SAND2018-13631R

Predicting Atmospheric Green's Functions using the Weather Research and Forecasting Model

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Abstract
This report shows the results of constructing predictive atmospheric models for the Source Physics Experiments 1-6. Historic atmospheric data are combined with topography to construct an atmospheric model that corresponds to the predicted (or actual) time of a given SPE event. The models are ultimately used to construct atmospheric Green's functions to be used for subsequent analysis. We present three atmospheric models for each SPE event: an average model based on ten one-hour snap shots of the atmosphere and two extrema models corresponding to the warmest, coolest, windiest, etc. atmospheric snap shots. The atmospheric snap shots consist of wind, temperature, and pressure profiles of the atmosphere for a one-hour time window centered at the time of the predicted SPE event, as well as nine additional snap shots for each of the nine preceding years, centered at the time and day of the SPE event.

Introduction
Infrasonic data recorded in the far field can be a useful tool for inferring the physical attributes of underground explosions. For example, common data analysis methodologies are focused on explosive yield estimation and/or estimating the mechanism of the seismoacoustic source. Most analysis methods use the assumption that the far field data can be effectively modeled as a convolution of the explosion source time function and the atmospheric Green's functions at the time of the explosion. Therefore, having an accurate estimate of the atmospheric Green's function is vital for data analysis. The atmospheric Green's function describes the acoustic impulse response of the atmosphere between a given source and receiver and depends on the spatial properties of the atmosphere. However, since the atmosphere is dynamic, the Green's function between a given source-receiver pair can change depending on the state of the atmosphere. Therefore, in order to estimate the Green's function for a given source-receiver pair at a specific time, one must have a reasonable estimate of the atmospheric state at that time.

We describe our efforts at predicting the physical state of the atmosphere for a specified date and location using publicly available historic atmospheric data. The goal is to produce an estimate of the atmospheric state, and hence the Green's functions, for each of the six Source Physics Experiments (SPE) using only publically available data, which serves as a proxy to in-situ atmospheric observations. Our method uses snap shots of the atmosphere for a specified day-of-year for ten years preceding the date of a given SPE event. This data is averaged and combined with topography to produce a predicted atmospheric model. At a later date, we will directly compare our predicted atmospheric models with those produced using in-situ observations.

Research Accomplished
The main goal of the work here was to develop a method of producing estimates of atmospheric Green's functions using only publically available, regional scale data. To this end, we collected, summarized, and interpolated atmospheric data onto a regular grid, producing a predicted atmospheric model. We then use this atmospheric model to compute Green's functions from the SPE location to a series of receivers. Because the Green's functions are sensitive to wind and

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temperature, we explore the variability of Green's functions resulting from atmospheric variability by computing Green's functions for extrema years (e.g. coldest and windiest year, warmest and calmest year) for each SPE event.

Method

Atmospheric Predictions

We use the Weather Research and Forecasting (WRF) model to summarize atmospheric data and combine with topography to construct atmospheric models. WRF is an atmospheric prediction system designed for meteorological research and numerical atmospheric prediction. The output from WRF is a three-dimensional atmospheric model describing, among other things, the temperature, pressure, and wind velocity of all points within the model. In our case, WRF incorporates ground surface topography and historical atmospheric data to construct a model that predicts the state of the atmosphere at the time of a given SPE event. We use output from WRF as input to a Sandia-developed computer program to simulate Green's functions through these atmospheric models.

We produce two types of atmospheric-state models. In the first case, we produce an average model based on the historical data collected for the actual experiment date as well as the nine years preceding actual experiment. The data that we use represents the atmospheric state on the date of the SPE event for a one-hour window centered at the actual SPE event. The historical data is that which corresponds to the same one-hour window, but for the preceding nine years. An outline of the steps used to generate an atmospheric model are as follows:

