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The effects of atmospheric model variability on the inversion of infrasonic signals at the Source Physics Experiment

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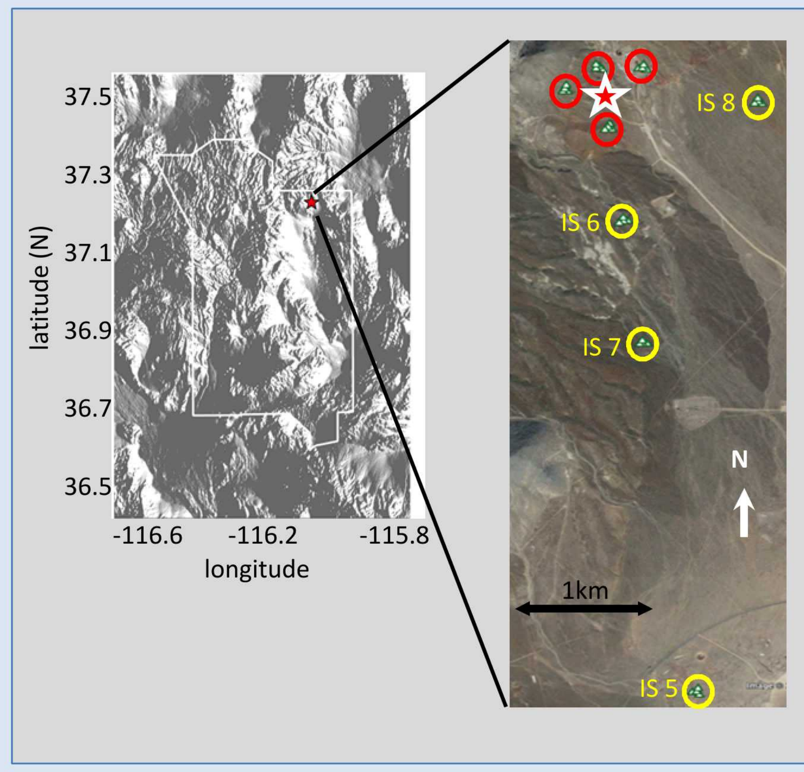
Introduction

Underground explosions can produce acoustic energy due to both linear seismic-to-acoustic conversions and near-source non-linear ground surface deformation (spall) . The resulting wave fields can be inverted for the effective seismoacoustic source parameters. Implicit in the waveform inversion process is a forward model that accounts for the propagation of wave energy. The forward model must account for all the relevant phenomena such as seismic and acoustic wave speeds and scattering as well as any coupling between the Earth and the atmosphere. In this work, we invert far field acoustic data recorded as part of the Source Physics Experiment. To produce the necessary Green's functions for the inversions, we rely on publicly available, regional atmospheric observations and the assumption that the acoustic energy results from a linear combination of 1) an underground isotropic explosion and 2) spall. The atmospheric observations are summarized and interpolated onto a 3D grid to produce a model of sound speed at the time of the experiment. The goal of this work is two-fold: the first goal is to investigate the sensitivity of the inversion to the variability of the estimated atmospheric model. The second goal is to determine the relative contribution of two possible source mechanisms to the total acoustic wave field. For four SPE chemical explosion events, we produced a suite of three atmospheric models, based on ten years of regional meteorological observations: an average model as well as two extrema models. We find that the inversion yields relatively repeatable results for the estimated spall source. Conversely, the estimated isotropic explosion source is highly variable. This suggests that 1) the majority of the observed acoustic energy is produced by the spall source and 2) the explosion source term is either not a significant source of acoustic energy or our modeling of the elastic energy propagation is too simplistic.

Experiment Design



The panel on the left shows the outline of the Nevada Nuclear Security Site (NNSS), with the location of the SPE indicated by the red star. The panel on the right shows the location of the infrasound arrays, where the yellow circles indicate the arrays that we used for the work here. The arrays are labeled according to usage throughout the poster. Each array is comprised of four Hyperion sensors connected with four porous hoses.

The red circles indicate infrasound arrays that we did not analyze due to a high degree of seismic energy contaminating the acoustic data. The arrival times of the seismic energy coincided with that of the acoustic energy, which we don't account for in our forward model.

