Global (Volcano) Infrasound

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NASA Earth Observatory image by Jeff Williams

Motivation and Overview

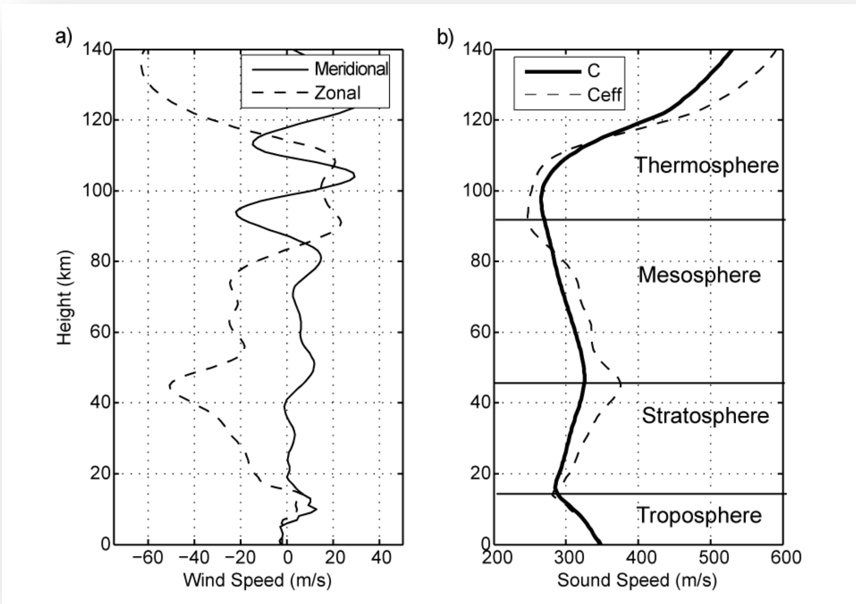
- Volcanoes are known sources of high amplitude infrasound
- Infrasound is able to propagate long distances with relatively little attenuation
- Numerous studies have demonstrated how infrasound can be used to detect, locate, characterize, and quantify volcanic eruptions – even at long ranges
  - Local monitoring networks are often difficult to establish and maintain
  - Limitations of satellite remote sensing and other techniques

Karymsky Volcano

Okmok Volcano

Infrasound Propagation – Global Ranges (>250 km)

Winds Sound Speed



Strong zonal (east-west, positive easterly) wind jet changes c_{eff}

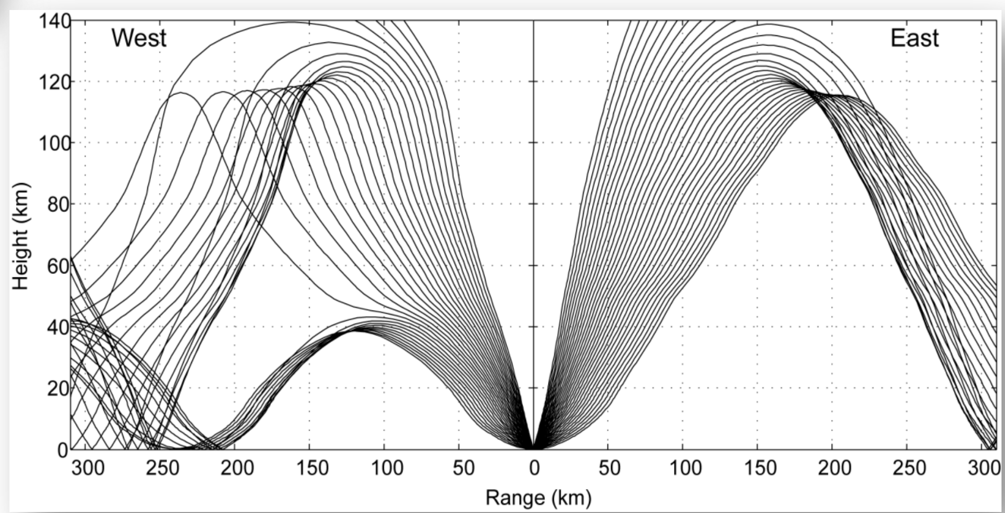
Sound propagating east refracted down around 115 km (thermospheric)

Sound propagating west refracted around 115 km (thermospheric) and 40 km (stratospheric)

Sound energy can be represented as rays refracting according to Snell's Law

Rays often refract up, until c_{eff} exceeds that at the source

$$c = \sqrt{\gamma RT} \qquad c_{eff} = c + \vec{v} \bullet \vec{n}$$



Attenuation

Geometric spreading

Spherical Spreading:

P α 1/r

I α $1/r^2$

Cylindrical Spreading:

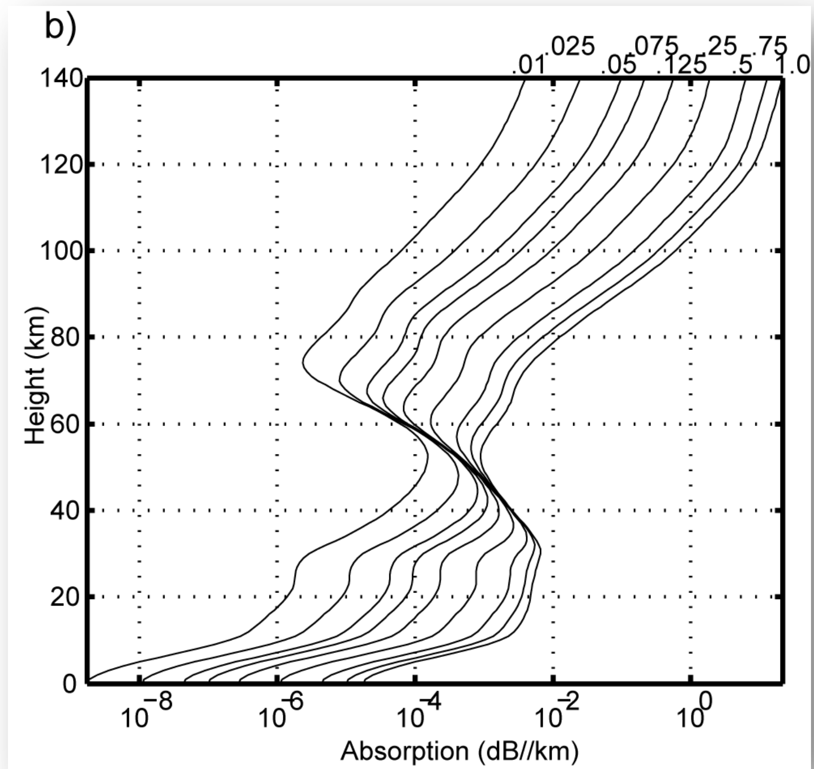
P α 1/√r

I α 1/r

Transmission Loss (TL): Accumulated sound loss during propagation

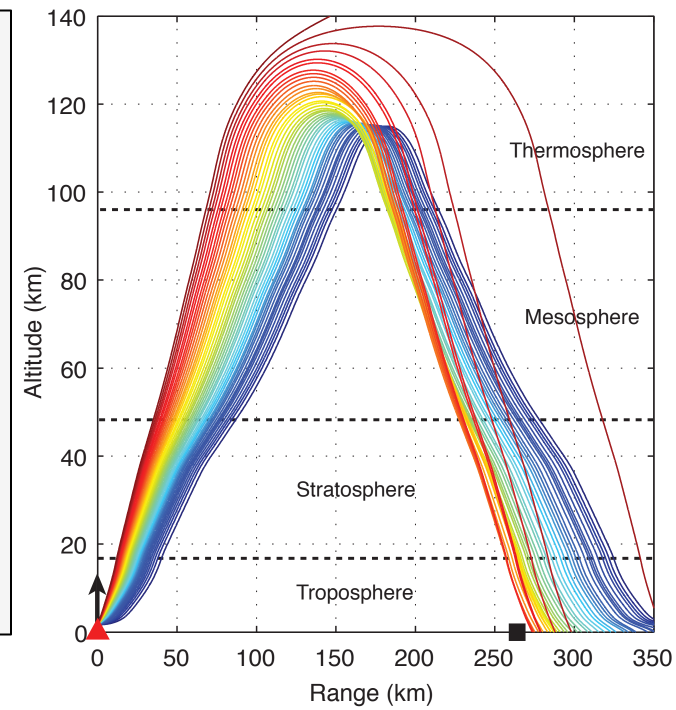
Quantitative Prediction of Atmospheric Absorption

- Total absorption as a function of height after Sutherland and Bass [2004]
- Absorption higher in thermosphere and at higher frequencies

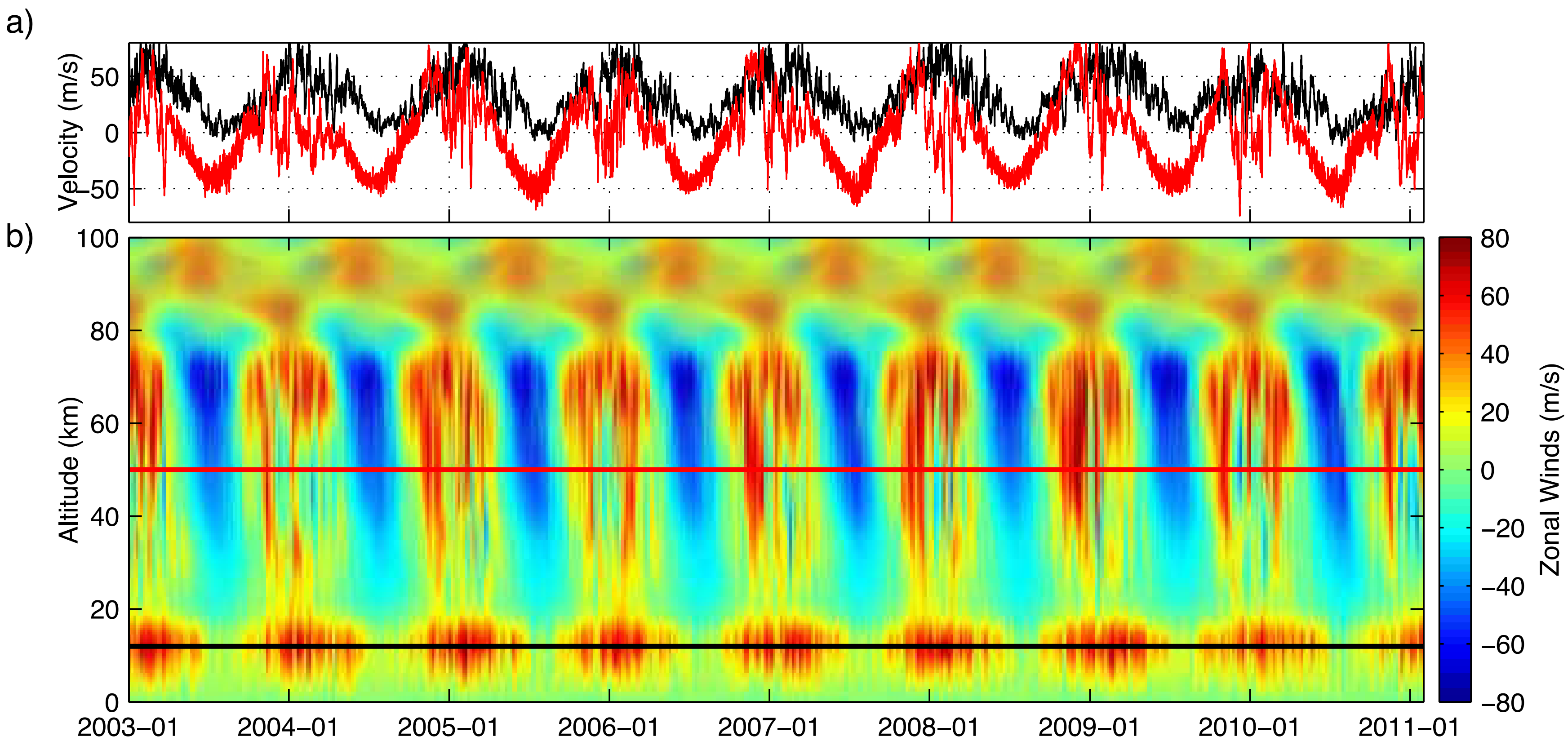


Infrasound Propagation Models

- Geometric Acoustics (ray tracing): sound energy treated as rays
  - Useful for travel times and visualizing propagation paths
  - No diffraction or scattering → shadow zones
- Continuous Wave
  - Parabolic Equation, Normal Mode, FDTD, etc.
  - Account for diffraction and scattering and able to predict TL
  - Can be extended to time domain through Fourier synthesis
  - Sensitive to source waveform and can be computational expensive.

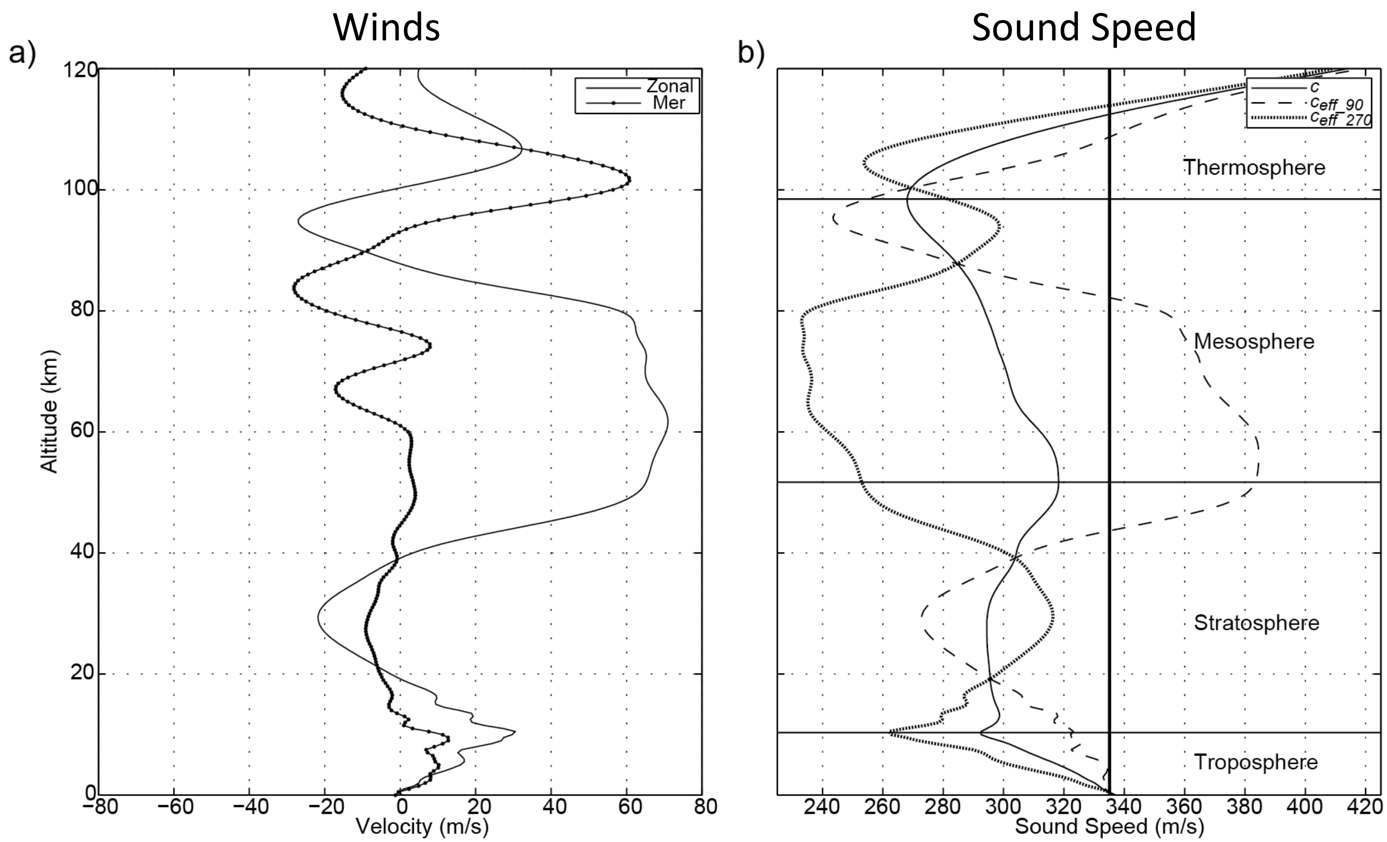


Global mid-latitude wind patterns



[Fee et al., 2013]