1) Define the geographic region of interest. Note that for this work, the region of interest is rectanglar, approximately 2000m wide in the east-west direction by 5500m in the north-south direction. The region is defined by the actual SPE event: located at latitude 37.221207N and longitude 116.0608674W. The SPE event defines the local origin.
2) Obtain topography information corresponding to the same area defined in the step described previous to this one. For our work, we obtained topography data from http://viewer.nationalmap.gov/basic/. The resolution of this data is 1/3 arc second in both cardinal directions.
3) Gather weather data in the region of interest. For our work, we obtained data from the University Corporation for Atmospheric Research (UCAR) at rda.ucar.edu. We gathered a single day's worth of data around the actual experiment time. We also gather data for the same day-of-year (DOY) for the nine years preceding the actual experiment date. We then cull the atmospheric data to include only a one hour window around the actual experiment time.
4) Determine the mean atmospheric state as a function of altitude by averaging the ten atmospheric states obtained in the previous step.
5) Build an atmospheric model for the region of interest. The topography information combined with the mean atmospheric state are used as input to WRF. WRF will use these data to predict the state of the atmosphere at the estimated (or actual) experiment time.
6) Estimate the Green's functions using the atmospheric model estimated by WRF.

The second type of model we produce are extrema models, but still based on historical atmospheric data. Specifically, based on the atmospheric states that we obtained in step 4 above, we choose two extrema: for example, the warmest and windiest year, or the coolest and calmest year. To choose the extrema, we generally only considered the data below 4000m in elevation. For each experiment time, we choose two individual years as input to produce extrema atmospheric models. Using these models, we compute Green's functions as before.

The ultimate goal of the steps listed above are to generate atmospheric Green's functions that are subsequently used for data analysis. Note that the steps listed above outline a method of predicting the state of the atmosphere at the time of a given SPE event, and is based on historical measurements of the atmosphere. The resulting atmospheric models do not contain any data that is actually measured on-site at the time of the experiment, and thus we refer to these models as Atmospheric Predictions.

The SPE events are listed in Table 1. For each SPE event, we show a summary of the atmospheric wind speed and temperature as a function of altitude (figures 1-6). It's these profiles, coupled with the topography information, that are used to construct three-dimensional atmospheric models using WRF. Table 1 summarizes the extrema years that we chose for a given SPE event. Note that, for example, the warmest-windiest year didn't necessarily exist for each SPE event. Rather, we chose a representative temperature/wind speed combination that generally produced the largest variability in acoustic wave speed for a given SPE event. Also, we eliminated any wind speed criteria where the wind speed was greater than 5 m/s, as SPE events were not conducted at wind speeds greater than this.

Table 1: Atmospheric extrema for a given day for the ten years preceding a given SPE event

SPE Event	SPE date	First extrema combination	Second extrema combination
SPE-1	3 May, 2011	2004: warm and windy	2007: cool and calm
SPE-2	25 October, 2011	2006: cool and windy	2007: warm and calm
SPE-3	24 July, 2012	2005: warm and calm	2011: cool and calm
SPE-4	21 May, 2015	2007: cool and calm	2012: warm and windy
SPE-5	26 April, 2016	2010: warm and calm	2016: cool and windy
SPE-6	12 October, 2016	2006: warm and windy	2009: cool and calm

Green’s Functions Estimation

We use the atmospheric models presented in the previous section to produce three sets of Green’s functions for each SPE event: one set corresponding to the 10-year average atmospheric model, and one set for each extrema model. Although we compute the Green’s functions over the entire domain of the models, we retain those corresponding to the source-receiver paths that correspond to the infrasound stations at the SPE site (Figures 2-7). Also, because we are mostly interested here in the effects of the atmospheric prediction variability on the wave form and timing of simulated infrasound energy, we model the source of the infrasound as an isotropic explosion located in the Earth’s subsurface. For more realistic (and complex) source simulations, see the work presented in Poppeliers et al. (in publication).