Forward Model

We assume that the pressure acoustogram time series at $\boldsymbol{x}'$ is a sum of two sources:

$$p(\boldsymbol{x}',t') = \sum_{i=1}^{N_s} \int_{-\infty}^{\infty} \int_{V_0} G^{(i)}(\boldsymbol{x}',t';\boldsymbol{x},t) S^{(i)}(\boldsymbol{x},t) dx^3 dt, \quad (1)$$

where $G^{(i)}$ is the pressure Green's function of the i^{th} general source $S^{(i)}$ located at $\boldsymbol{x}$. We assume two sources: 1) a buried chemical explosion $\boldsymbol{M}(\boldsymbol{x}_1, t)$ and 2) surface deformation (spall) $\boldsymbol{F}(x_2, t)$:

$$p(\boldsymbol{x}',t') = G_{expl}^{(1)}(\boldsymbol{x}':\boldsymbol{x}_1,t) \otimes \boldsymbol{M}_{(expl)}(\boldsymbol{x}_1,t) + G_F^{(2)}(\boldsymbol{x}':\boldsymbol{x}_2,t) \otimes \boldsymbol{F}(\boldsymbol{x}_2,t) \quad (2)$$

where $\otimes$ denotes time-domain convolution. We approximate the explosion source $\boldsymbol{M}_{expl}$ as a isotropic moment tensor and the spall source $\boldsymbol{F}$ as a vertically directed force:

$$\boldsymbol{M}_{(expl)}(\boldsymbol{x}_i,t) = \begin{bmatrix} M_{xx}(t) & 0 & 0 \\ 0 & M_{yy}(t) & 0 \\ 0 & 0 & M_{zz}(t) \end{bmatrix} \qquad \boldsymbol{F}(\boldsymbol{x}_i,t) = \begin{bmatrix} 0 \\ 0 \\ F_z(t) \end{bmatrix}$$

Note that we assume that for the explosion term, $M_{xx}(t)=M_{yy}(t)=M_{zz}(t)$ and therefore treat the explosion term as a 1D vector in the inversion.

Inverse Method

Equation (2) is recast in the frequency domain

$$p(f) = \sum_{i=1}^{2} G^{(i)}(f) S^{(i)}(f) \quad (3)$$

where $S^{(1)}=M_{expl}(f)$ and $S^{(2)}=F_z(f)$ are the spectra of the source terms. In matrix form, equation 4 is written as

$$\boldsymbol{p} = \boldsymbol{GS}$$

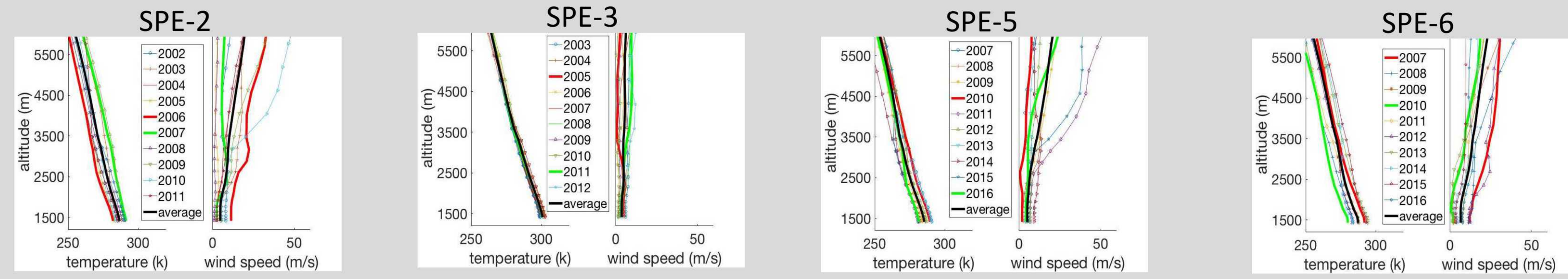
and solved for $\boldsymbol{S}$ using generalized least squares. The term $\boldsymbol{S}$ contains the complex spectra of both of the estimated source terms.

