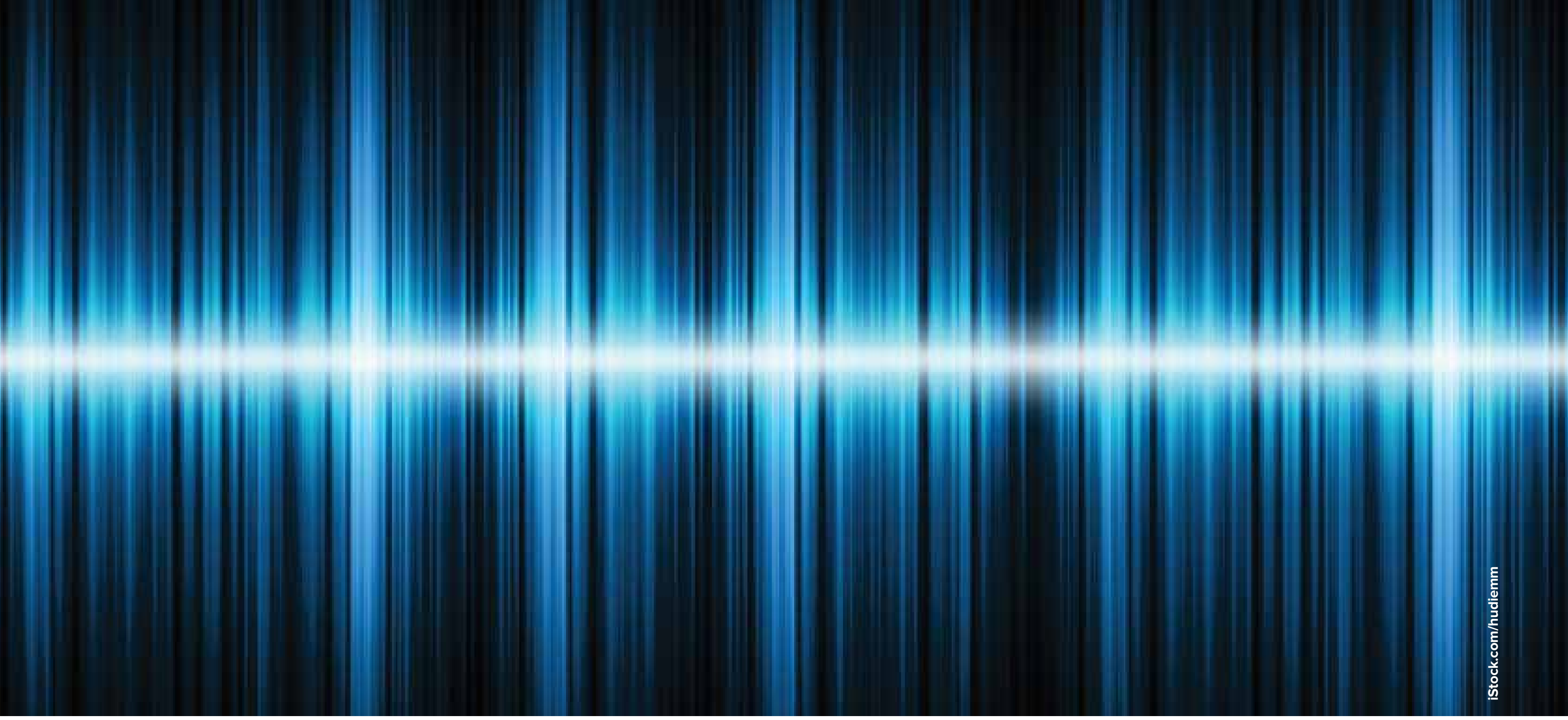
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Using Sounds from the Ocean to Measure Winds in the Stratosphere

By Marie Arrowsmith, Stephen Arrowsmith, and Omar Marcillo

Stratospheric winds deflect acoustic waves from the oceans. With the right data and the math to analyze them, these waves tell us about the weather aloft.

Improving weather forecasts and climate models over both short and seasonal timescales requires a better understanding of the stratosphere [*Shaw and Shepherd,* 2008]. In this atmospheric layer (10–50 kilometers in altitude), temperature increases with altitude because of an increase in ozone, which absorbs ultraviolet light. This layer also plays a crucial role in weather generation.