Propagation Example

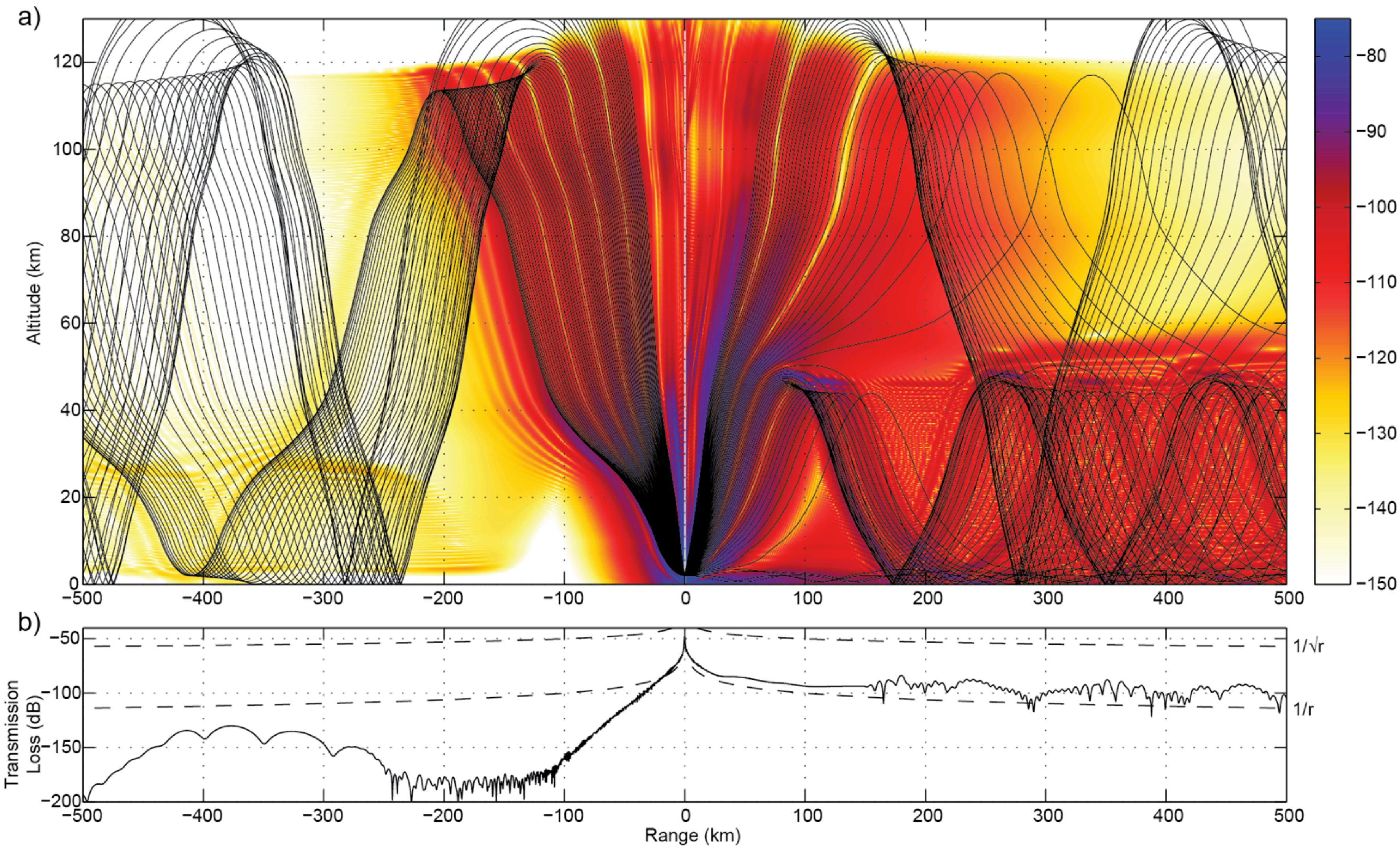


[Fee and Matoza, 2013]

Mount St. Helens 1 February 2012 0000 UTC

- Strong tropospheric and stratospheric wind jet
- Winds strongly affect c_{eff}

Propagation Example



[Fee and Matoza, 2013]

Long-range propagation strongly anisotropic

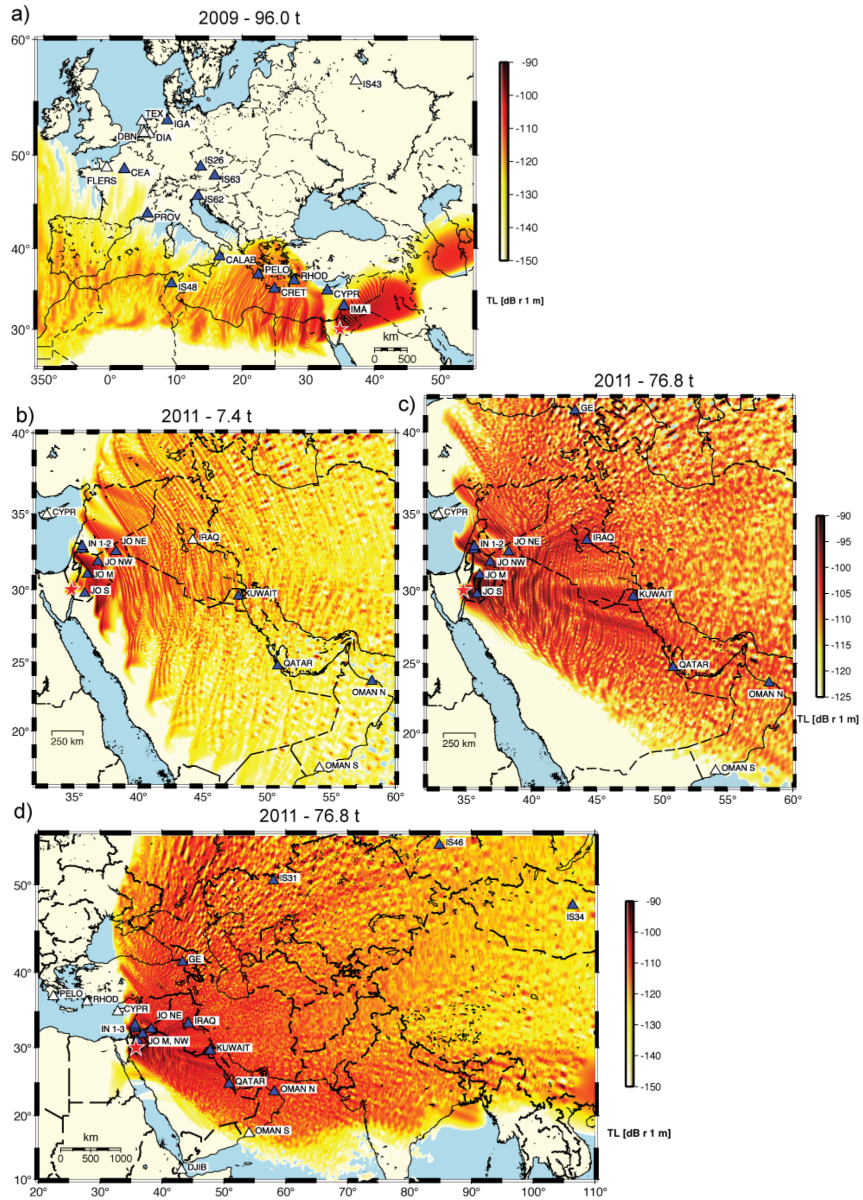
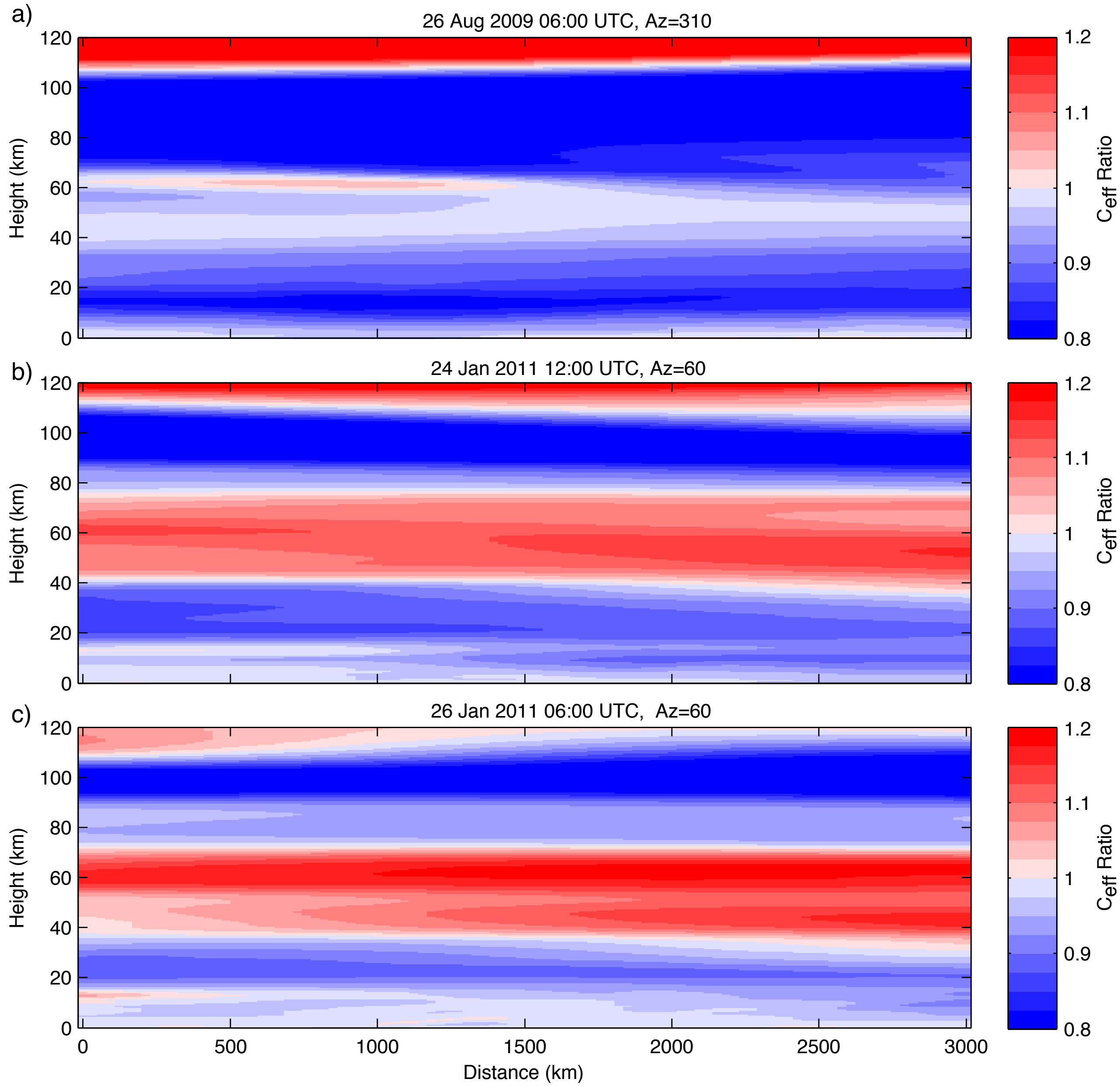


Figure 15

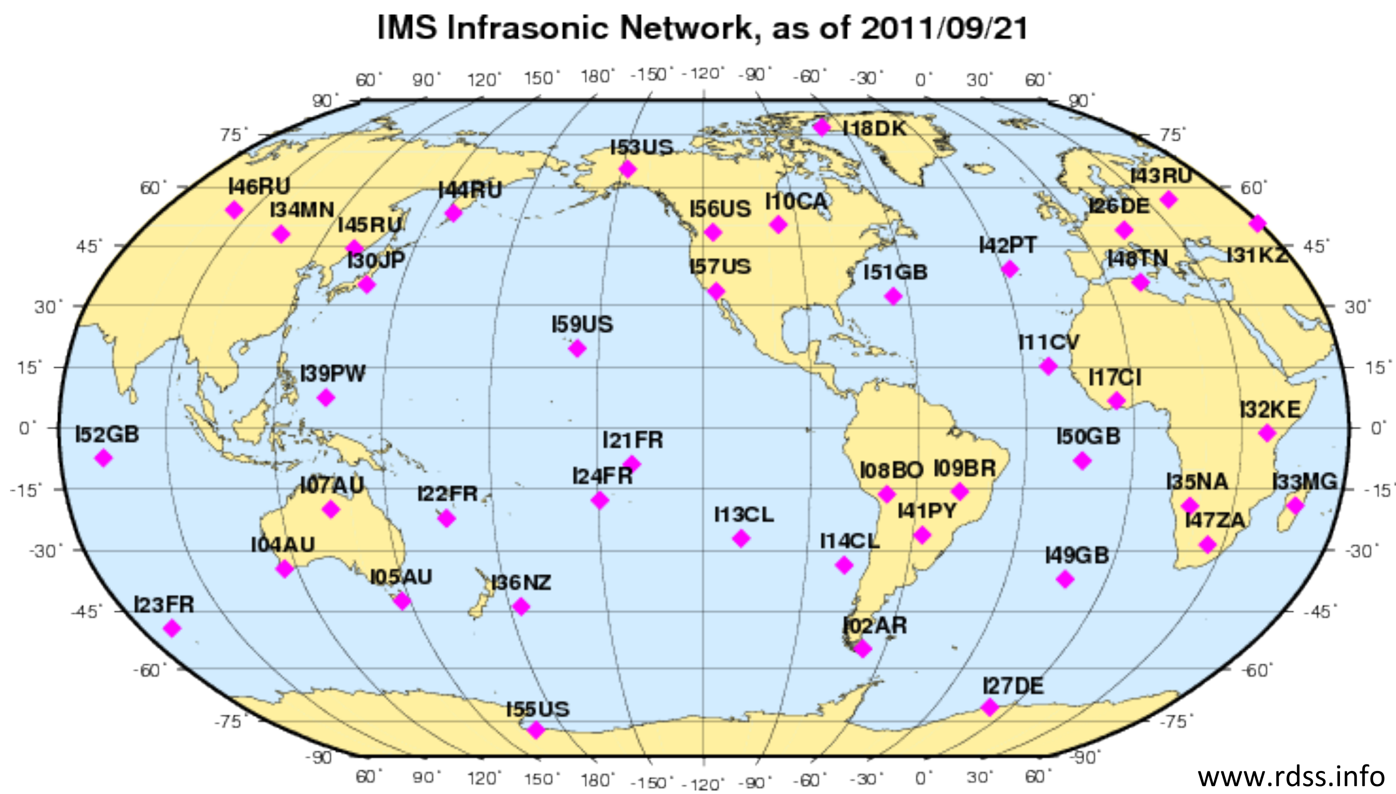
[Fee et al., 2013]

Range Dependence



[Fee et al., 2013]