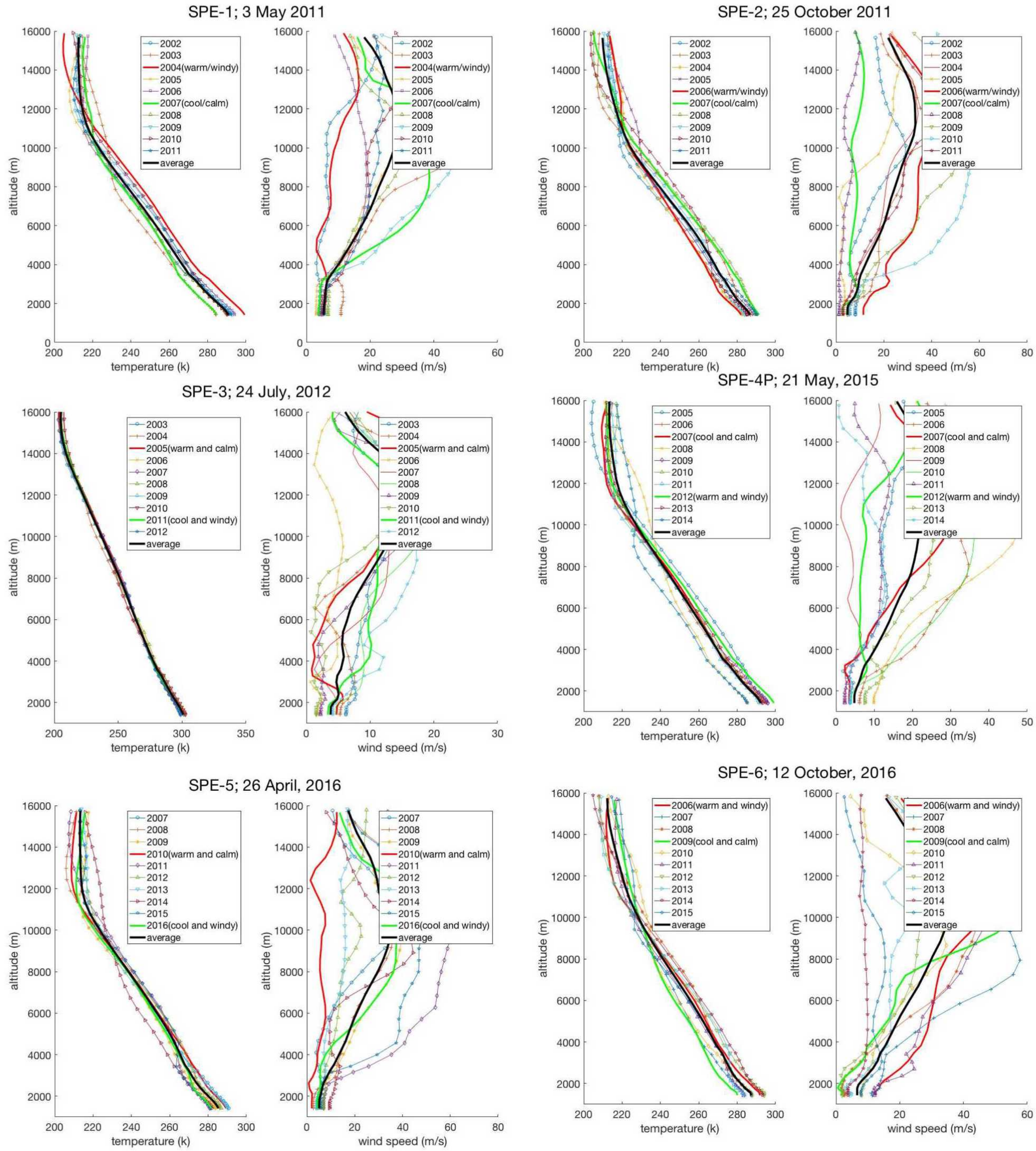

Figure 1: Temperature and wind profiles for all six of the SPE Phase 1 experiment dates. Each profile represents the average wind/temperature for a one-hour window about the experiment time. The average temperature/wind is indicated by the heavy black line, and the extrema are indicated in the legend as read and green heavy lines.

To estimate the passage of an acoustic wave in a heterogeneous, moving atmosphere, we model the acoustic waves using a non-dimensionalized velocity-pressure equations of linear elastodynamics as implemented in the Sandia-developed program TDAAPS (Symons et al, 2006). The code solves for the three components of particle velocity and pressure using an explicit, time domain, staggered grid, finite differences, where the finite difference operators posses 4th-order accuracy in space and 2nd-order accuracy in time. This approach is described in detail in Ostashev et al. (2005; equations 52-63, therein) and not repeated here for brevity. Regardless, this computational algorithm is a direct numerical implementation of the governing equations of linear acoustic wave propagation in a heterogeneous moving atmosphere. No theoretical approximations, such as far-field distances, high frequencies, weak scattering, or one-way wave propagation, are adopted.