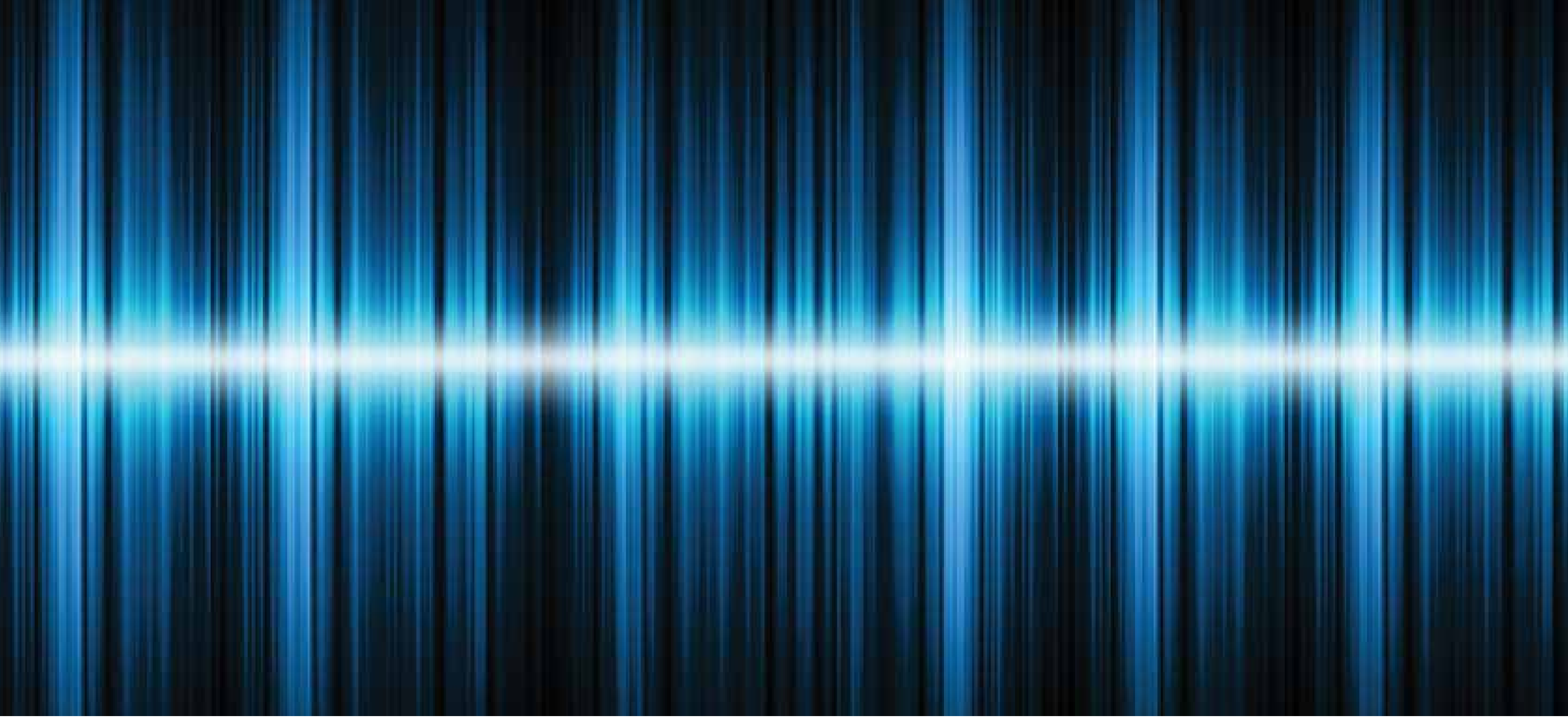
Many properties of the atmospheric state—temperature, pressure, and density—are well understood or well modeled in the stratosphere. However, a critical property, wind state, is poorly understood because it varies considerably across time and space and because of a lack of direct measurements, which are generally limited to discrete samples obtained by very specialized instruments. The need for new ways to measure stratospheric dynamics is a topic of active study, including a major scientific initiative in Europe [*World Meteorological Organization,* 2013].

Recently, lidar has been employed to provide more detailed stratospheric wind measurements [*Baumgarten,* 2010]. Because aerosol and molecular densities are lower in the stratosphere, this technology requires a complicated setup of large-aperture telescopes and powerful lasers; such facilities are expensive to build and operate, and they provide wind profiles only at their particular location.

Using Sound to Study Winds

In parallel with improving models and measurements of stratospheric properties, there has also been a renaissance of research on low-frequency acoustic propagation. The field has been revitalized by nuclear explosion monitoring efforts and the ongoing installation of the International Monitoring System (IMS) infrasound network.