Estimating Green's functions

STEP 1: Estimate the state of the atmosphere:

A) We estimate the atmosphere using historical, regional-scaled observations. For four SPE events, we compiled observations for each time-of-day and day-of-year for the ten years preceding the actual SPE event.

B) These observations are combined with topography and input into the Weather Research and Forecasting (WFR) to construct high-resolution atmospheric state predictions for each day-of-year for each SPE event analyzed here.



Profiles of temperature and wind speed for each estimated atmospheric model. Each panel corresponds to a given SPE event, where the colors correspond to the model estimated for the indicated year. The extrema models are chosen to maximize the range in acoustic wave speed, however, no models with surface winds greater than 5.0 m/s are used, as SPE explosions are not conducted in this situation.

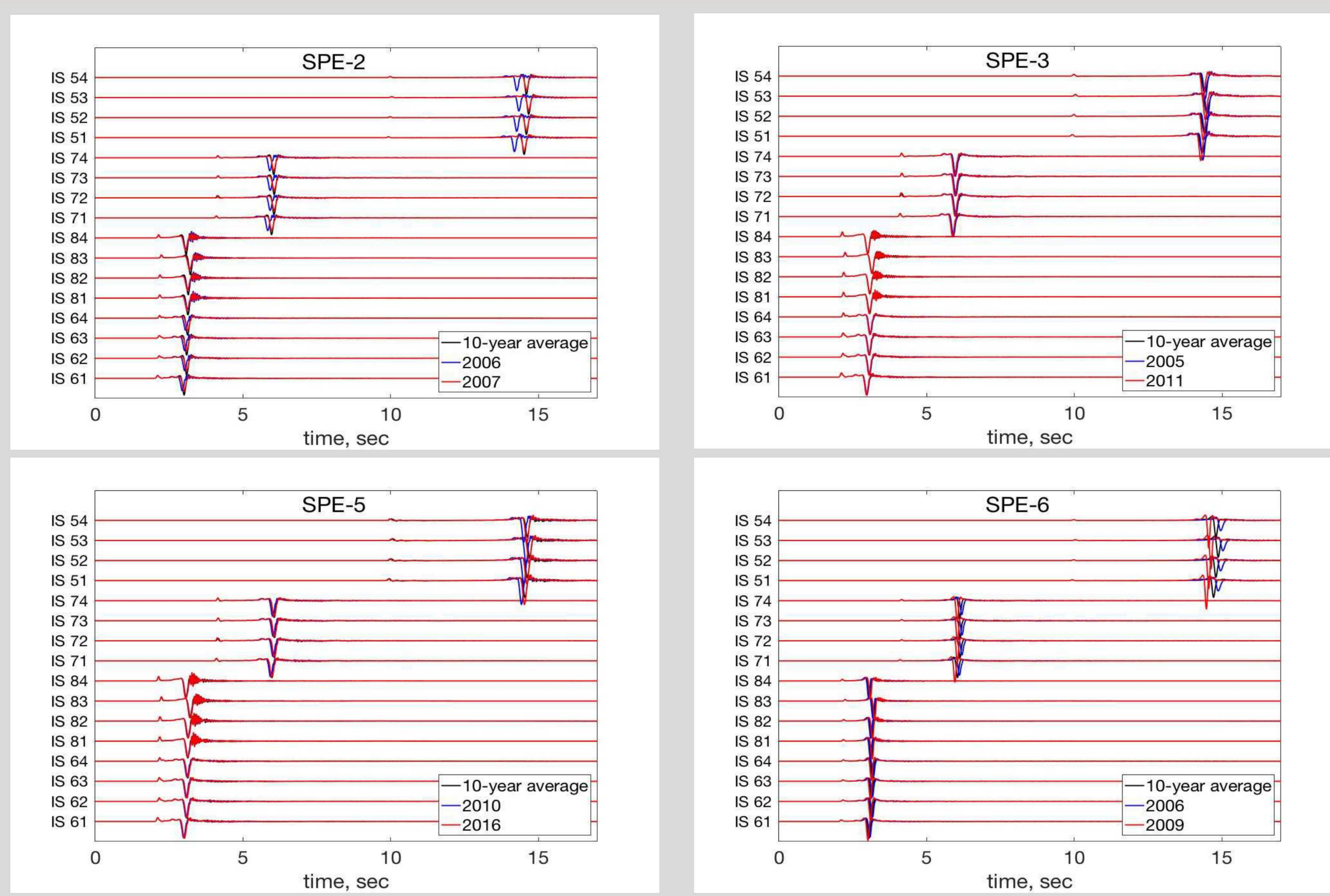
STEP 2: Compute Green's functions:

A) We select three atmospheric models for each SPE event: an average model (formed by averaging all ten atmospheric states obtained in step 1) and two extrema states (Table 1)

B) We estimate the Green's functions for each model using a 3D, staggered grid finite difference algorithm. The finite difference scheme takes into account the surface topography, and relevant atmospheric variables (wind velocity, pressure, humidity, etc.) to solve the time domain velocity-pressure system. The two source terms are simulated as band-limited (0-360Hz) delta functions. The Green's functions are collected at model points that correspond to the actual infrasonic station locations.

Table 1: The date and explosive yield of each SPE event analyzed here. The last two columns indicate which years we used to to estimate the extrema weather conditions for each SPE event

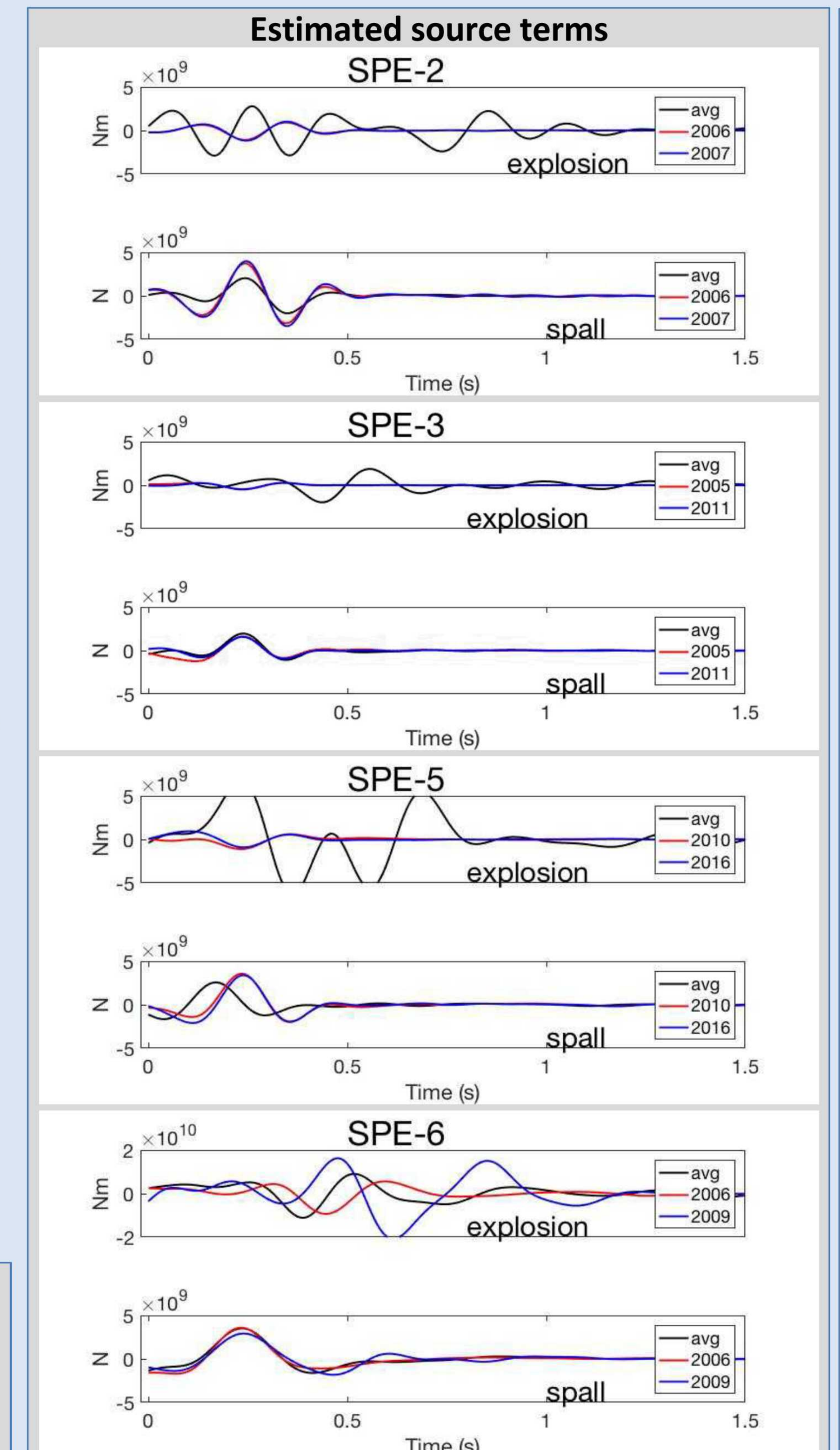
SPE event	Date of Experiment	Yield (tons)	Depth of Burial (m)	Scaled Depth of Burial (m/kt^(1/3))	first extrema combination	first extrema combination
SPE-2	25 October, 2011	1	45.7	457	2006; cool and windy	2007; warm and calm
SPE-3	24 July, 2012	0.9	47.2	488	2005; warmand calm	2011; cool and windy
SPE-5	26 April, 2016	5.04	76.5	446	2010; warm and calm	2016; cool and windy
SPE-6	12 October, 2016	2.2	31.4	241	2006; warm and windy	2009; cool and calm