The finite difference scheme takes into account the surface topography of the SPE field area as well as the relevant atmospheric variables (wind speed, pressure, humidity, etc.) to solve the time domain velocity-pressure system. For each SPE event and atmospheric model, the source term is simulated as band-limited (3.5-354 Hz, to the 1% level) delta functions at the appropriate time and location, and the scheme propagates the wave field to all points in the model. The atmospheric models contain 852, 2232, and 404 discrete nodes in the *x*, *y* and *z* directions, respectively, with a node size of 2.4m, and a finite difference time step of 0.0014 seconds. For our model and delta function source, the simulated wave field will be accurate for frequencies less than approximately 25Hz, which corresponds to wave lengths greater than 25m. The higher frequency portion of the simulated wave field will suffer from numerical dispersion, and will thus need to be filtered out of the solution.

For regions of the model that are located beneath the Earth's surface, the scheme approximates the Earth as a fluid with a velocity of 500 m/s and density of 2000 kg/m^3, which precludes the modeling of physically realistic seismic arrivals, but does reasonably replicate the appropriate reflection and transmission of acoustic energy across the Earth-air interface.

In Figures 2-7, we show the logarithm of the peak acoustic pressure at the Earth's surface for all of the models. To obtain the peak pressure, we convolve a 6.0-Hz Gaussian wavelet with the estimated Green's functions, correct for geometric spreading, and sort the resulting time series by the magnitude amplitude. This value is then plotted at its appropriate x-y coordinate, where the color corresponds to amplitude. Note that for each SPE event, there are only subtle differences in the peak pressure, which is solely due to the differing atmospheric conditions for each model. However, for all models, the gross features are preserved.

Results and Discussion

The goal of the work presented here is to demonstrate that we can use historical atmospheric data to predict the state of the atmosphere at a given time and location of a specific SPE event. The resulting atmospheric models can be used to construct Green's functions that we can subsequently use in data inversion schemes, which are ultimately used to estimate the size, location, and mechanisms of the seismoacoustic source. We developed a method to estimate atmospheric models using publically available, regional-scaled data. The method uses roughly one hour of atmospheric data centered about the actual (or predicted) experiment date for each of the preceding nine years as well as the data centered at the actual (or predicted) experiment time.

We computed atmospheric models, as well the Green's functions through those models for all six SPE events for the 10-year averaged model as well as the extrema models.

We note that the peak acoustic pressure, as estimated by simulating an acoustic wave through the atmospheric models, isn't significantly altered by the variability in the models. However, for waveform inversions, the relative timing and waveform shape is critical, and thus we investigate the effects of atmospheric variability for the three models for each SPE event. To show this, we plot the Green's functions for the stations 1, 25, and 17, which represent the nearest, mid-range, and farthest station from the experiment point. We expect that the nearest station would be the least effected by