Global Infrasound Network - CTBTO

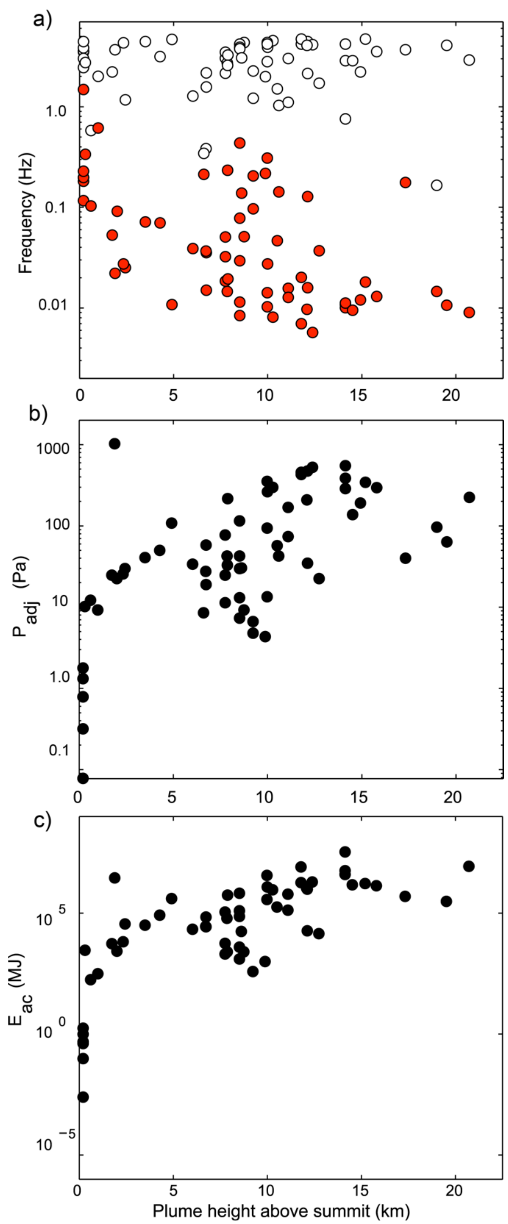


Global network of infrasound arrays built to monitor for clandestine atmospheric nuclear tests

Detection of moderate-large volcanic eruptions at multiple arrays common

More permanent arrays being added…

IMS Volcano Infrasound Observations

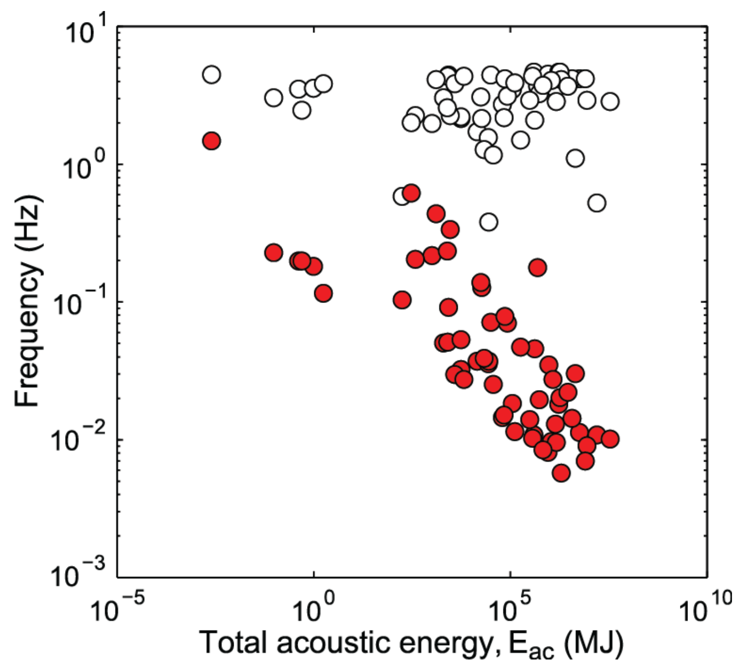


Dabrowa et al. [2011]: comprehensive study on IMS volcano infrasound observations

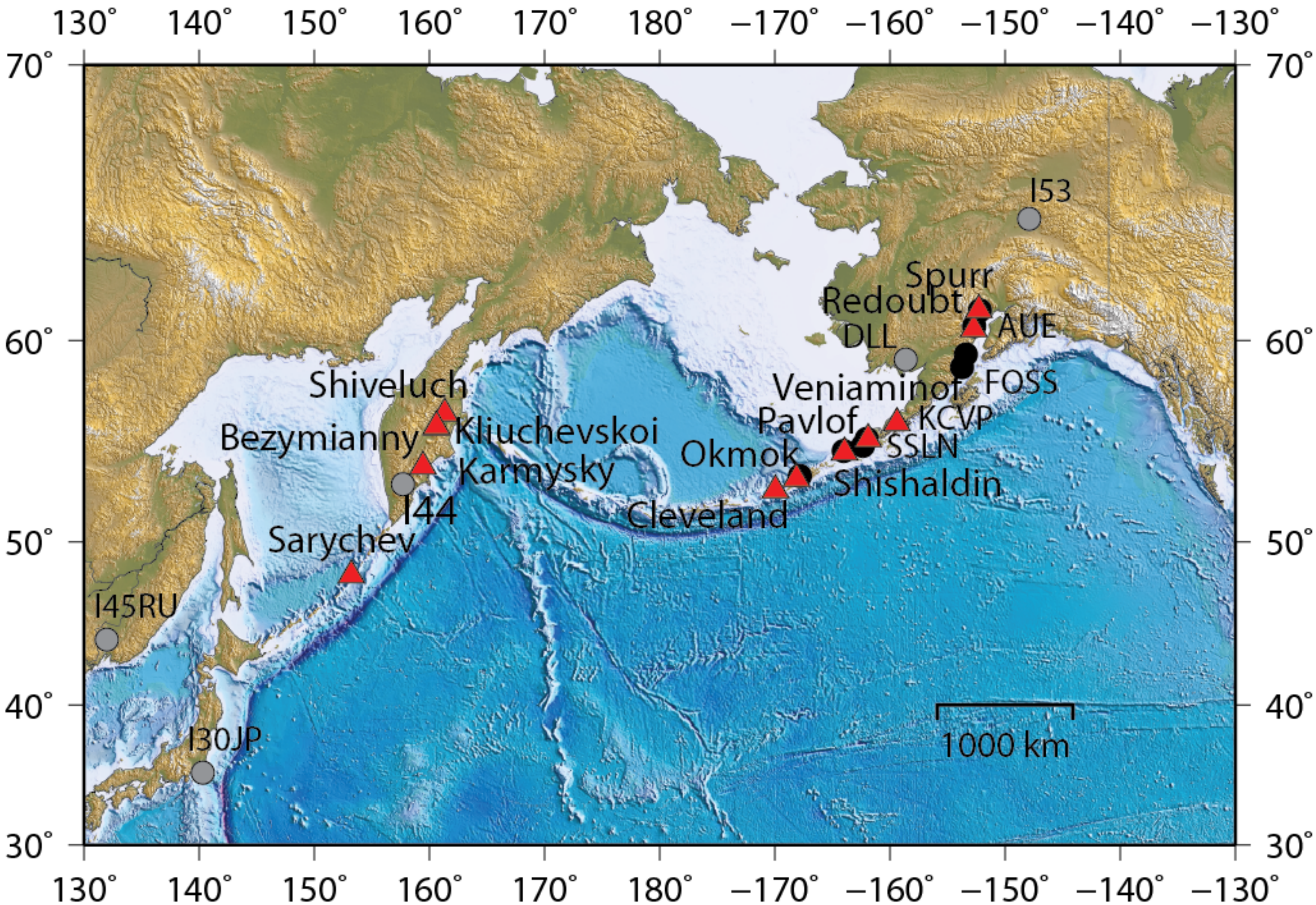
1) recorded distance increases with ash plume height

2) lowest detected infrasonic frequency decreases with increasing plume height

3) total acoustic energy and distance-corrected amplitude increase as a function of plume height



North Pacific Volcano Infrasound

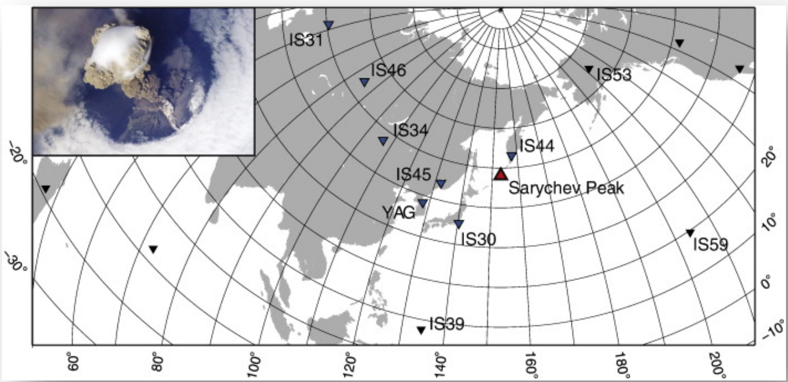


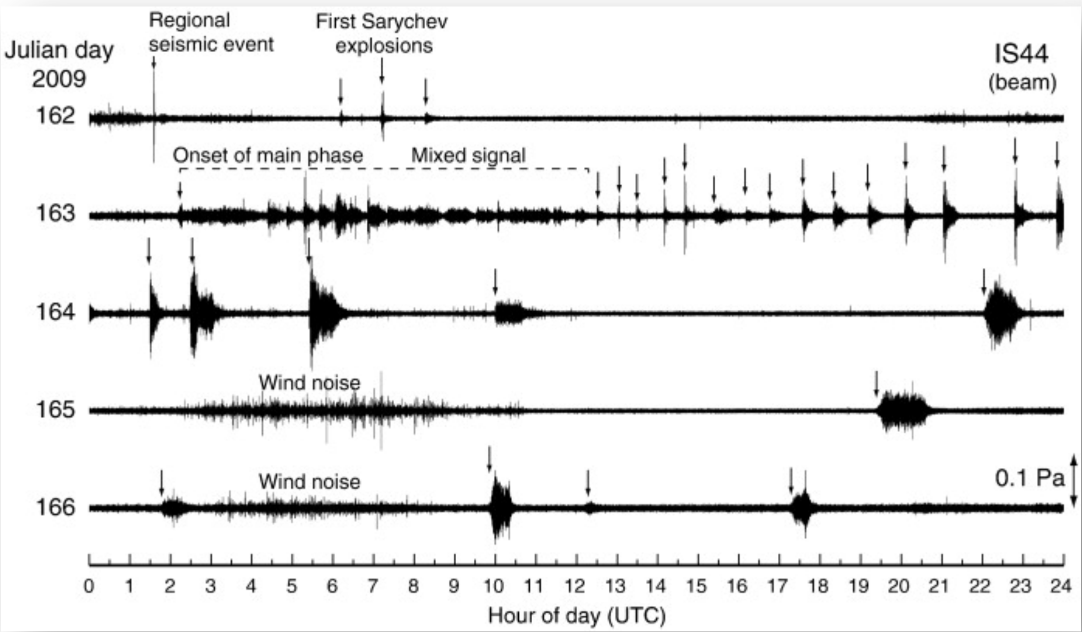
Sarychev Peak, Kurile Islands

2009 Sarychev Peak Eruption

Remote volcano, poorly characterized eruption

Detected well by numerous IMS array and satellites [Matoza et al., 2011]





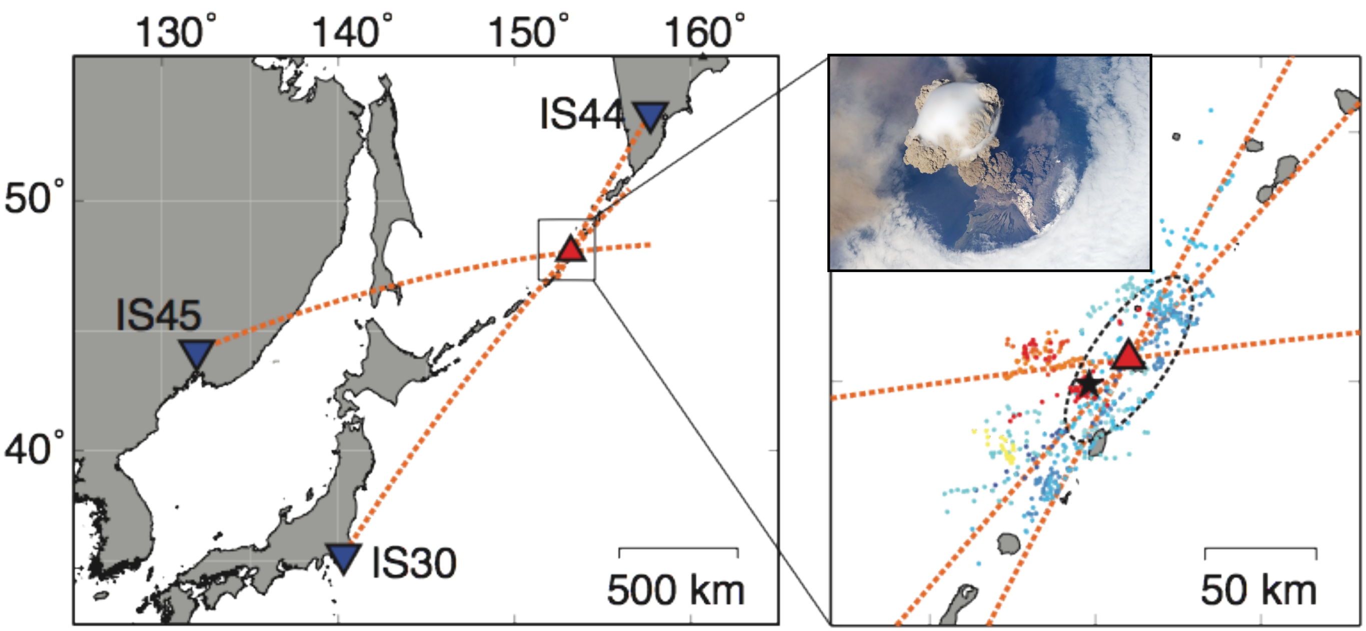
[Matoza et al., 2011]

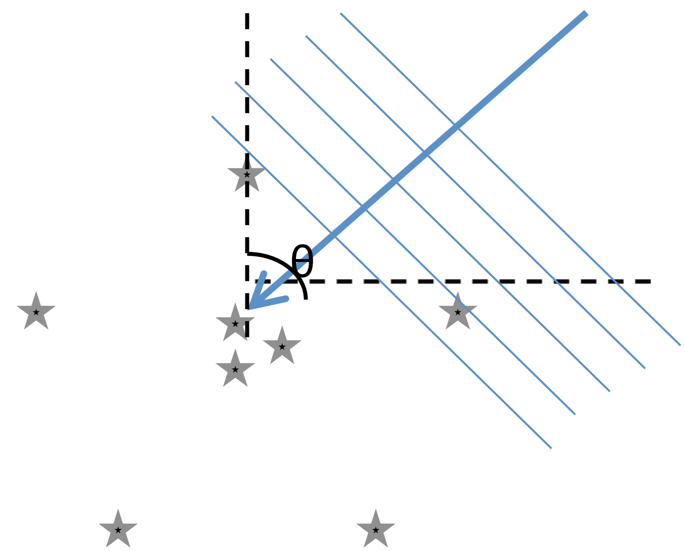
Remote infrasound arrays (640-6400 km) provide most detailed eruption chronology

High signal-noise at IS44, Kamchatka (640 km northeast)