The estimated atmospheric Green's functions for the spall source model for the four SPE event analyzed here. Each panel shows three sets of Green's functions, corresponding to the average atmospheric model (1—year average, black), and the two extrema models (red and green). The Green's functions have been convolved with an 8.0-Hz Gaussian wavelet and trace normalized for display purposes.

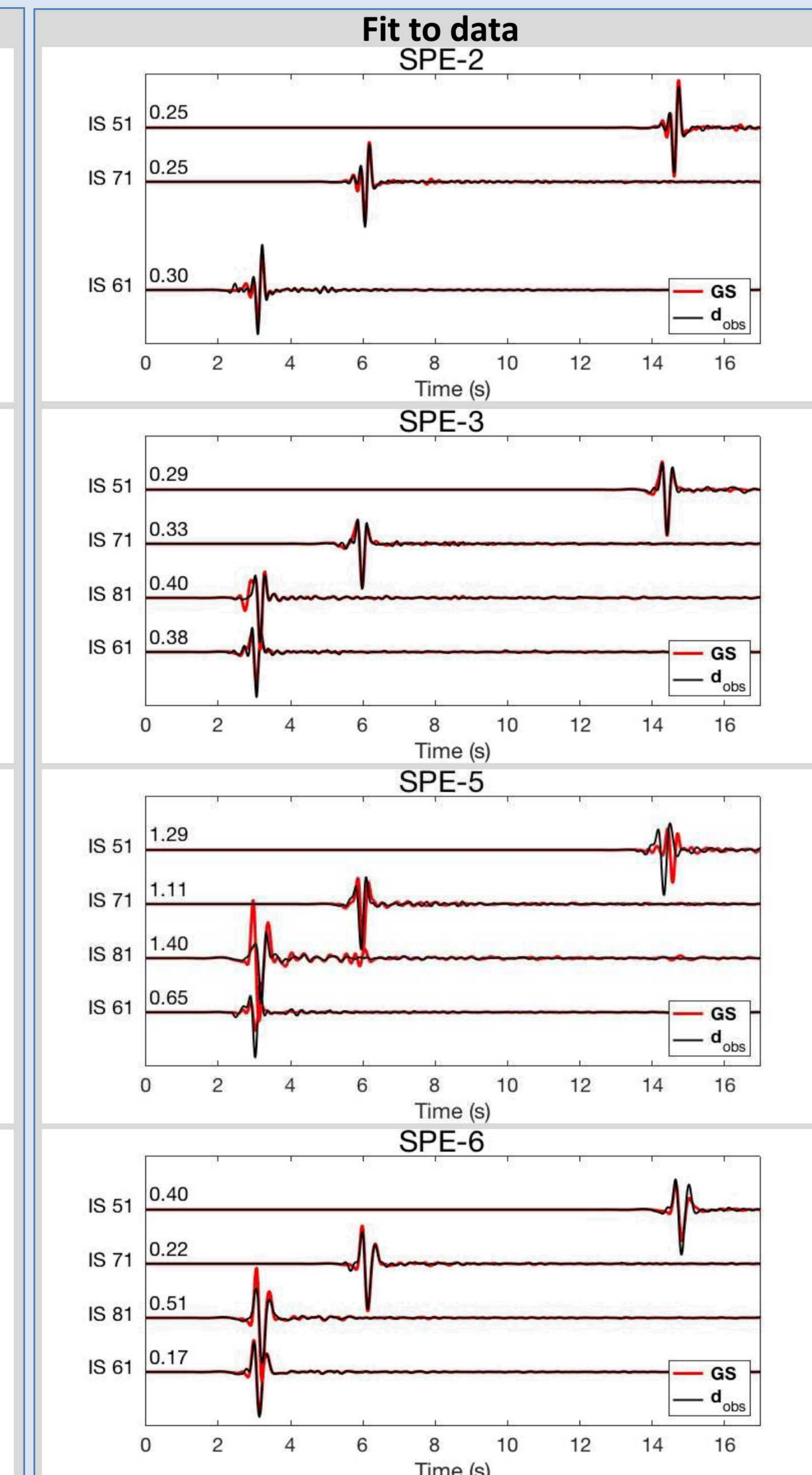
Results

Estimated source terms



The estimated source terms for the three atmospheric models, for all four SPE events analyzed: the black is the estimated source term using the average atmospheric model and the red and blue are the estimated source terms using the two extrema models. The results shown here have been filtered to 1-5Hz passband. In general, the estimated spall source term is stable and repeatable whereas the estimated explosion source term is highly erratic.

Fit to data



We computed the data misfit by convolving the estimated source terms with the Green's functions (equation 2). Observed data is in black and the computed data is in red. The numbers above the time series indicate the degree of misfit: lower numbers indicate a better fit to the data. To compute this, we compute L2 norm of the data residual and normalized by the L2 norm of the observed data. We only show the misfit for the first station of each array, and only for the 10-year average model. We note that the data misfit is the lowest when using both source terms.

Discussion and Conclusions

A) Atmospheric prediction and Green's function estimation

- We didn't use any on-site atmospheric measurements to build the atmospheric models. Rather, we used regional-scaled historic data to **predict** the state of the atmosphere at the day-of-year and time-of-day for each SPE event. For each SPE event, we formed an average model based on ten years of historical atmospheric data, as well as two extrema models.