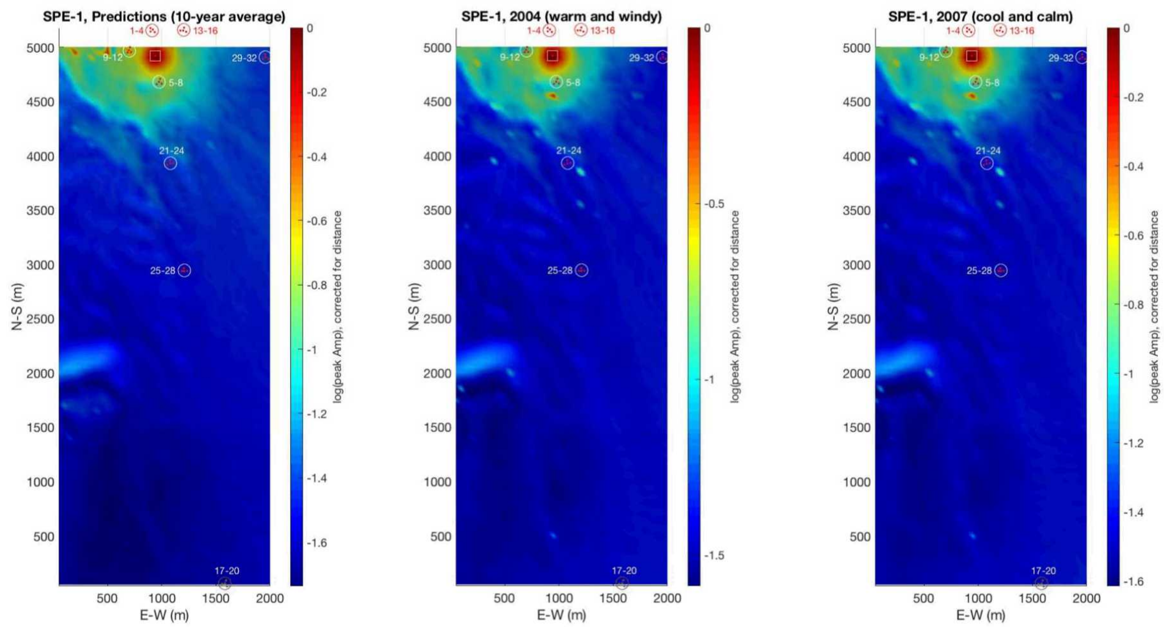

Figure 2: Logarithm of peak acoustic pressure, corrected for radial distance, for SPE-1. The peak pressure is computed by simulating the acoustic Green's function via finite differences, where the source is simulated by a buried, isotropic explosion. The SPE event occurred at the local coordinates [942,4920]m which corresponds to latitude 37.221207N, longitude 116.0608674W. The three panels show the peak pressure for the 10-year average model (left) and the two extrema models (middle and right). The small numbers represent the station numbers of the deployed infrasonic stations, and correspond to the acoustograms in Figure 8. Finally, note that the model appears to not extend to stations 1-4 and 13-16, but this is a display artifact and doesn't represent the true extent of the model which includes these stations.

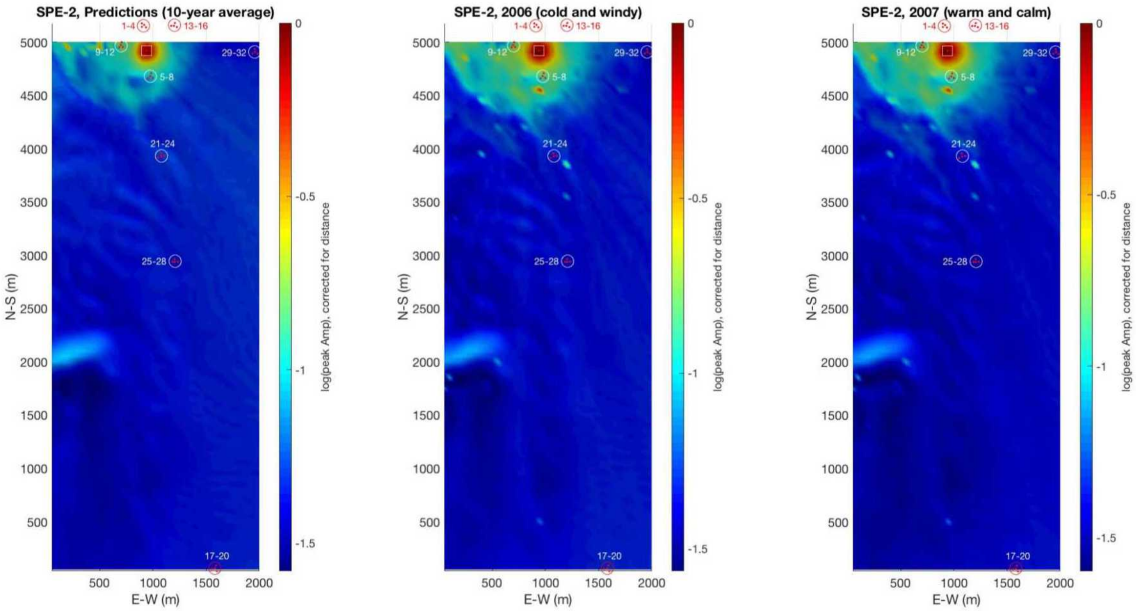

Figure 3: Same as Figure 2, but for SPE-2.