Correlates well with eruption chronology from satellite data

Sarychev Peak - Location

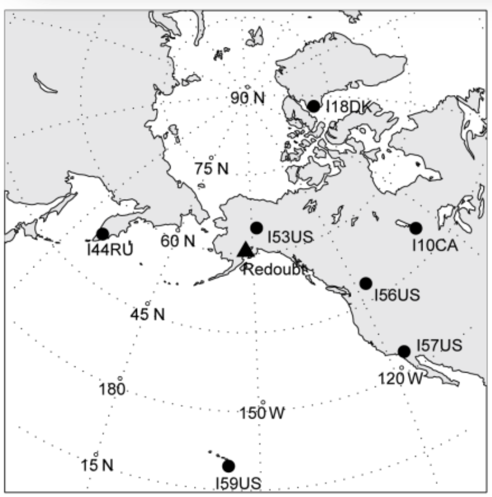




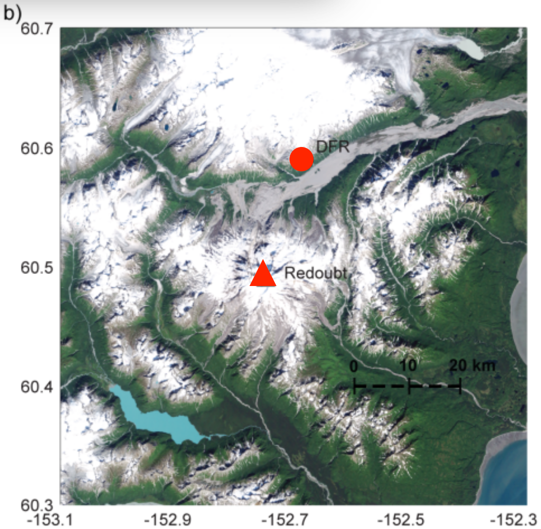
2009 Redoubt Volcano Eruption

- Erupted 23 March - 4 April 2009
- >19 explosive eruptions (events)
- Ash plumes to 19 km
- Significant pyroclastic flows, lightning, and seismicity
- Relative proximity to Anchorage and North Pacific air routes

a)



b)



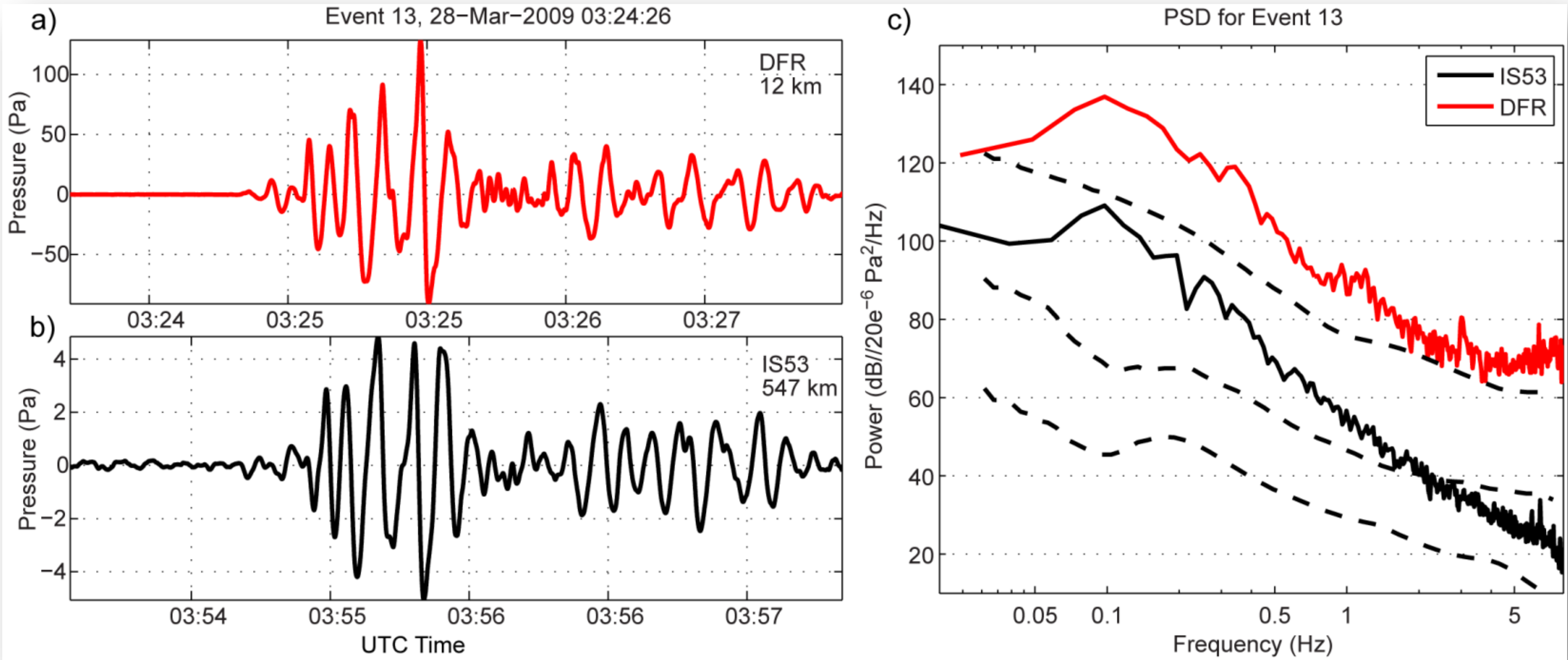
DFR: Single Microphone→12 km

IS53 : 8-element infrasound array → 547 km

Also recorded at numerous other remote arrays (Kamchatka, Greenland, etc)

All significant explosive events clearly detected IS53

Local and Remote Infrasound Comparison



[Fee et al., 2011]

High waveform similarity between local (red) and remote (black) stations

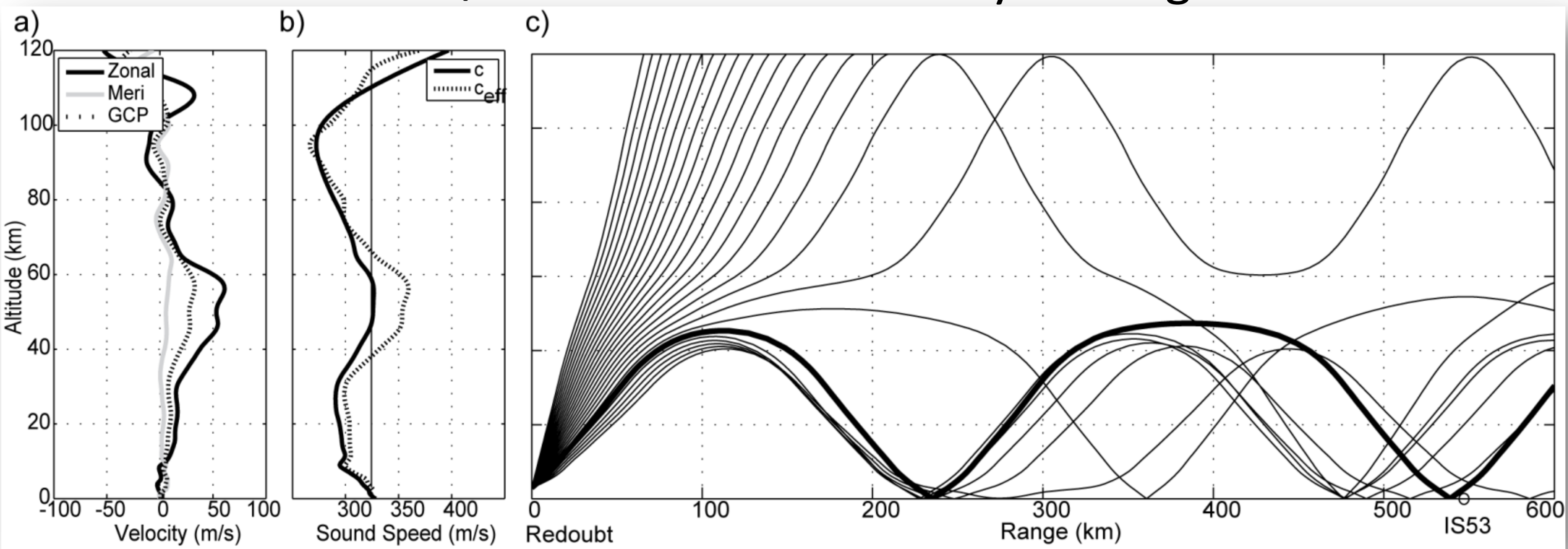
Frequency content similar at both stations

→ Principal source features apparent at 547 km (IS53) for most events

Short-duration, very high-amplitude infrasound → explosive eruption

Redoubt Propagation: Strong Stratospheric Waveguide

Winds Sound Speed Ray Tracing

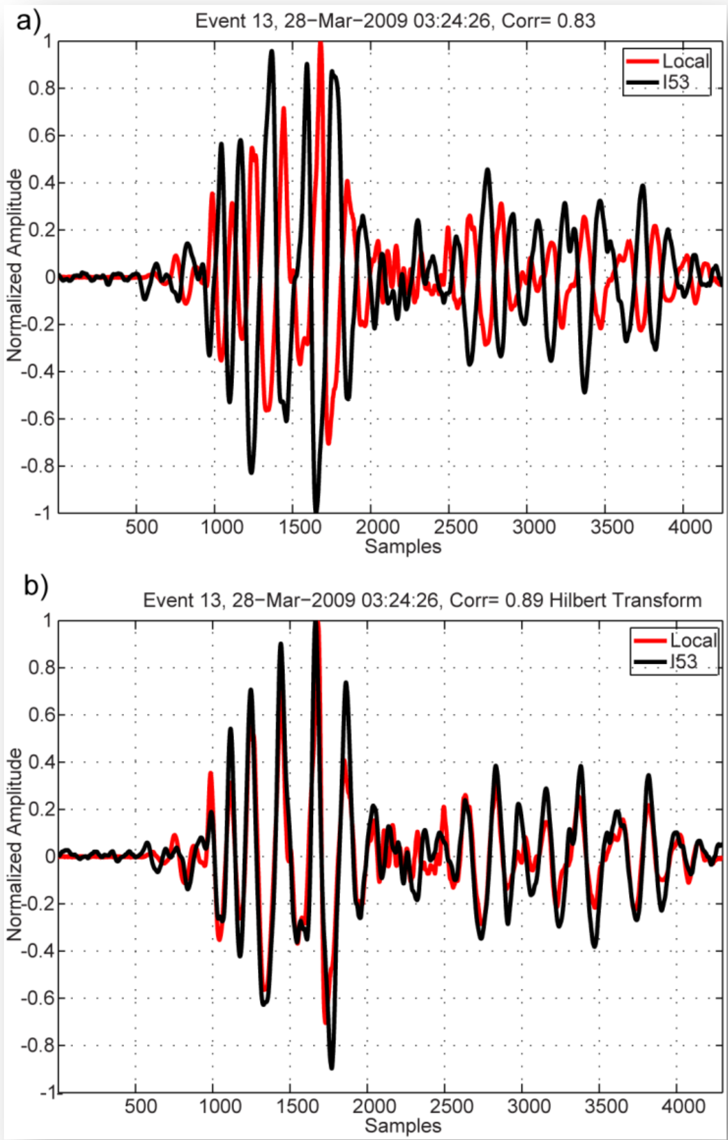


Strong atmospheric waveguide between ~40-60 km

Significant easterly stratospheric winds → propagation enhanced to the east

Ray tracing predicts a single ground reflection between source and receiver

Waveform Cross-Correlation



[Fee et al., 2011]

Compute cross-correlation between local and remote data

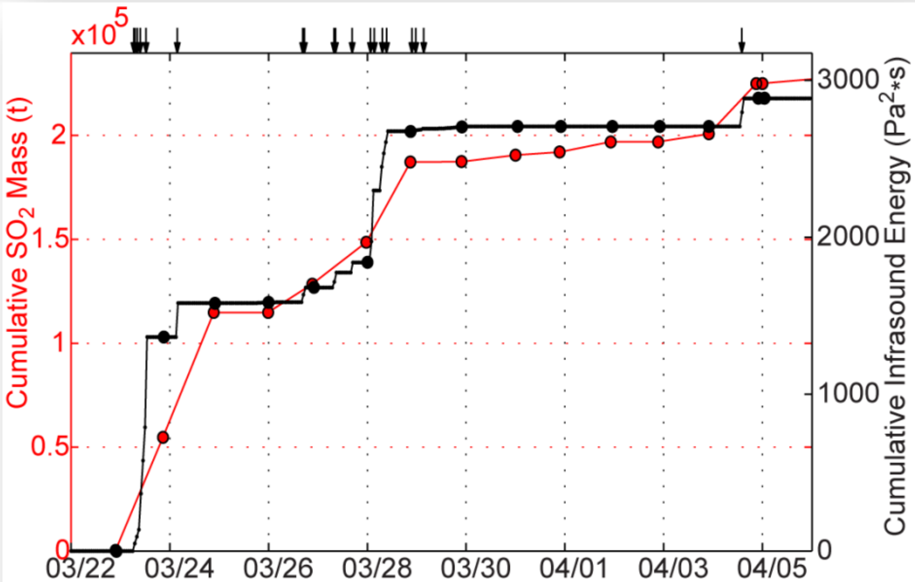
Deep atmospheric waveguide between ~40-60 km likely responsible for high waveform similarity

Ray tracing predicts a single ground reflection between source and receiver

Hilbert transform predicted from ray theory (90° phase shift) improves cross-correlation to 0.89

→ Remote infrasound gives good representation of source

Redoubt Infrasound and SO_2

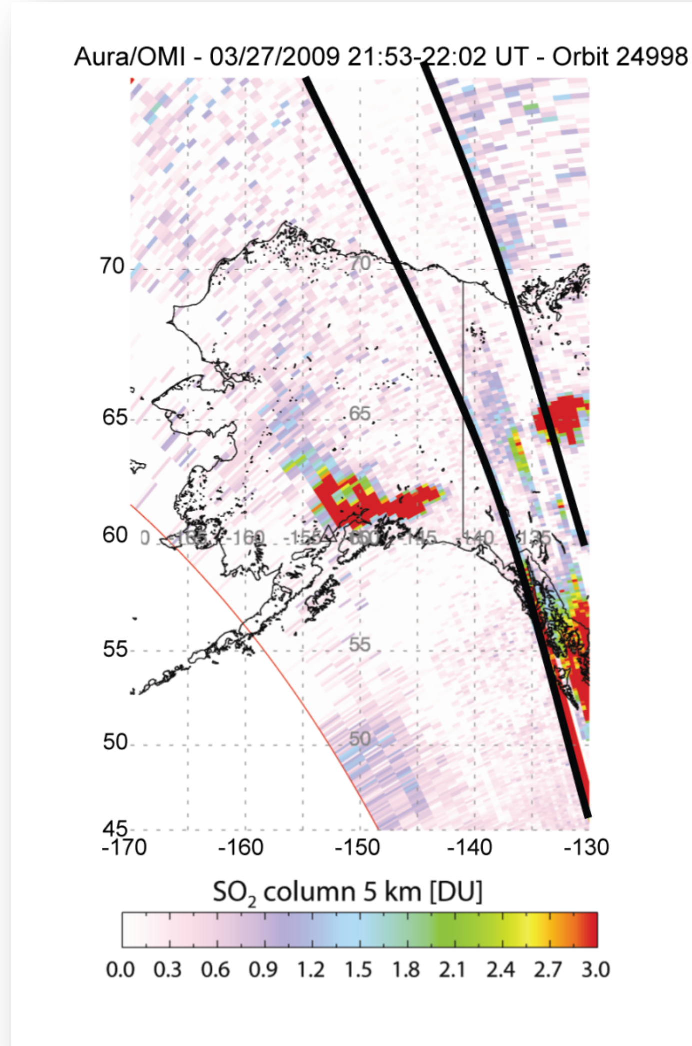


[Fee et al., 2011]

Very good correlation between cumulative infrasound energy (black) and daily SO_2 estimates (red)

Relationship between SO_2 production and infrasound energy not well understood

Potential to use remote infrasound arrays as real-time detector of elevated SO_2 (and ash?)



