194/angeo-39-515-2021](https://doi.org/10.5194/angeo-39-515-2021).
- [40] Brissaud, Q.; Näsholm, S. P.; Turquet, A.; Le Pichon, A. "Predicting infrasound transmission loss using deep learning". *American Geophysical Union Fall Meeting* (Dec. 17, 2021). New Orleans, US / hybrid online, 2021. Conference online oral presentation, held by S. P. Näsholm.
- [41] ★ Vierinen, J.; Aslaksen, T.; Chau, J. L.; Gritsevich, M.; Gustavsson, B.; Kastinen, D.; Kero, J.; Kozlovsky, A.; Kvaerna, T.; Midskogen, S.; Näsholm, S. P.; Ulich, T.; Vegum, K.; Lester, M. "Multi-instrument observations of the Pajala Fireball: Origin, characteristics, and atmospheric implications". *Frontiers in Astronomy and Space Sciences* (2022), p. 326. DOI: [10.3389/fspas.2022.1027750](https://doi.org/10.3389/fspas.2022.1027750).
- [42] ★ Vergoz, J.; Hupe, P.; Listowski, C.; Le Pichon, A.; Garcés, M. A.; Marchetti, E.; Labazuy, P.; Ceranna, L.; Pilger, C.; Gaebler, P.; Näsholm, S. P.; Brissaud, Q.; Poli, P.; Shapiro, N.; De Negri, R.; Mialle, P. "IMS observations of infrasound and acoustic-gravity waves produced by the January 2022 volcanic eruption of Hunga, Tonga: A global analysis". *Earth and Planetary Science Letters* 591 (2022), p. 117639. ISSN: 0012-821X. DOI: <https://doi.org/10.1016/j.epsl.2022.117639>.
- [43] ★ Näsholm, S. P.; Iranpour, K.; Wuestefeld, A.; Dando, B. D. E.; Baird, A. F.; Oye, V. "Array signal processing on distributed acoustic sensing data: directivity effects in slowness space". *Journal of Geophysical Research: Solid Earth* 127.2 (2022), e2021JB023587. DOI: <https://doi.org/10.1029/2021JB023587>.
- [44] ★ Eggen, M. D.; Dahl, K. R.; Näsholm, S. P.; Mæland, S. "Stochastic modeling of stratospheric temperature". *Mathematical Geosciences* 54 (2022), pp. 651–678. DOI: <https://doi.org/10.1007/s11004-021-09990-6>.
- [45] Belova, E.; Barabash, V.; Godin, O. A.; Kero, J.; Näsholm, S. P.; Vorobeva, E.; Le Pichon, A. "Infrasound as a Probable Cause of Fast-travelling Polar Mesosphere Winter Echoes". *International Workshop on Layered Phenomena in the Mesopause Region* (Aug. 16, 2022). Eskilstuna, Sweden, 2022. Conference poster.
- [46] Forestier, E.; Brissaud, Q.; Näsholm, S. P.; Le Pichon, A. "Training a recurrent neural network (RNN) to predict long-range infrasound ground-to-ground transmission loss in range-dependent realistic atmospheres". *American Geophysical Union fall meeting* (Dec. 13, 2022). Online everywhere, 2022. Conference poster.
- [47] Näsholm, S. P. "Infralydbasert karakterisering av vind i den midtre atmosfæren". *Oslo Geofysikeres forenings medlemsmøte* (Oct. 27, 2022). Oslo, Norway, 2022. Invited conference talk.
- [48] Näsholm, S. P.; Iranpour, K.; Wuestefeld, A.; Dando, B.; Baird, A.; Oye, V. "Array signal processing on distributed acoustic sensing data: directivity effects in slowness space". *European Geosciences Union General Assembly* (May 24, 2022). Vienna, Austria, 2022. DOI: <https://doi.org/10.5194/egusphere-egu22-6984>. Conference presentation.
- [49] Vergoz, J.; Le Pichon, A.; Listowski, C.; Hupe, P.; Pilger, C.; Gaebler, P.; Ceranna, L.; Garcés, M.; Marchetti, E.; Labazuy, P.; Mialle, P.; Brissaud, Q.; Näsholm, S. P.; Shapiro, N.; Poli, P. "A global analysis of deep infrasound produced by the January 2022 eruption of Hunga volcano". *European Geosciences Union General Assembly* (May 26, 2022). Vienna, Austria, 2022. DOI: <https://doi.org/10.5194/egusphere-egu22-13598>. Conference presentation.
- [50] Eggen, M.; Rognlien Dahl, K.; Näsholm, S. P.; Mæland, S. "Stochastic Modeling of Stratospheric Temperature". *European Geosciences Union General Assembly* (May 24, 2022). Vienna, Austria, 2022. DOI: <https://doi.org/10.5194/egusphere-egu22-8745>. Conference presentation.