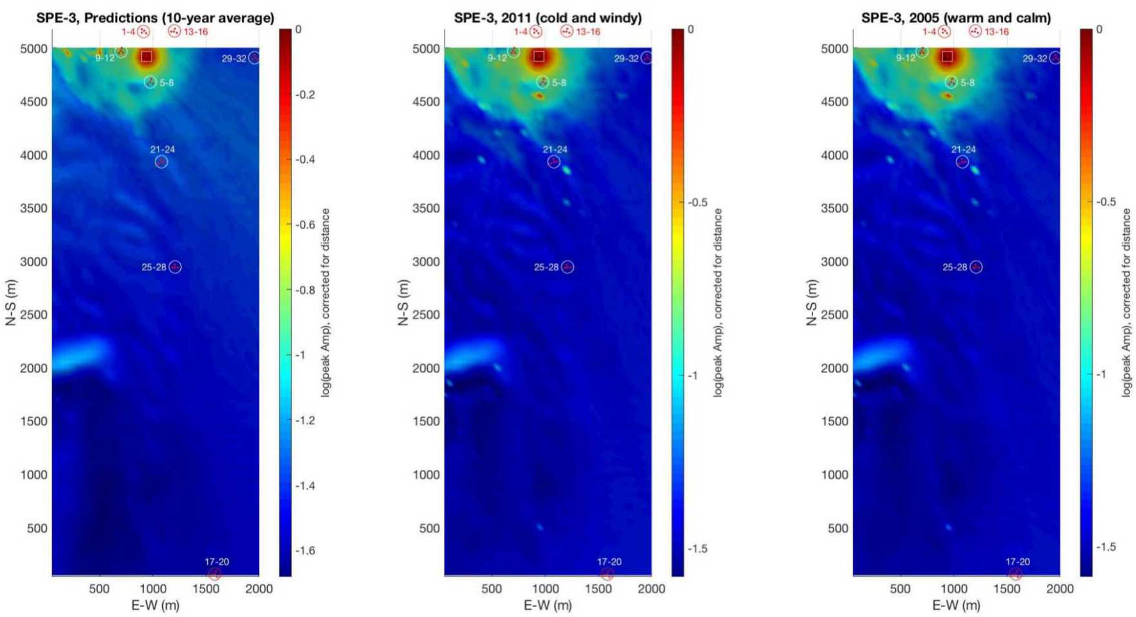

Figure 4: Same as Figure 2, but for SPE-3.

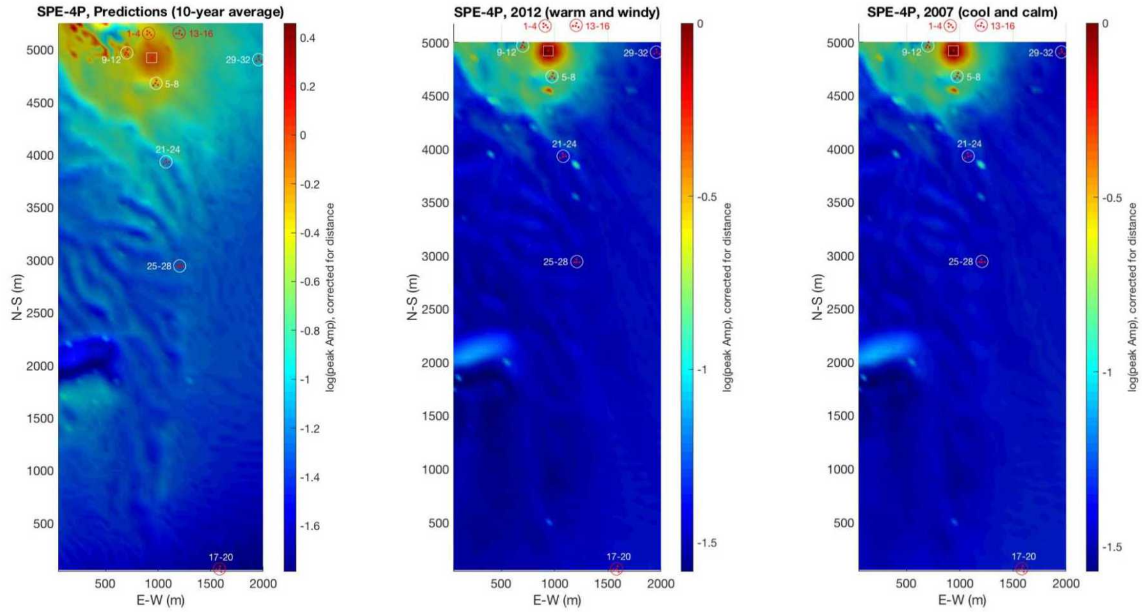

Figure 5: Same as Figure 2, but for SPE-4P.