Lopez et al. [2012]

Mt. Cleveland Volcano, AK

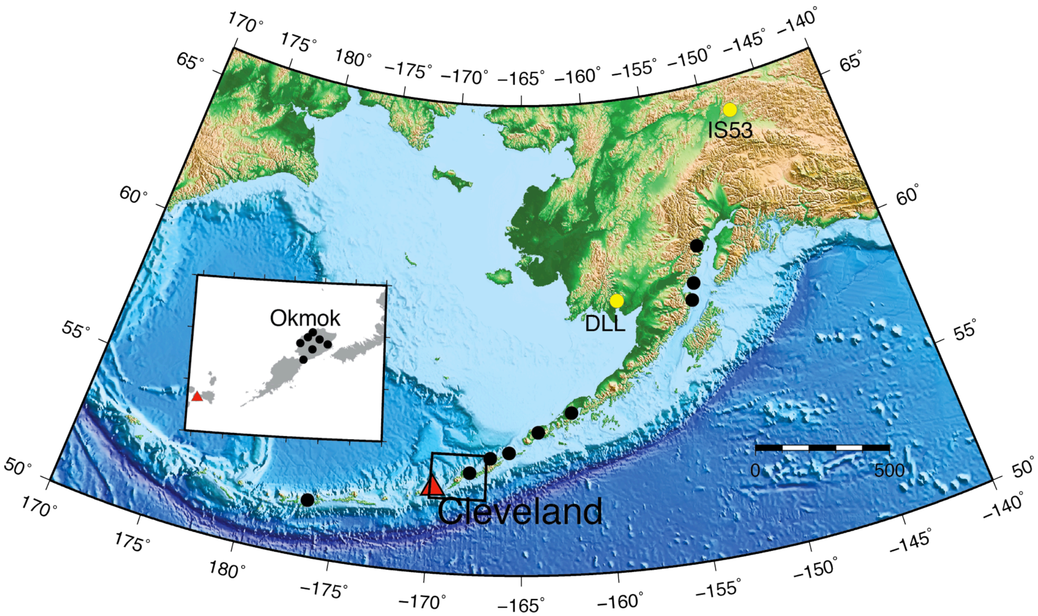
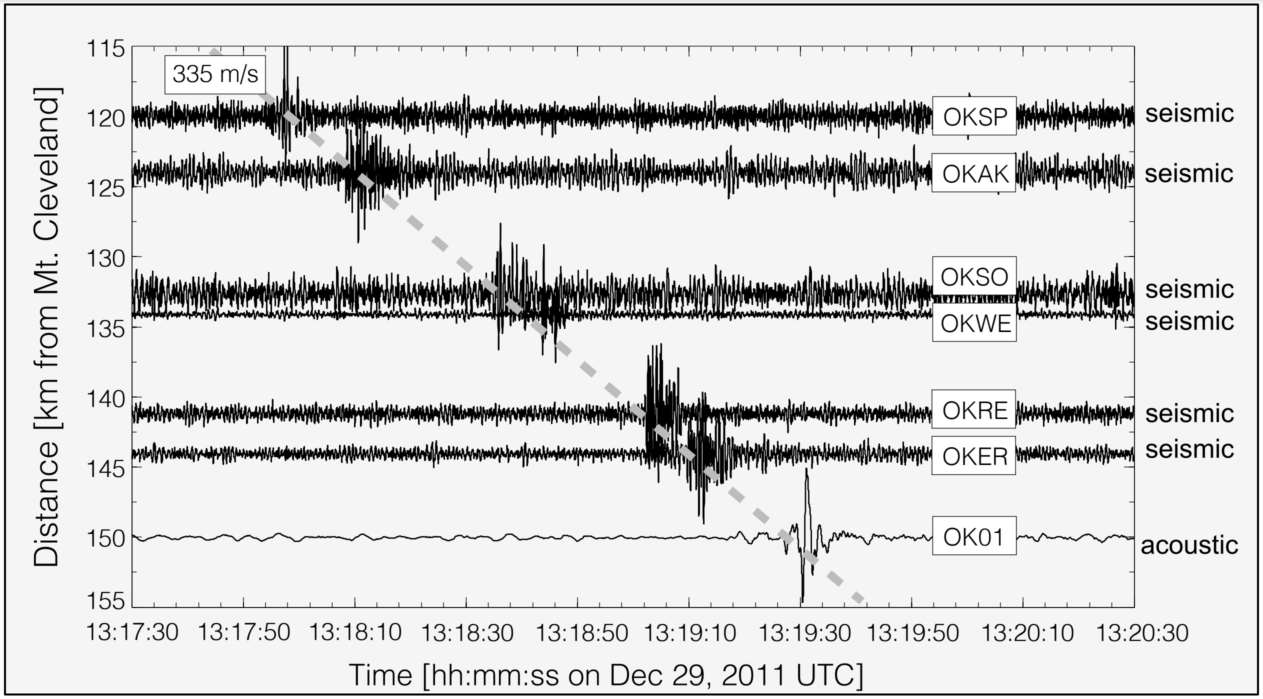


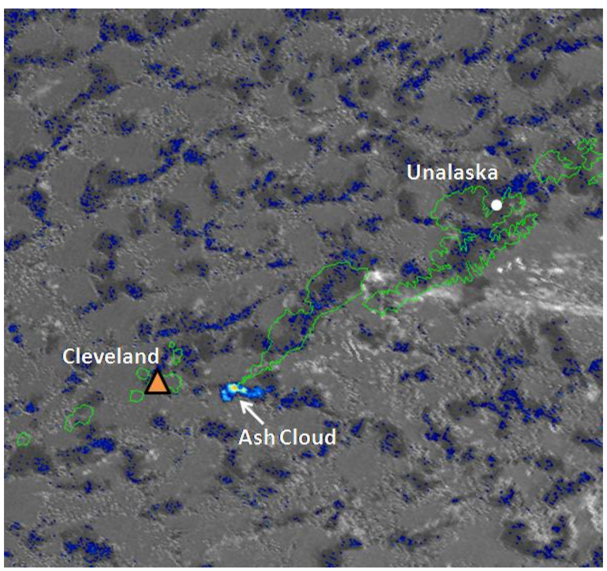
Photo courtesy Cyrus Read

- Mt. Cleveland is one of the most active and remote volcanoes in the Aleutian arc
- Mostly small, ash-producing eruptions (<7 km), but occasionally >10 km
- No real-time, local, seismic network due to logistical challenges (closest seismic station is 75 km)
- Primarily monitored using frequent coarse spatial resolution meteorological satellites and occasional high spatial resolution land remote sensing systems.

Example Event – 29 December 2011



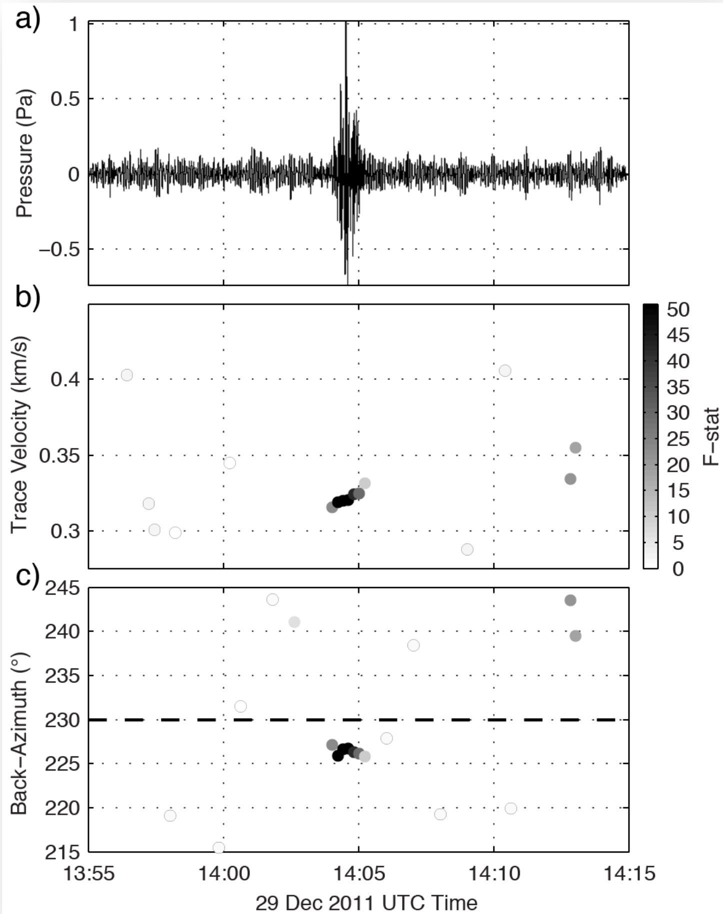
- Ground-coupled airwaves clearly recorded on Okmok seismic network
- Infrasound also detected at Okmok
- ~7 minutes travel time



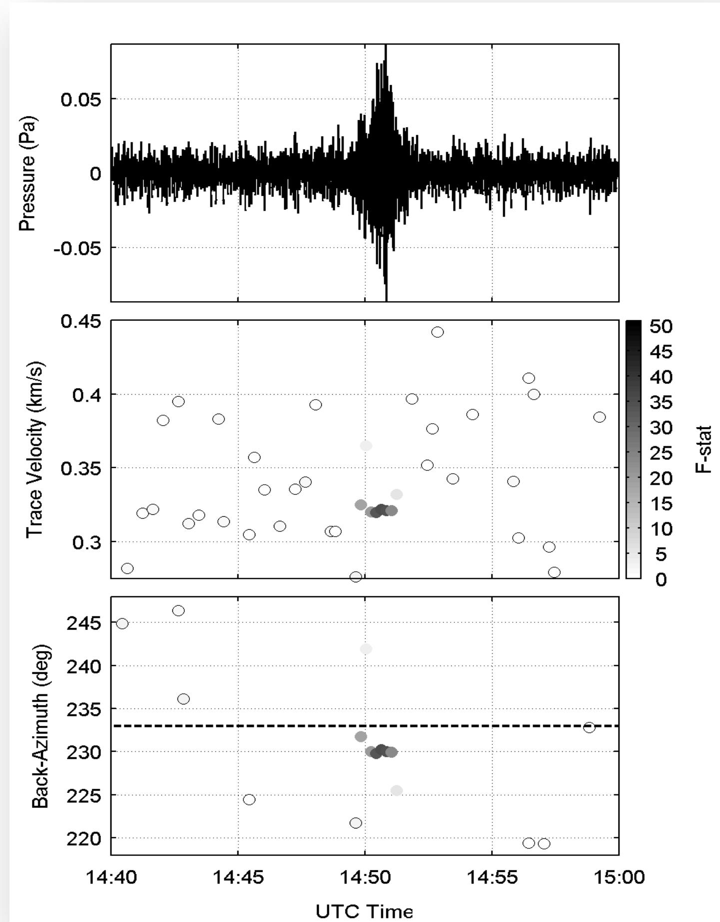
- Detected with satellite ash alarm
- Ash cloud height ~6 km ASL
- Relatively small ash cloud

Remote Cleveland Infrasound Detection

DLL
992 km



IS53
1827 km



- Clear detection at Dillingham DLL (992 km) and IS53 (1827 km)
- Travel time correlates with that predicted from ray tracing (tropospheric arrival)
- Retrospective analysis revealed two similar events on 25 Dec
- Automatic detection algorithm set-up
- 18/20 events detected at DLL between Dec 2011 – August 2012

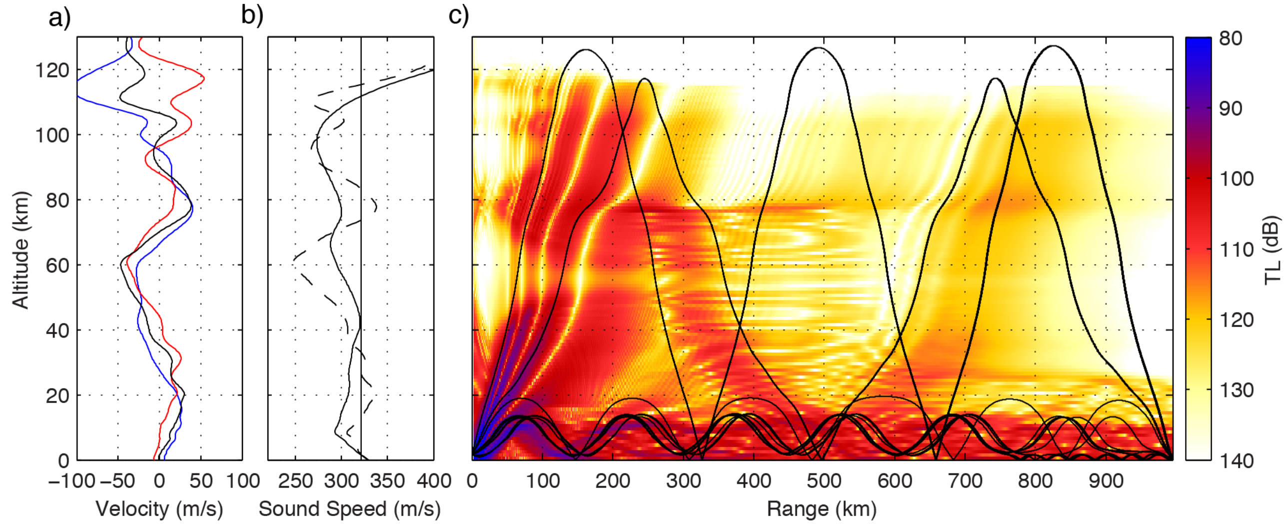
Propagation – 29 December 2012

0.5 Hz PE [Gibson and Norris, 2002]

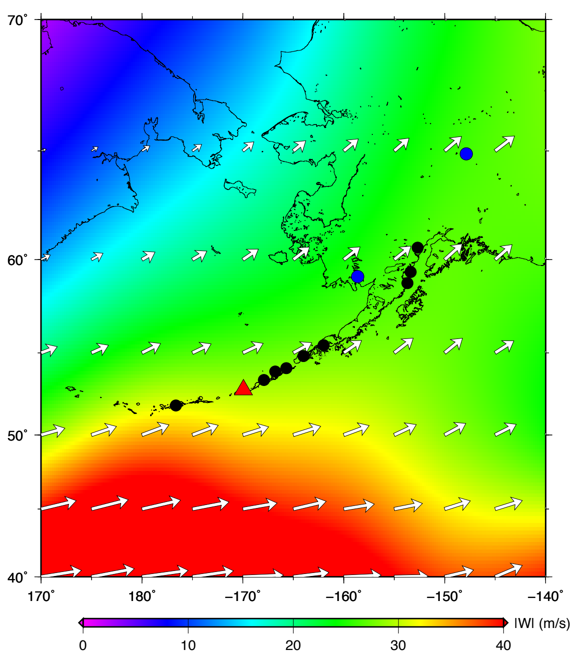
Ray tracing after Gossard and Hook [1975]