Infrasound—sound below the frequency threshold of human hearing—can be detected at large distances because the atmosphere absorbs very little of it. Infrasound waves are refracted in the stratosphere because a combination of increasing heat and wind near the stratopause, the boundary between the stratosphere and mesosphere (50–100 kilometers in altitude), affects the speed



of sound in the atmosphere. Thus, the refraction of infrasound is dependent on stratospheric temperature and wind state.

A mathematical formulation known as inversion can be used to infer temperature and wind state from the observed changes in infrasound. Until recently, studying wind using inversion of infrasound data required known, short-lived events such as large chemical explosions. However, the concept of using continuous measurements to quantify stratospheric winds was proposed more than 40 years ago, when *Donn and Rind* [1972] suggested that microbaroms—ocean-generated infrasound—could be used to infer upper atmospheric conditions.

Microbaroms originate when ocean waves having similar wavelengths and traveling in approximately opposite directions interact. Several factors have limited progress in using inversion of microbarom signals for characterizing the atmospheric state:

- Microbaroms are radiated from large areas of ocean.
- Their location is variable and dependent on the ocean state.
- Microbarom signals are continuous and narrowband (they occur over a narrow range of frequencies), in contrast to the transient broadband signals used in other studies.

The first two issues increase the number of variables that must be accounted for when inverting infrasonic observations for winds, requiring many more observations to solve the governing equations. The third issue degrades our ability to measure propagation time differences between arrays using cross-correlation techniques.

In 2013, we proposed an algorithm for inverting for winds in the stratosphere using transient sources with unknown location [*Arrowsmith et al.*, 2013]. Recently, *Fricke et al.* [2014] demonstrated that microbarom correlations from waves refracted in the troposphere can be observed at distances of up to approximately 40 kilometers using single-channel stations, which addresses the narrowband observation issue.

Our work with the Norwegian Stratosphere (NORSE) experiment addresses the major unknown: whether observable waveform correlations can be related to the refraction of waves, and thus the conditions, in the stratosphere.

A Microbarom Network in Norway

Recently, a team of researchers organized a field experiment to study microbarom signals that are refracted in the stratosphere to characterize the winds using waveform correlations. This effort is led by the Laboratory Directed Research and Development program at Los Alamos National Laboratory (LANL), and team members come from LANL, the Andoya Space Center (Norway), the Leibniz-Institute of Atmospheric Physics (Germany), and the Norwegian Seismic Array (NORSAR) research foundation (Norway).

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A view from one of the elements at the SKD infrasound array near Andenes, Norway, looking west at the brightest time of day during October, the last day the Sun came across the horizon in 2014.