- [51] Amezcua, J.; Näsholm, S. P.; Vera-Rodriguez, I. "Constraining middle and upper atmospheric variables by assimilating measurements from infrasound propagation". *European Geosciences Union General Assembly* (May 25, 2022). Vienna, Austria, 2022. DOI: <https://doi.org/10.5194/egusphere-egu22-6803>. Invited conference talk held by Javier Amezcua.
- [52] Belova, E.; Barabash, V.; Godin, O. A.; Kero, J.; Näsholm, S. P.; Vorobeva, E.; Le Pichon, A. "Fast-travelling Polar Mesosphere Winter Echoes: Infrasound as a Probable Cause". X (2023). Submitted to Advances in Space Research, p. X.
- [53] Amezcua, J.; Näsholm, S. P.; Vera Rodriguez, I. "Using satellite data assimilation techniques to combine infrasound observations and a full ray-tracing model to constrain stratospheric variables". X (2023). Submitted to the Journal of the Acoustical Society of America, p. X.
- [54] Vorobeva, E.; Eggen, M. D.; Midtfjord, A. D.; Benth, F. E.; Hupe, P.; Brissaud, Q.; Orsolini, Y.; Näsholm, S. P. "Estimating stratospheric polar vortex strength using ambient ocean noise and stochastics-based machine learning". X X.X (2023). Manuscript in preparation.
- [55] Vorobeva, E.; Assink, J.; Chunchuzov, I.; Renkwitz, T.; Espy, P.; Näsholm, S. P. "Probing gravity waves in the middle atmosphere using infrasound from explosions". *Journal of Geophysical Research: Atmospheres* X.X (2023). Revised manuscript in preparation (minor revision review).
- [56] Brissaud, Q.; Näsholm, S. P.; Turquet, A.; Le Pichon, A. "Predicting infrasound transmission loss using deep learning". *Geophysical Journal International* 232.1 (2023), pp. 274–286. ISSN: 0956-540X. DOI: [10.1093/gji/ggac307](https://doi.org/10.1093/gji/ggac307).
- [57] Forestier, E.; Näsholm, S. P.; Brissaud, Q.; Le Pichon, A. "Rapid estimation of ground-to-ground infrasonic transmission loss using a recurrent neural network (RNN) trained on simulations through realistic atmosphere model specifications". *CTBTO Infrasound Technology Workshop* (Jan. 31, 2023). Ponta Delgada, Portugal, 2023. Conference talk.
- [58] Näsholm, S. P.; Brissaud, Q.; Schweitzer, J.; Vorobeva, E.; Eggen, M. D. "Introduction to Infrasound and Atmospheric Sensing". *Atom Interferometric Sensing of Earth's Spheres* (Mar. 27, 2023). Queen's College, Cambridge, UK, 2023. Invited conference talk.
- [59] Brissaud, Q.; Schweitzer, J.; Näsholm, S. P.; Vorobeva, E.; Eggen, M. D. "Infrasound arrays as probes for atmospheric and ice dynamics in polar regions". *Security and preparedness in the changing North – research perspectives* (Mar. 23, 2023). Oslo, Norway, 2023. Invited conference talk held by Quentin Brissaud.
- [60] Hupe, P.; Vergoz, J.; Listowski, C.; Le Pichon, A.; Garces, M.; Marchetti, E.; Labazuy, P.; Ceranna, L.; Pilger, C.; Gaebler, P.; Näsholm, S. P.; Brissaud, Q.; Piero, P.; Shapiro, N. M.; De Negri, R.; Mialle, P. "IMS observations of infrasound and acoustic-gravity waves produced by the January 2022 volcanic eruption of Hunga, Tonga: A global analysis". *CTBTO Infrasound Technology Workshop* (Feb. 3, 2023). Ponta Delgada, Portugal, 2023. Conference talk.
- [61] Vorobeva, E.; Assink, J.; Belova, E.; Latteck, R.; Espy, P.; Baumgarten, G.; Strelnikova, I.; Orsolini, Y.; Näsholm, S. P. "Probing internal gravity waves in the middle atmosphere using infrasound from explosions". *CTBTO Infrasound Technology Workshop* (Feb. 3, 2023). Ponta Delgada, Portugal, 2023. Conference talk.
- [62] Amezcua, J.; Näsholm, S. P. "Using satellite data assimilation techniques to combine infrasound observations and a full ray-tracing model to constrain atmospheric variable". *European Geosciences Union General Assembly* (May 24, 2023). Vienna, Austria, 2023. DOI: <https://doi.org/10.5194/egusphere-egu23-8665>. Conference presentation.
- [63] Vorobeva, E.; Assink, J.; Chunchuzov, I.; Renkwitz, T.; Espy, P.; Näsholm, S. P. "Using infrasound from explosions for probing internal gravity waves in the middle atmosphere". *European Geosciences Union General Assembly* (May 27, 2023). Vienna, Austria, 2023. DOI: <https://doi.org/10.5194/egusphere-egu23-6993>. Conference presentation.