Polar jet at 10-20 km

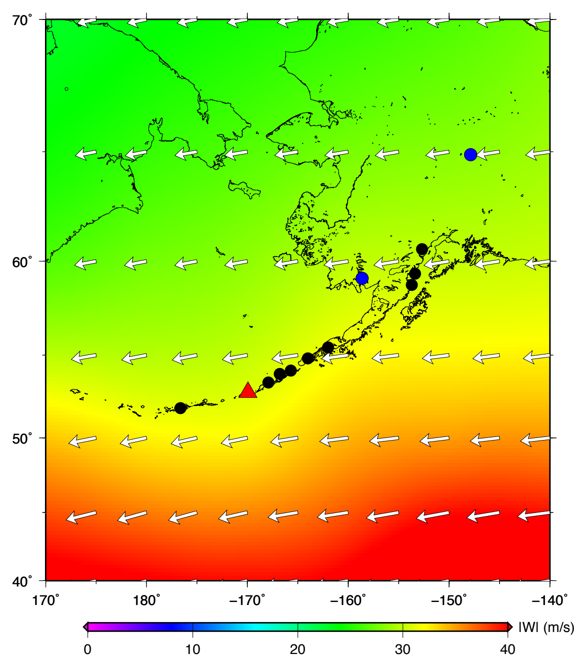
- Long-range tropospheric ducting



Wind at 15 km



Wind at 50 km



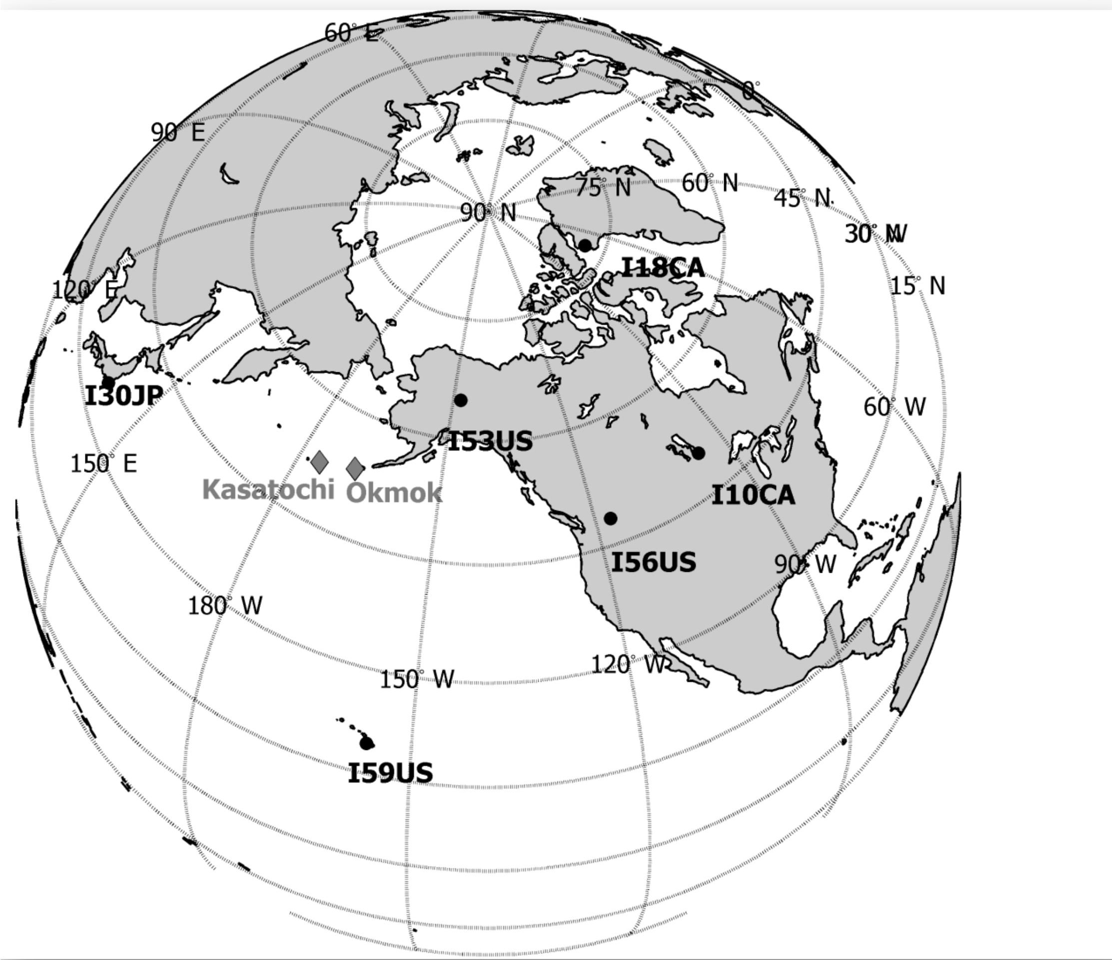
Polar jet blows to NE

- Favorable direction for detection
- SSW – stratospheric winds blowing west
- Range-dependence

Conclusions and Future Directions

- Infrasound effective tool for constraining a variety of eruption styles at multiple distances
  - Location, timing, changes in intensity, etc
  - Particularly useful for remote, difficult to monitor regions like the North Pacific
- Long-range infrasound propagation is highly anisotropic
- Under typical meteorological conditions, remote infrasound arrays can provide an accurate representation of the acoustic source
- Intense, low frequency, sustained infrasound coincident with high-altitude ash emissions
  - Promising correlation between infrasound energy and SO_2
- Additional infrasound deployments will increase volcanic activity detection and reduce detection latency

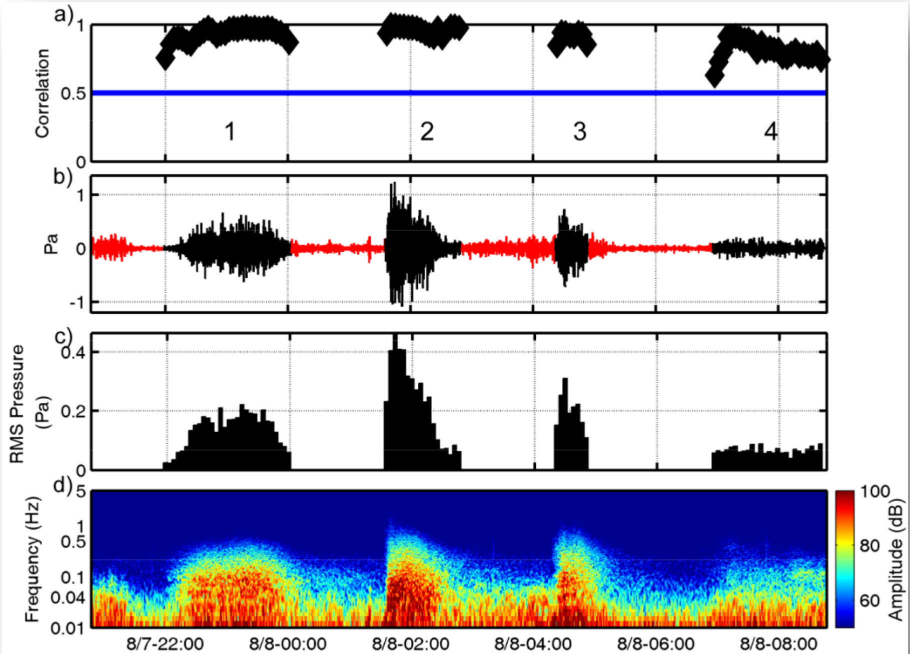
Kasatochi Volcano



Kasatochi Volcano

- Erupted August 7^{th}-9^{th}, 2008
- Previously unmonitored
- Ash to ~55,000' (17 km)
- Extensive SO_2 and ash
- Disrupted N Pacific air travel

Kasatochi: Infrasound



Fee et al., 2010

Signal focused in VLP (0.01-0.1 Hz) band

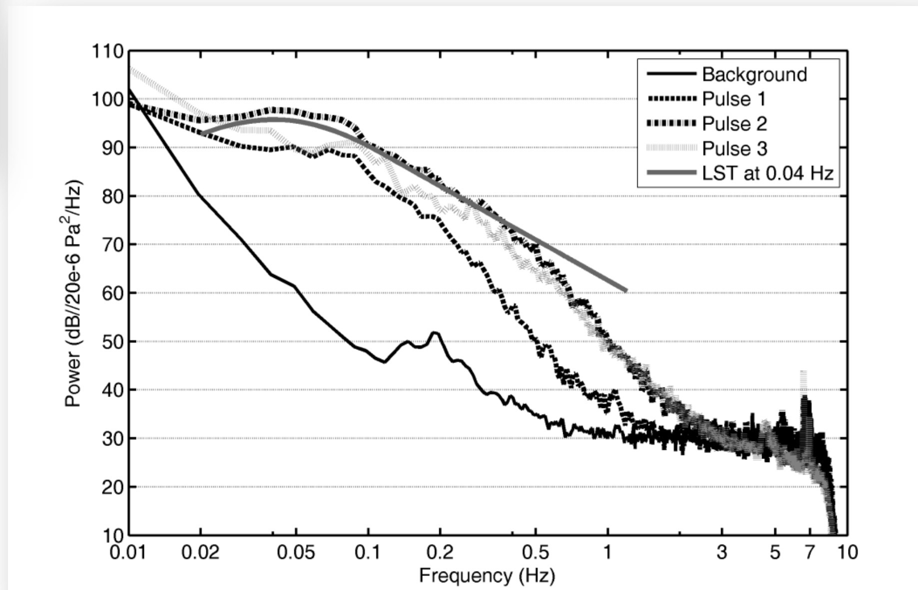
Four pulses detected:
1: 2159 UTC, 123 min
2: 0135 UTC, 59 min
3: 0420 UTC, 33 min
4: 0654 UTC, 112 min

Significant low frequency infrasound coincident with high altitude ash emissions

Spectra of three main pulses resemble that of man made jets (solid gray)

Minor variations in spectra between eruption pulses
- -Negligible effect of ash particles in jet

Highly correlated at three stations with similar spectral shape
- -Frequency-dependent propagation effects similar between stations



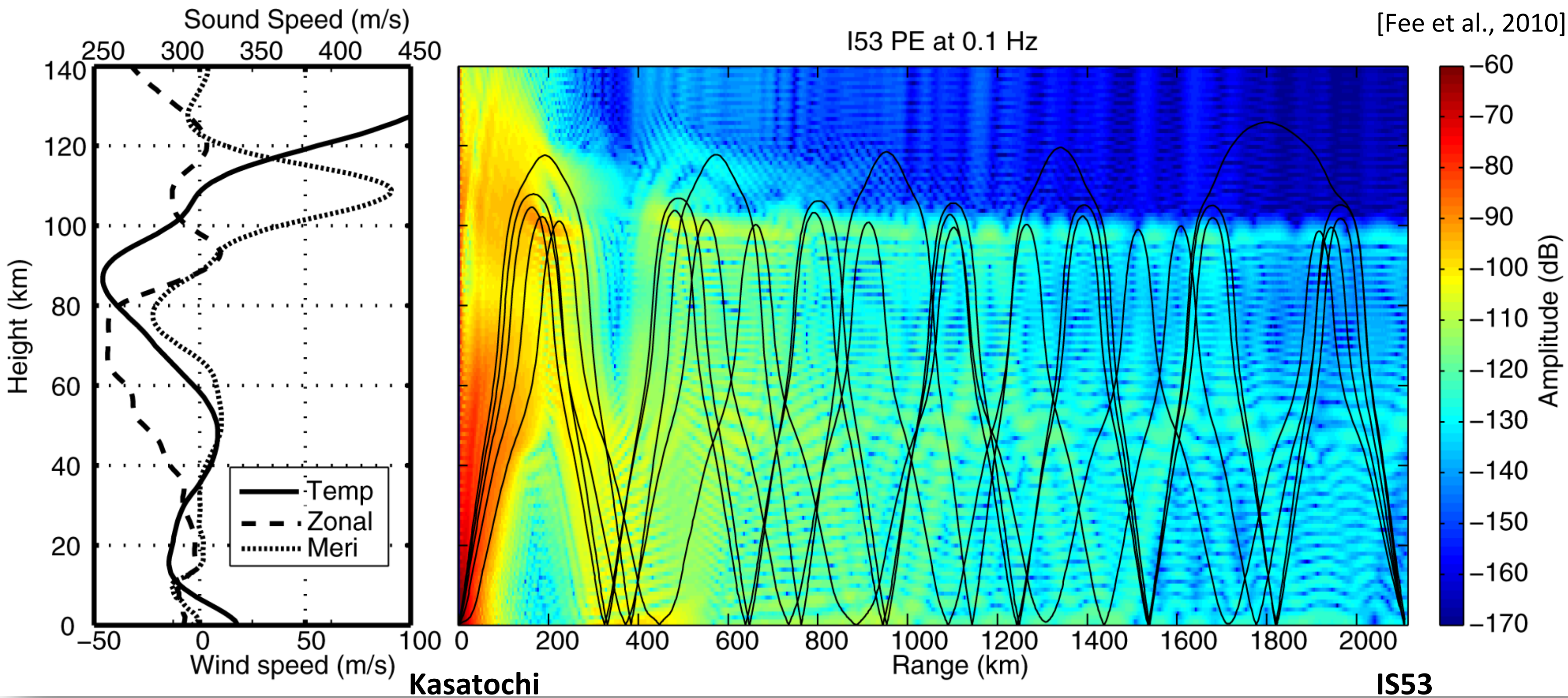
Kasatochi →IS53: Theoretical Propagation

Sound energy refracted down around 90-110 km (thermospheric)

No stratospheric arrivals predicted

Travel Time: ~7968 s (2 h 12 min)

Increased attenuation due to thermospheric propagation path



[Fee et al., 2010]

Eruption Onsets and Durations

Pulse	Seismic Onset	First Satellite Observation	Inferred Eruption Interval at Source	Onset Time Difference (min)	Acoustic Duration (sec, mins)
Kas 1	22:01	22:30	21:59:41-00:03:01	-1.3	123.3
Kas 2	01:50	02:30	01:34:41-02:47:11	-15	59
Kas 3	04:35	05:00	04:20:31-04:53:51	-14	33
Kas 4	07:12	N/A	06:53:51-08:46:11	-18	112
Okmok	19:43	20:00	19:41:54-~05:00	-1	540

[Fee et al., 2010]

IVLP acoustic onset times for Kasatochi Pulse 1 and Okmok eruption consistent with seismic and remote sensing

Modeled acoustic onsets for Pulse 2-4 begin prior to the ash emissions visible in the satellite imagery and AVO detected seismicity (15-20 minutes)

- Consistent with predicted onsets at other arrays
- Either acoustic signals begin prior to ash/seismicity or calculated travel times too long
- Stratospheric arrivals predicted to occur **~16 minutes later**