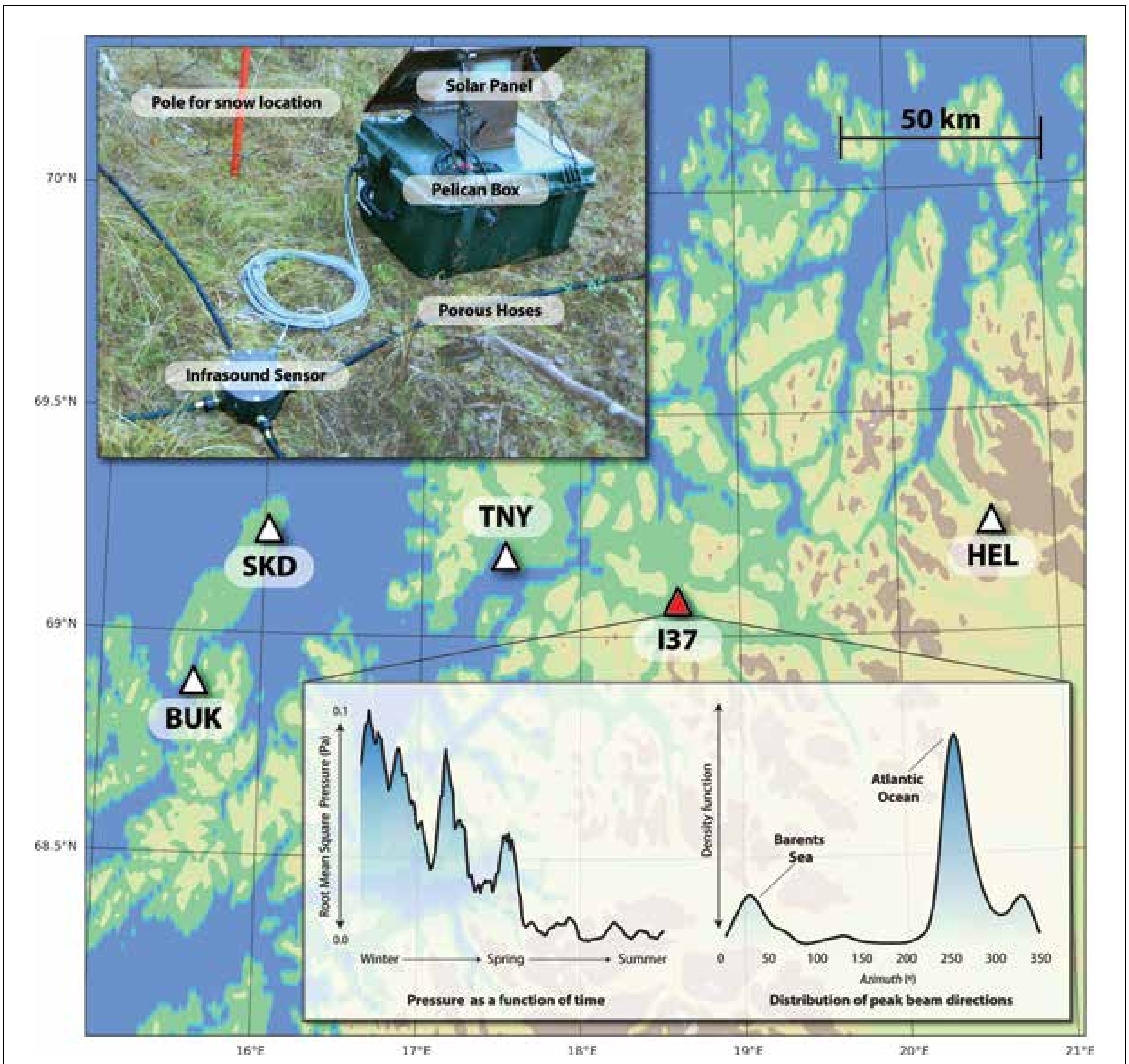
Our team selected a field area in northern Norway, located near both the Arctic Lidar Observatory for Middle Atmosphere Research (ALOMAR) and the IMS I37 infrasound array. ALOMAR has the capability to make direct measurements of stratospheric winds that will provide an independent validation of the infrasound-derived measurements [*Baumgarten*, 2010]. We analyzed data from the I37 array to configure the network, and we deployed it beginning in 2014. Signals are strongest in the winter months, propagating from a west-southwest direction (Figure 1). The correlation of microbarom signals is strongest along the direction of propagation. Because our proposed technique [*Arrowsmith et al.*, 2013] depends on strong correlations, we designed the network to lie along the axis of propagation at I37.

In October 2014, the NORSE team deployed two four-element infrasound arrays near ALOMAR. We used one full winter of data collected from these two arrays (SKD and BUK, Figure 1) to finalize the network design and conduct on-site tests of various noise reduction systems. In April 2015, we installed two additional four-element arrays (TNY and HEL, Figure 1), which will operate until April 2016. For optimal spatial filtering (beamforming), the distance between sensors in the array is approximately 850 meters, or half a microbarom wavelength.

Preliminary Results and Future Work

Our team analyzed data from the SKD, BUK, and I37 arrays. Strong microbaroms were present at all three arrays and exhibited similar trends in direction and pres-

Fig. 1. The Norwegian Stratosphere (NORSE) experiment involves the installation of four arrays near the Arctic Lidar Observatory for Middle Atmosphere Research (ALOMAR) and the International Monitoring System (IMS) I37 infrasound array in Norway. The top inset shows a typical station setup. The bottom inset shows that microbarom pressure at I37 is strongest during the winter months. Microbarom beam directions from separate sources in the North Atlantic and Barents Sea are prominent peaks in the bearings along the horizontal axis in the graph at right.