- For each atmospheric model, we estimated the atmospheric Green's functions. Acoustic wave speeds vary by as much as +/- 3%, between the models, effecting the the timing of the modeled acoustic arrivals accordingly.
- The waveforms of the (filtered) Green's functions were only minimally affected by the variation in the atmospheric model estimates.
- The method that we used to estimate the Green's functions treats the Earth as a fluid, with a acoustic velocity of 500m/s. This precludes the realistic simulation of shear waves, surface waves, and elastic-to-acoustic coupling at the Earth-air interface.

B) Inversion results

- The estimated spall term is relatively stable and repeatable for all of the SPE data that we invert, regardless of the atmospheric model used to construct the Green's functions.
- Conversely, the estimated explosion term is highly variable in all cases.
- These two results suggest that 1) the explosion source term is not a significant contributor to the the observed acoustic data and/or 2) the model we use to construct the explosion Green's function is too simplistic to realistically simulate the acoustic response of the buried isotropic explosion. Our analysis is not able to assess the relative importance of these two possibilities.
- The inversion results for SPE-5 have the poorest fit to the data, suggesting that this large explosion produced non-linear affects that are not captured by our forward models.

Take-away point

Using historical weather data to estimate or predict the state of the atmosphere appears to be a viable technique of inverting high-quality, low noise infrasound data for the seismoacoustic source when on-site, *in situ* measurements are not available. However, more realistic simulation techniques will likely be needed to capture the explosion portion of the source model.

Acknowledgments

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