Acoustic durations similar to seismic, but slightly longer

Volcanic Jetting Spectra

Mount St. Helens spectra resemble LST spectra

Tungurahua spectra similar for all 3 eruptions, LST fits best

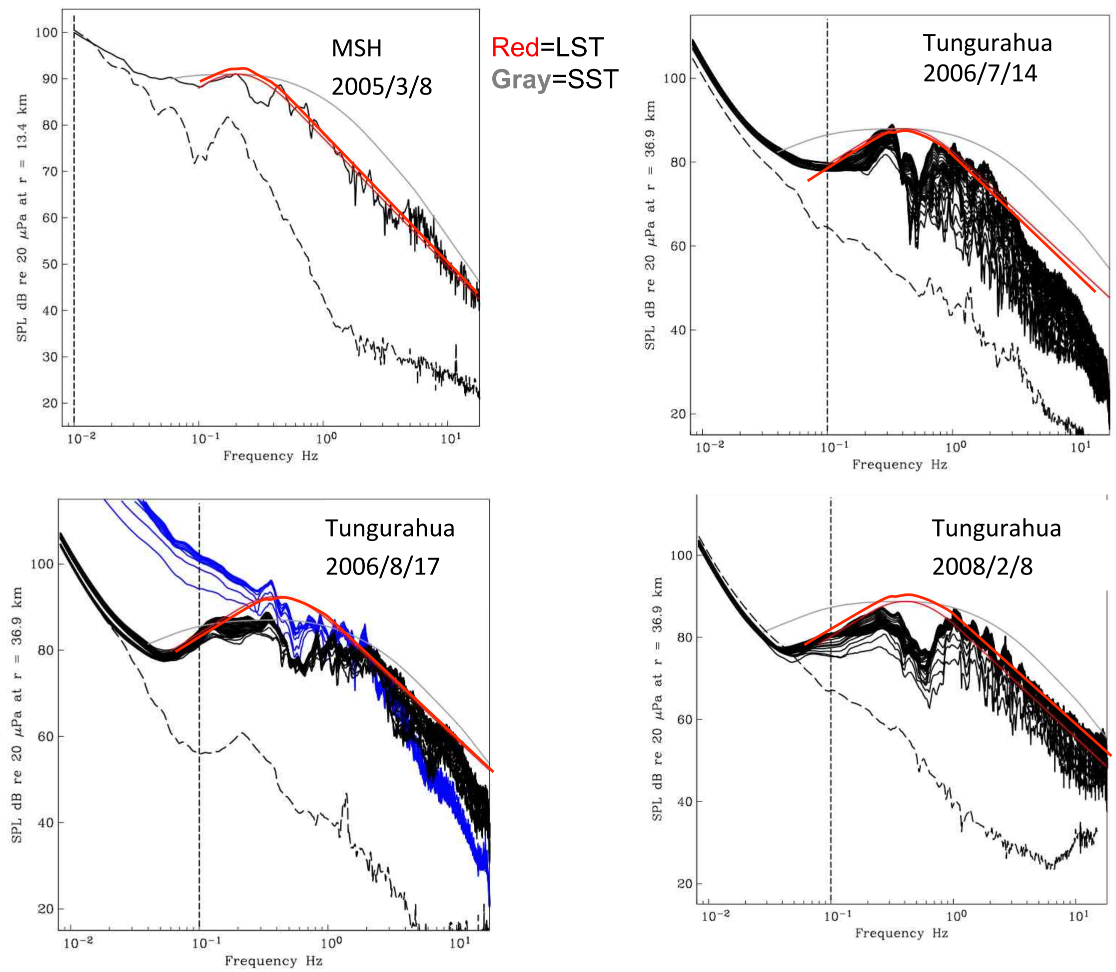
“Notch” in Tungurahua spectra

Roll-off for Tungurahua 7/14 and 8/17 does not match as well

Complexities

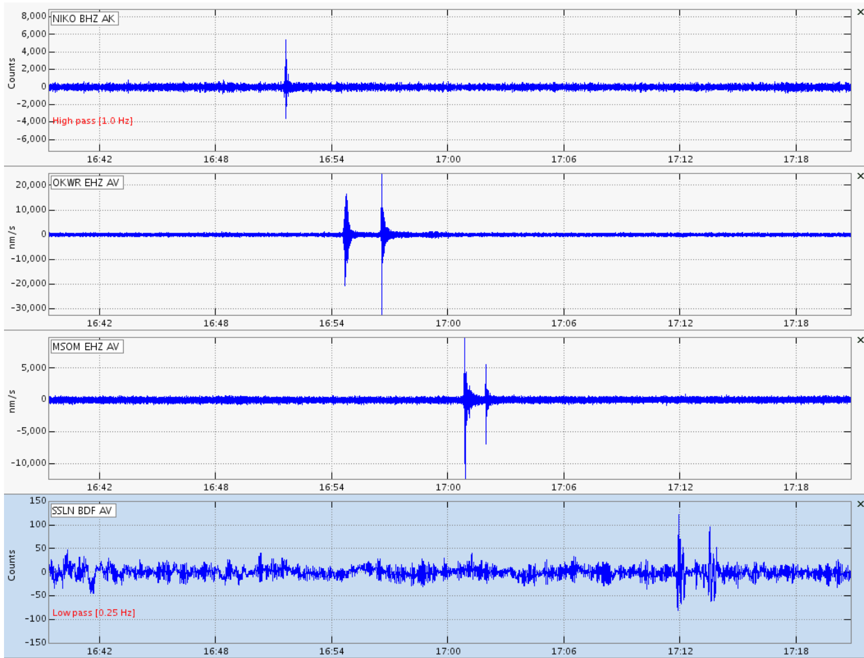
- -Interactions with crater
- -Volcanic jets multiphase, high temp
- -Propagation
- -Anisotropic source

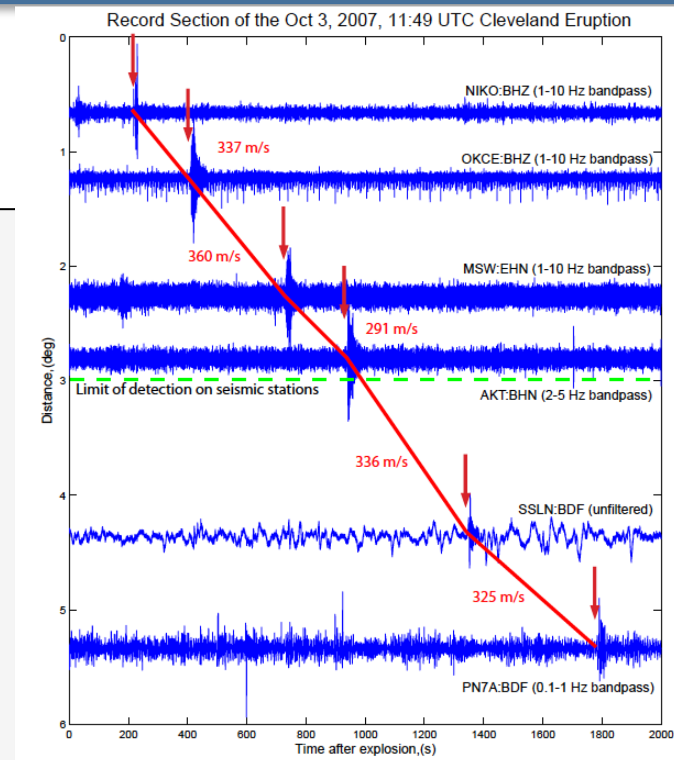
<u>Jetting coincident with high-altitude ash emissions</u>

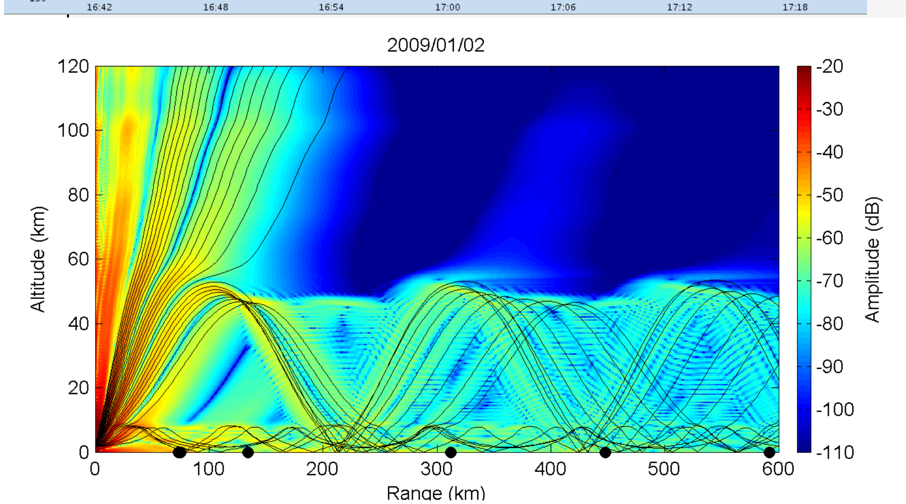


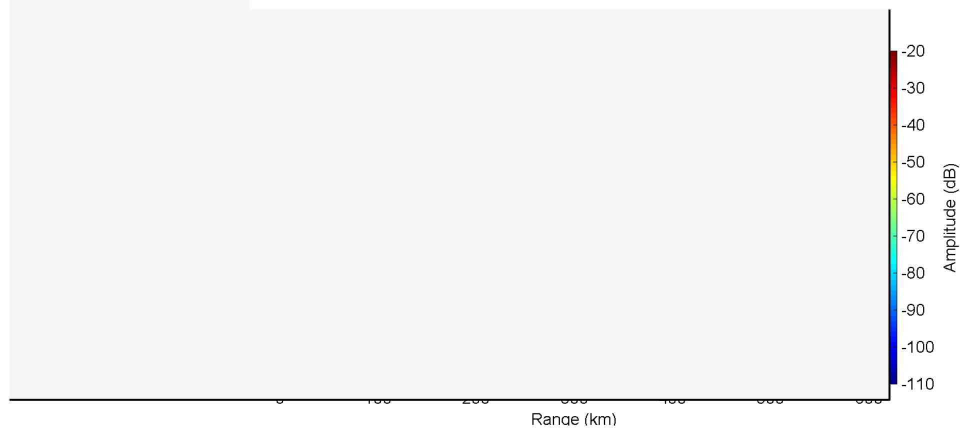
[Matoza et al., 2009]

Cleveland Airwaves: Jan. and Oct. 2007 Eruptions









Okmok Infrasound

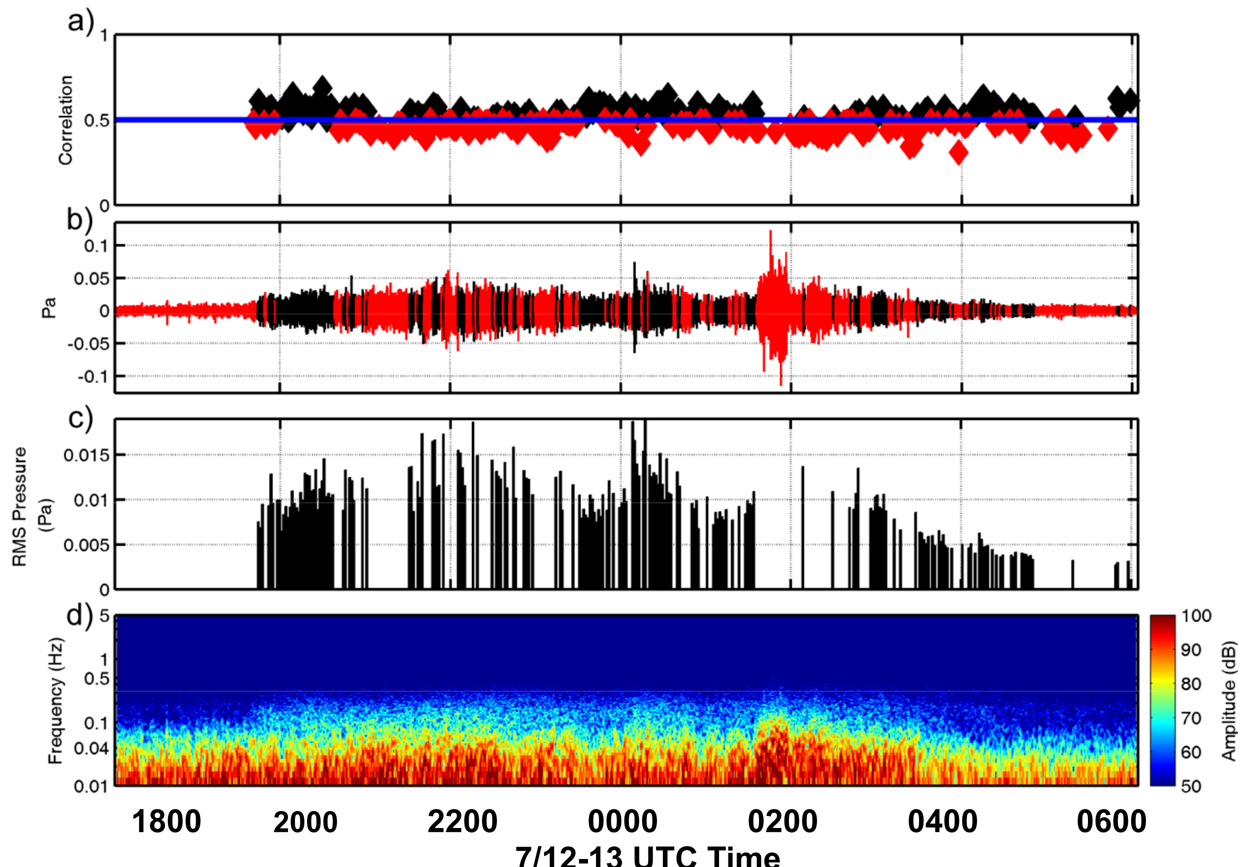
Eruption >10 hours

Onset: ~19:41:54 UTC

-Consistent with seismic and satellite

Signal focused in microbarom (0.1-0.5 Hz) band, with some VLP energy

Amplitude and correlation levels much lower than Kasatochi



[Fee et al., 2010]

Black = Correlated Signal from Okmok
Red = Uncorrelated Noise

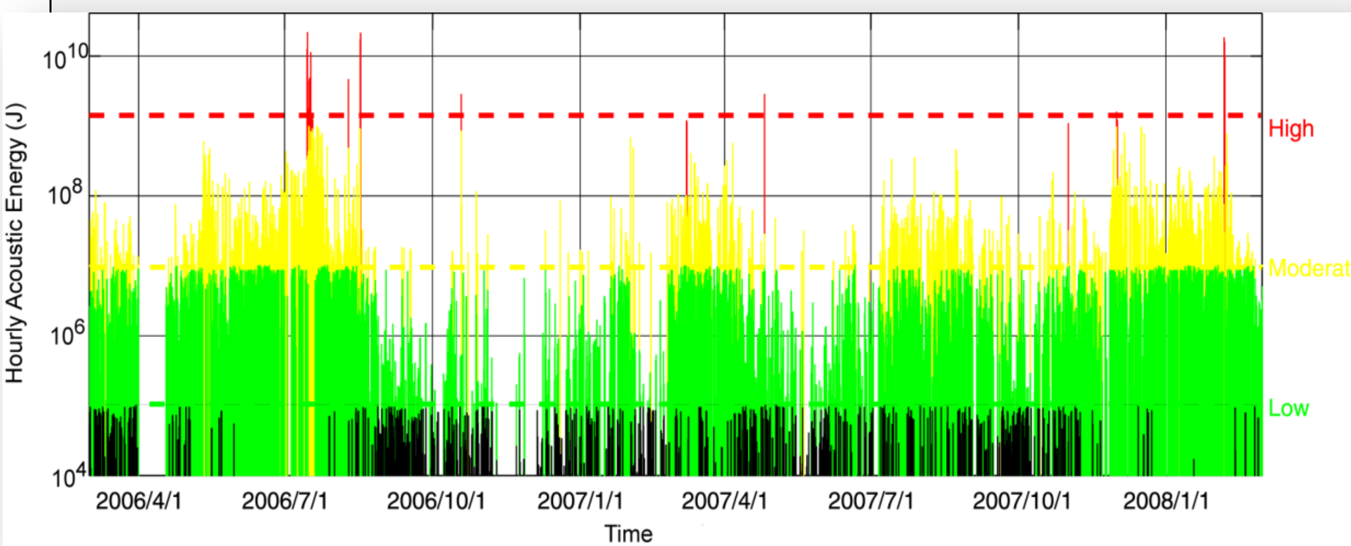
Infrasound Magnitudes - Energy

Acoustic source energy: integrate acoustic intensity over time and surface through which it passes (e.g. sphere, hemisphere)