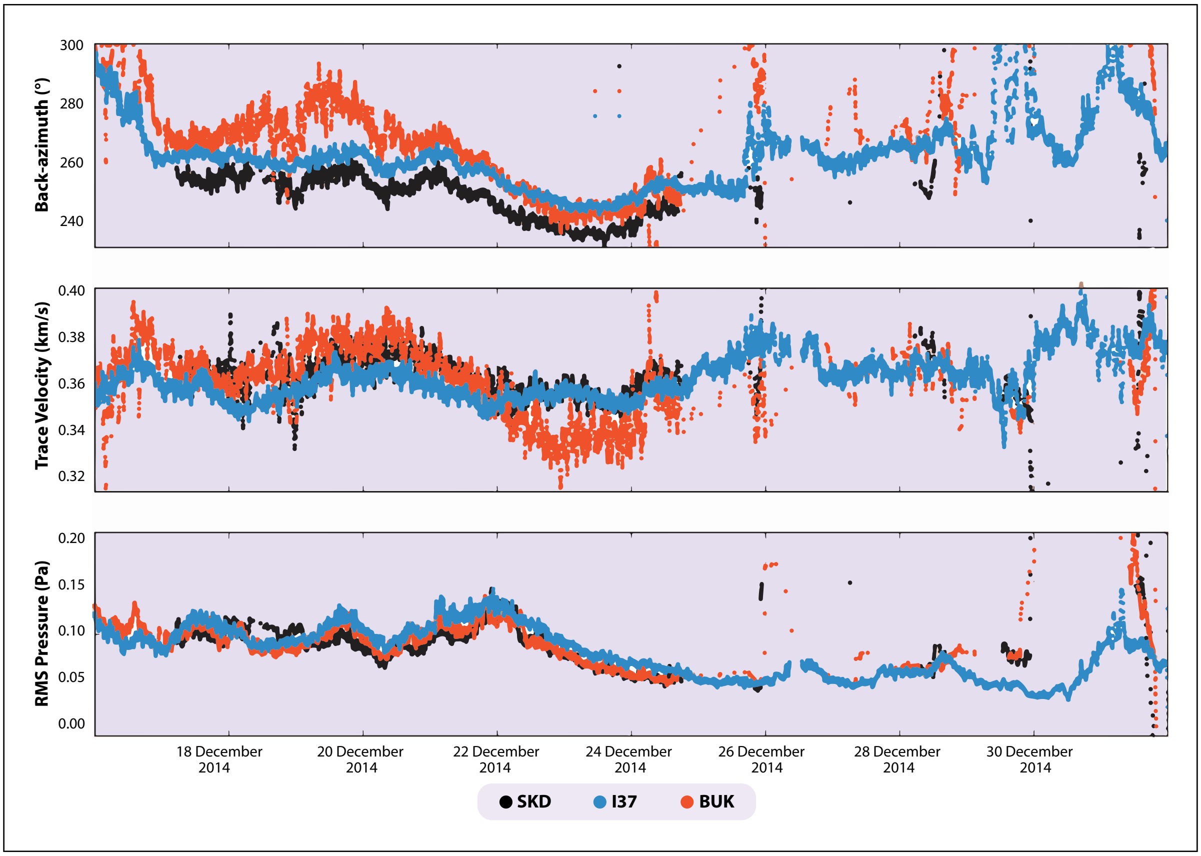


Fig. 2. An analysis of (top) the direction, (middle) trace velocity, and (bottom) power of the dominant microbarom signals observed at the SKD, I37, and BUK arrays from 16 December 2014 through 1 January 2015. RMS = root mean square.

sure as a function of time (Figure 2). This result provides clear evidence that microbarom signals at the three arrays originated from the same broad North Atlantic Ocean source, and they encountered similar atmospheric conditions from source to receiver.

These are the conditions that must be met to use microbarom observations to invert for wind in the stratosphere. If these conditions had not been met, there would have been too many variables, the inverse problem would have been unconstrained, and we would not have been able to apply the inversion method to analyze the data.

This result provides clear evidence that microbarom signals at the three arrays originated from the same broad North Atlantic Ocean source.

The observations also show that properties of microbaroms are highly dynamic: The direction and power of the signals change over time, with acoustic noise levels at each individual array strongly affecting the estimates. For example, high noise levels from 26 December 2014 to 1 January 2015 caused gaps in the observations at SKD and BUK.

It is likely that variations in noise will degrade our ability to perform inversions at certain times; however, our preliminary data analysis suggests that the observations of this fickle oceanic source have enough consistency between arrays—and that this consistency lasts for adequate periods of time—for this data set to yield unique constraints on the dynamics of the stratosphere.

Current numerical weather and climate models are capped at about 35 kilometers in altitude and do not properly account for dynamic coupling between the troposphere and stratosphere. Although measurements using low-frequency sound may provide just one part of a broader suite of measurements needed to characterize the stratosphere at the necessary resolution, a better understanding of the dynamics of the stratosphere ultimately has strong potential to improve our ability to forecast weather and climate.

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A better understanding of the dynamics of the stratosphere ultimately has strong potential to improve our ability to forecast weather and climate.

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