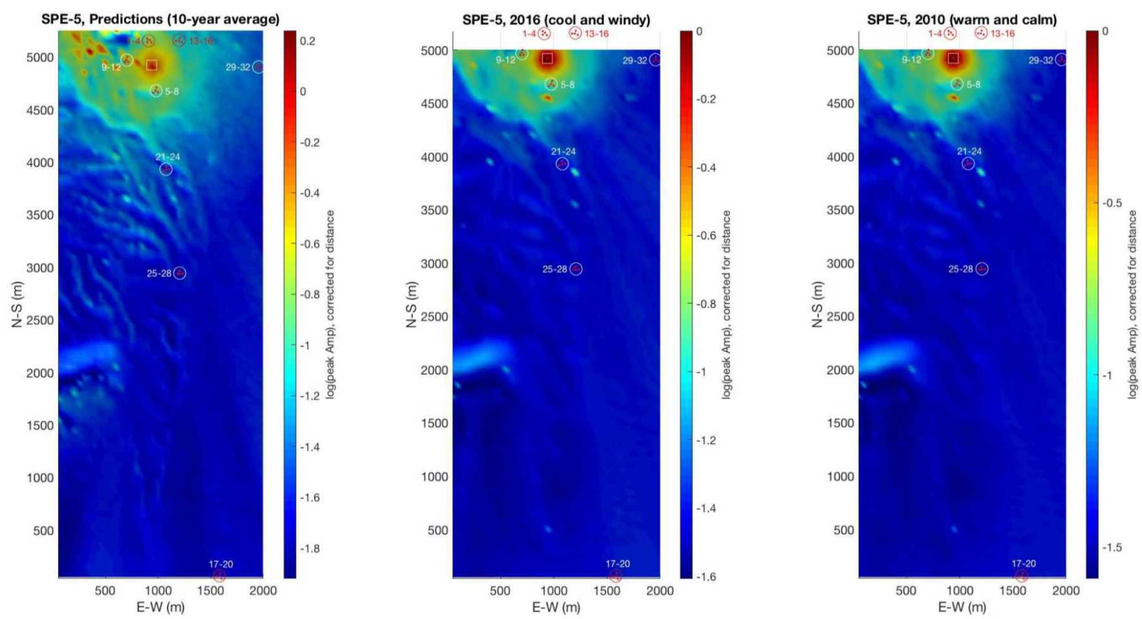

Figure 6: Same as Figure 2, but for SPE-5.

An additional effect that's quite apparent in the Green's functions, is that the time of year that a given experiment occurred can have a significant influence on the variability of the estimated Green's functions. Specifically, experiment dates that occur in the summer will likely have corresponding atmospheric models that show much less variability, due to the fact that the temperature variability during the summer months is far less than that seen in the spring or fall.

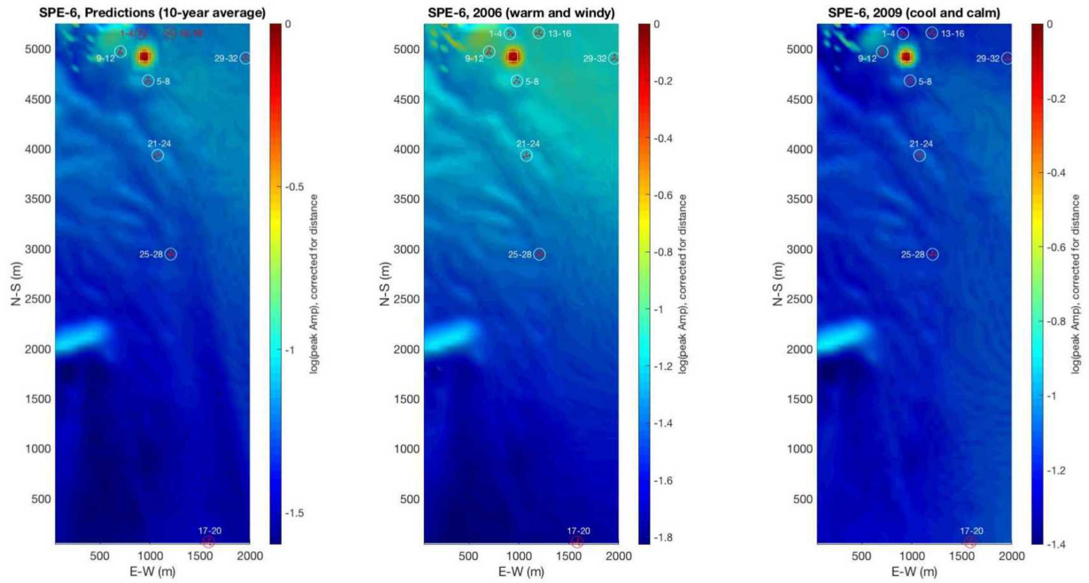

Figure 7: Same as Figure 2, but for SPE-6.