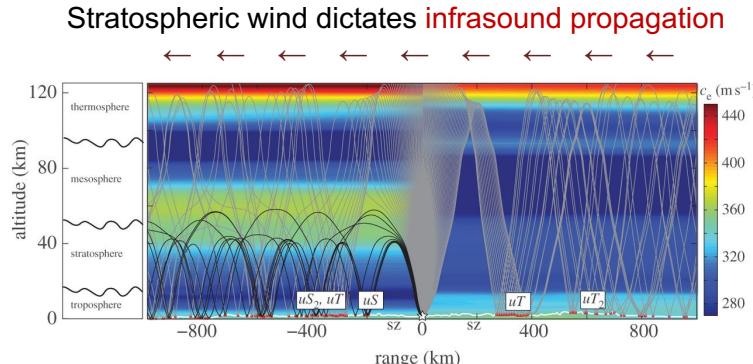
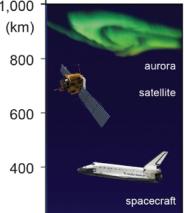
- [64] Eggen, M.; Midtfjord, A. D.; Vorobeva, E.; Benth, F. E.; Hupe, P.; Brissaud, Q.; Orsolini, Y.; Le Pichon, A.; Listowski, C.; Näsholm, S. P.
“Using a machine learning and stochastics-founded model to provide near real-time stratospheric polar vortex diagnostics based on high-latitude infrasound data”.
European Geosciences Union General Assembly (May 27, 2023). Vienna, Austria, 2023. DOI: <https://doi.org/10.5194/egusphere-egu23-11977>. Conference presentation.
- [65] Näsholm, S. P.; Amezcua, J.; Assink, J. D.; Belova, E.; Blixt, E. M.; Brissaud, Q.; Eggen, M. D.; Espy, P. J.; Hibbins, R.; Kero, J.; Kvaerna, T.; Le Pichon, A.; Orsolini, Y. J.; Vera Rodriguez, I.; Turquet, A.; Vorobeva, E.
“Summarizing the research of the MADEIRA project – Middle atmosphere dynamics: exploiting infrasound using a multidisciplinary approach at high latitudes”.
European Geosciences Union General Assembly (May 27, 2023). Vienna, Austria, 2023. DOI: <https://doi.org/10.5194/egusphere-egu23-7121>. Conference presentation.

One-pager at Norwegian
Research Council
pre-funding interview →

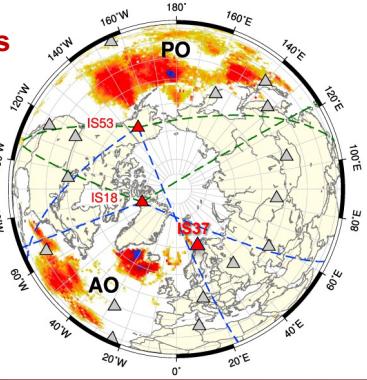


Middle atmosphere

Numerical weather prediction lacks wind data assimilation



Infrasound source: microbaroms
from colliding ocean waves



PRIMARY OBJECTIVE

Constraints to wind & temperature

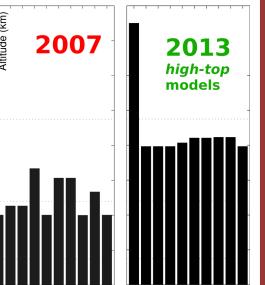
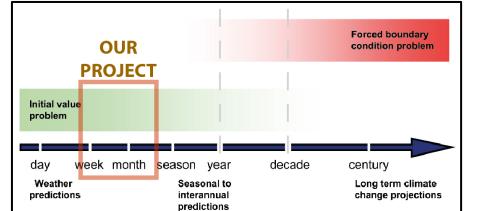
- 30–60 km: ground-based infrasound
- 70–100 km: ground-based meteor radar

Innovative approaches

- Multi-station & multi-source infrasound
- Constraints / assessments both to numerical weather prediction initial values & output ensembles

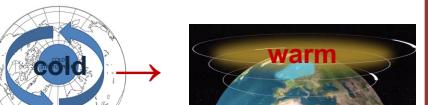
Paving the way for numerical weather prediction improvements

- Recent introduction of *high-top* models \Rightarrow enhanced predictions
- Potential for even further improvements when including new middle atmospheric data

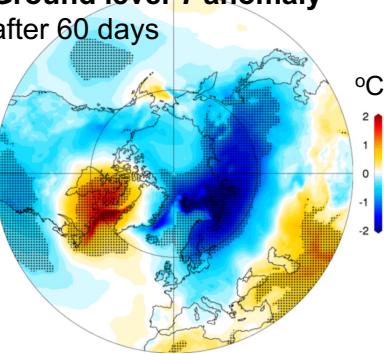


Coupling down to ground level

Example: Sudden Stratospheric Warming



Ground level T anomaly
after 60 days



Case: Stratospheric warming / mesospheric cooling 2016