$$E_a = \frac{4\pi r^2}{\rho c}\int_0^T \Delta p^2(t)dt$$

r=source-receiver distance, ρ=air density, c=sound speed, Δp=change in pressure

Acoustic Power: Energy/time



Tungurahua Eruption Notifcation - ASHE

Hourly Acoustic Energy

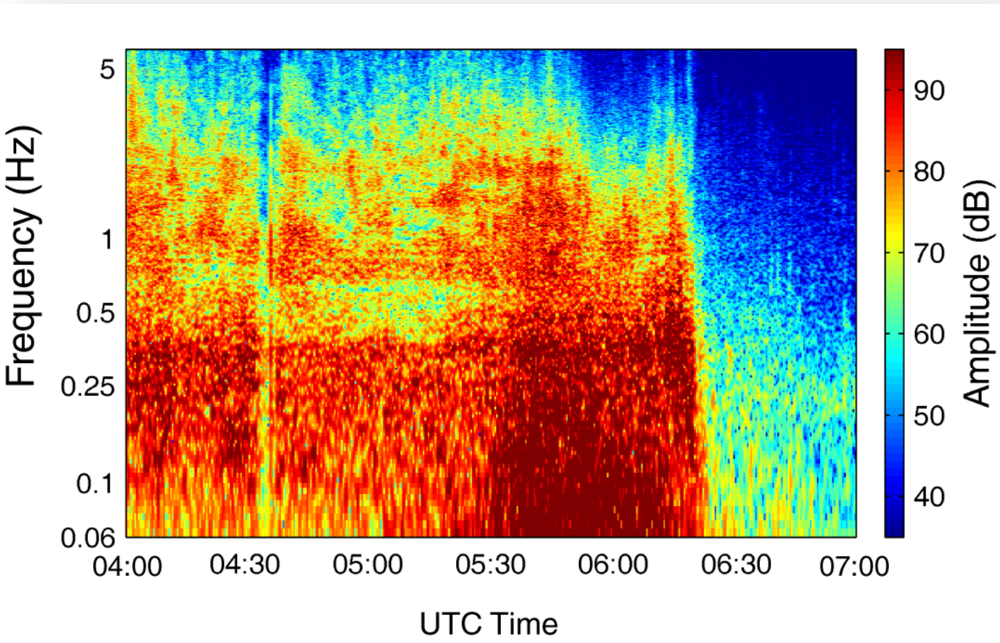
High: Significant eruption in progress

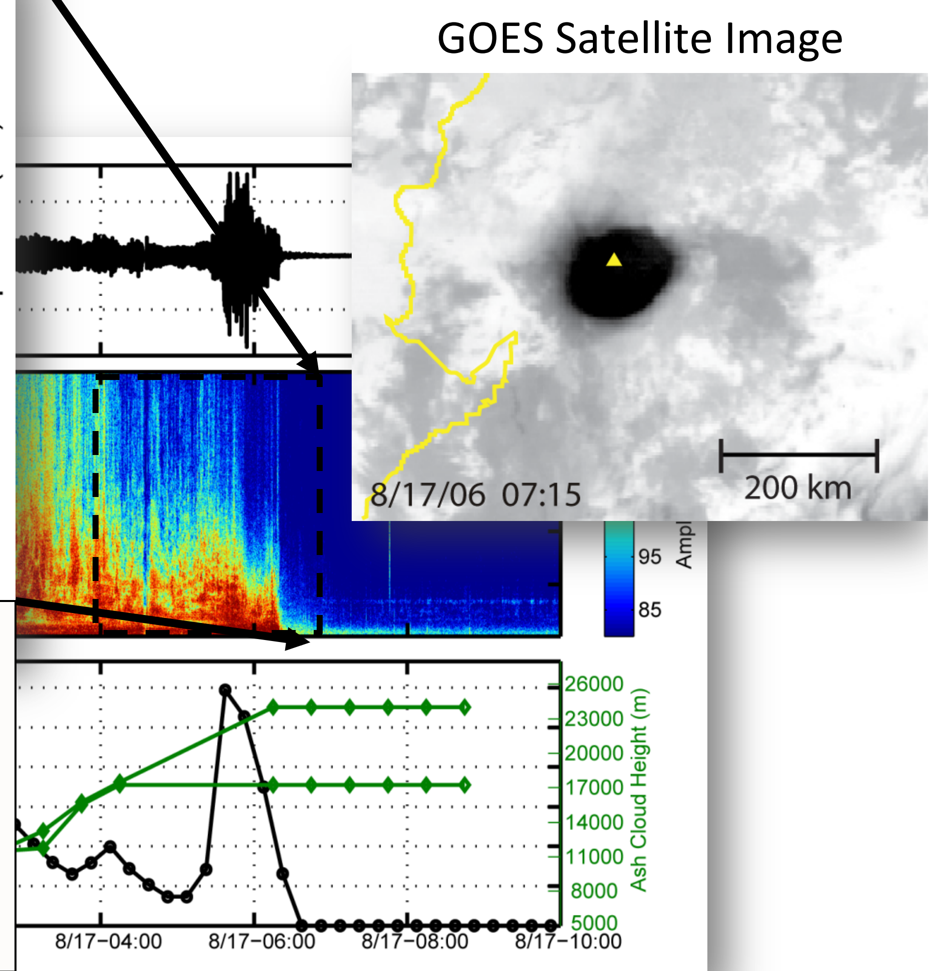
Moderate: Elevated activity, some ash

Low: Background tremor and/or explosions, minor ash emissions

Fee et al., 2010

16-17 August 2006: Subplinian-Plinian





Spectrum shifts to low frequency (<0.1 Hz) during stratospheric ash emission

Ash plume >25 km high and over 200 km wide

Over 50 MW of acoustic power at the vent

Sustained, energetic infrasound for 8.5 hours, ash up to 25 km
Acoustic power scales with ash height
Paroxysmal Plinian phase of eruption coincides with lower frequency infrasound and higher acoustic power

6 February 2008

Numerous pulses of activity over 10.5 total hours

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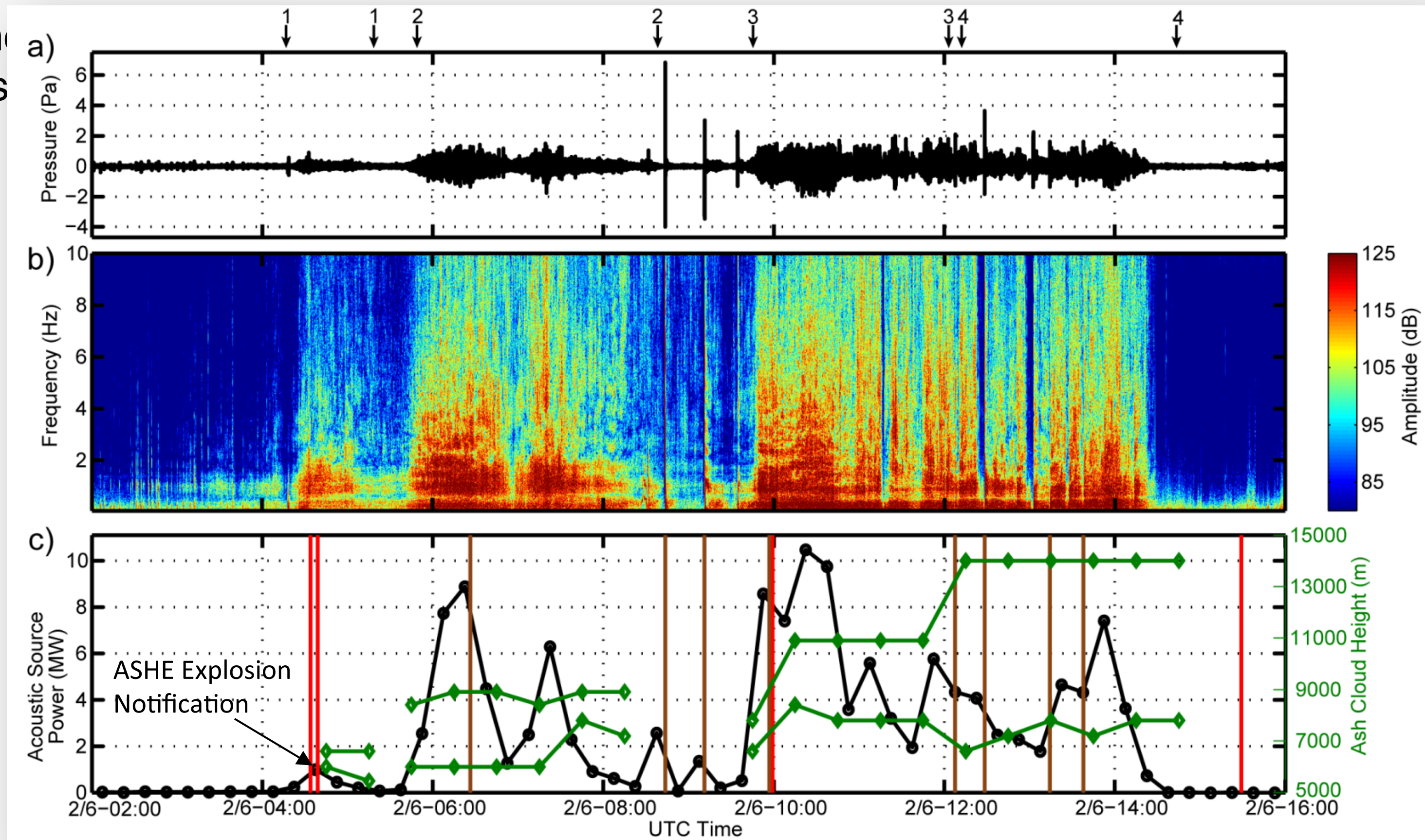
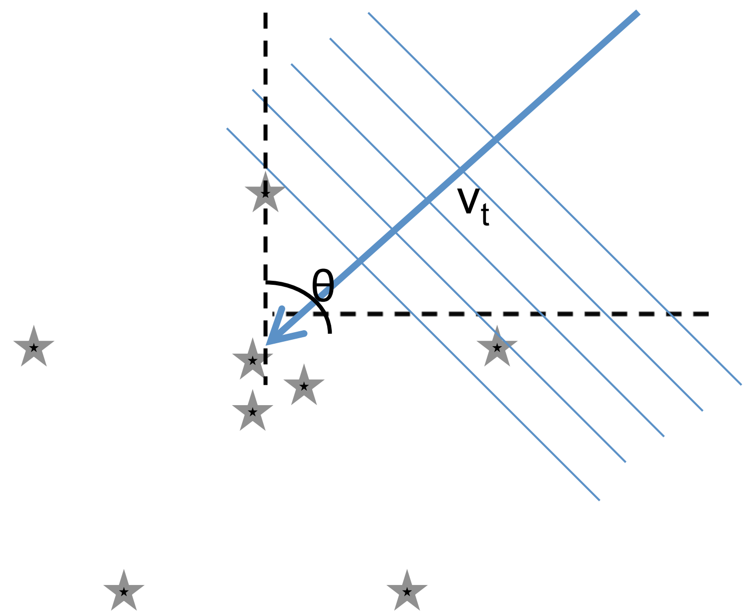


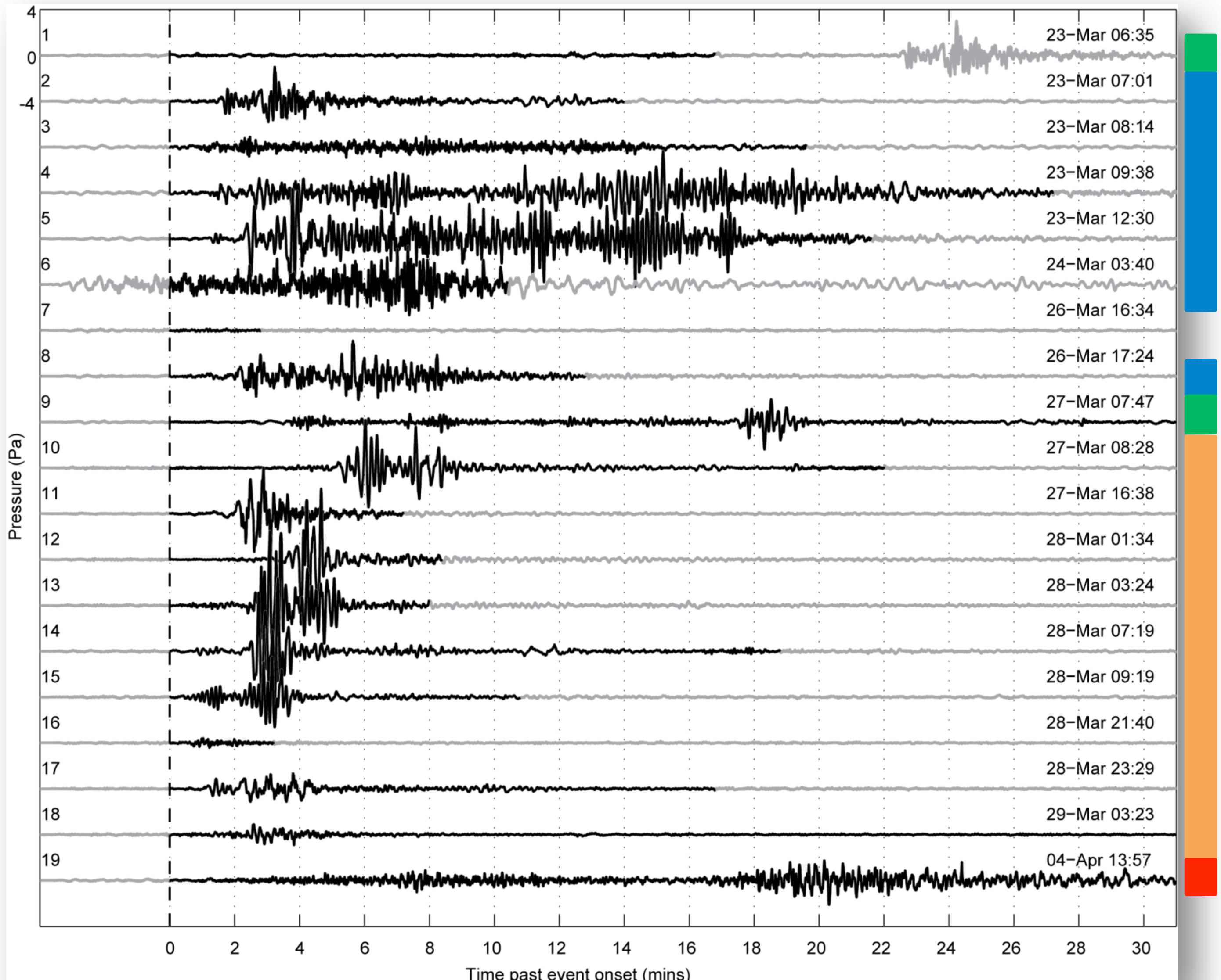
Infrasound Arrays and Array Processing

Array Processing → Detect coherent acoustic waves propagating across an array

- Deploy groups of microphones in systematic configuration
- Time delays between sensor pairs are then computed from waveform cross-correlation
- Determine signal azimuth (θ), trace velocity (v_t), and other parameters
- Increase signal-noise ratio



Redoubt - Classified by Acoustic Characteristics



[Fee et al., 2011]

<u>1: Events 1 and 9</u>
Long duration, multiple pulses; relatively low acoustic energies and ash clouds

<u>2: Events 2-6, 8</u>
Long durations, sustained infrasound; high acoustic energy and ash clouds

<u>3- Events 10-18</u>
Relatively short durations, high acoustic energy and ash clouds, Impulsive onsets, similar frequency content

<u>4: Event 19</u>
Two pulses, long duration, dome collapse