To illustrate this, SPE-6 occurred during the month of July, and the corresponding weather data shows much less variability than the other SPE events. As expected, the variability in the estimated Green's functions for SPE-6 is much less than the others, as the other SPE events occurred in the fall or spring. At the scale of the SPE, it appears that the atmospheric temperature is the most important factor effecting the variability of the Green's function estimates.

Acknowledgements
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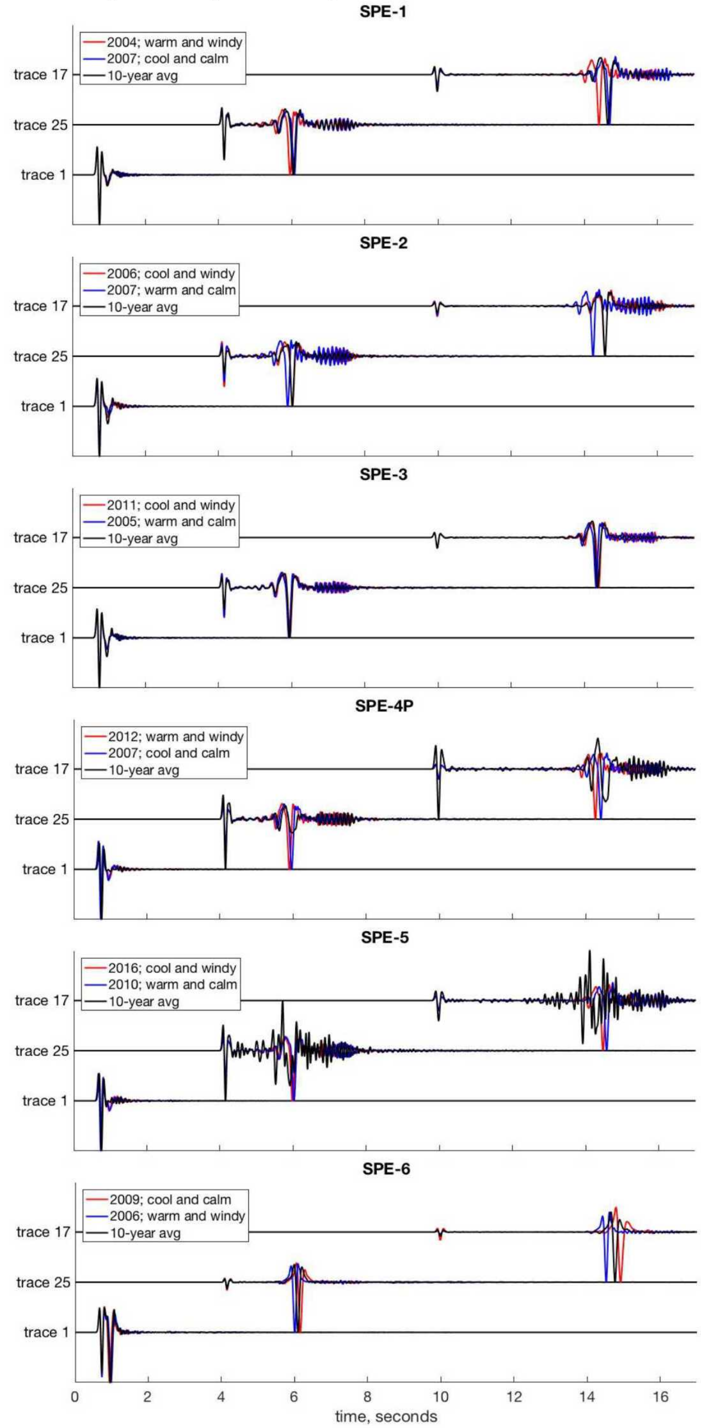

Figure 8: The Green's functions for stations 1, 25, and 17, for all six SPE events, and for all atmospheric models. For this figure, the Green's functions were convolved with a 6.0-Hz Gaussian wavelet. Note that for station 1, which is the closest station to the experiment site is