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Infrasound Predictions using the Weather Research and Forecasting model: Atmospheric Green's Functions for the Source Physics Experiments 1-6

Christian Poppeliers, Katherine Anderson Aur, and Leiph Preston

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Christian Poppeliers, Katherine Anderson Aur, and Leiph Preston
Geophysics Department
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-9999
cpoppel@sandia.gov

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.

Acknowledgment

The authors acknowledge the National Nuclear Security Administration, Defense Nuclear Nonproliferation Research and Development (DNN R&D), and the Source Physics Experiment (SPE) working group, a multi-institutional and interdisciplinary group of scientists and engineers. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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Chapter 1

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 the mechanism of the source (e.g. isotropic explosion, double couple, compensated linear vector dipole, or some combination of these). Most analysis methods use the assumption that the far field data can be effectively modeled as a linear combination of the explosion source time function and the atmospheric Green's functions at the time of the explosion.

The atmospheric Green's function describes the acoustic impulse response of the atmosphere between a given source and receiver. 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.

This report describes 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). 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. 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 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.

Chapter 2

Method

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. In WRF, simulations may be generated using real atmospheric data or idealized atmospheric conditions. The output from WRF is an 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 the Time-Domain Atmospheric Acoustic Propagation Suite (TDAAPS) which performs staggered-grid finite difference modeling of the acoustic velocity pressure system to produce Green's functions through these atmospheric models (Symons et al., 2006).

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 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. The atmospheric model estimated by WRF will now be used as input to TDAAPS to compute the impulse response of the atmosphere for each source-receiver pair of SPE.

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. In a subsequent SAND report, we will describe a method to incorporate atmospheric measurements obtained locally, and at the actual time, of a given experiment.

The SPE events are listed in Table 2.1. For each SPE event, we show a summary of the atmospheric wind speed and temperature as a function of altitude (figures 2.1-2.6). It's these profiles, coupled with the topography information, that are used to construct three-dimensional atmospheric models using WRF. The data correspond to a single, one hour window of data centered about the given SPE event, for ten years. Table 2.1 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.

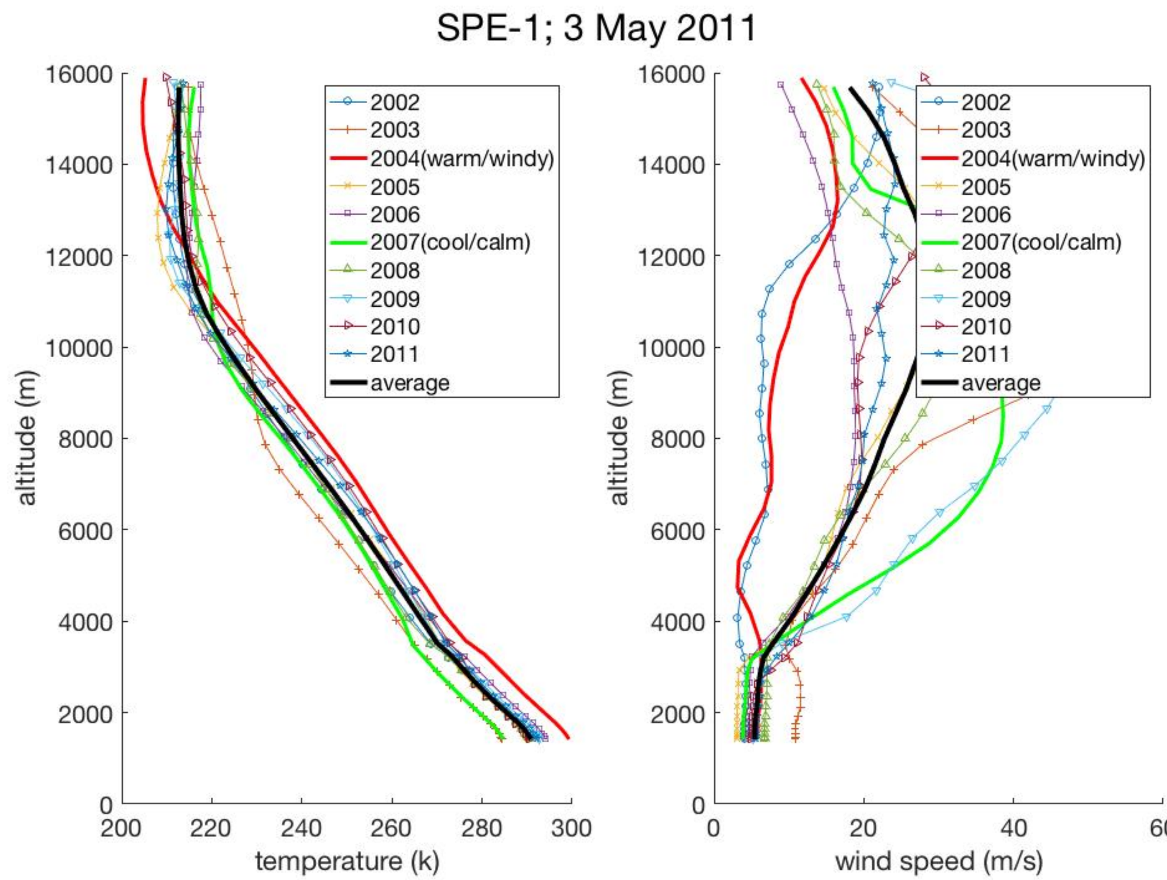

Figure 2.1. Temperature and wind profile on the SPE-1 date. Each profile represents the average wind/temperature for a one-hour window about the experiment time. The average temperature/wind is indicated by the heavy black line, and the extrema are indicated in the legend as red and green heavy lines.

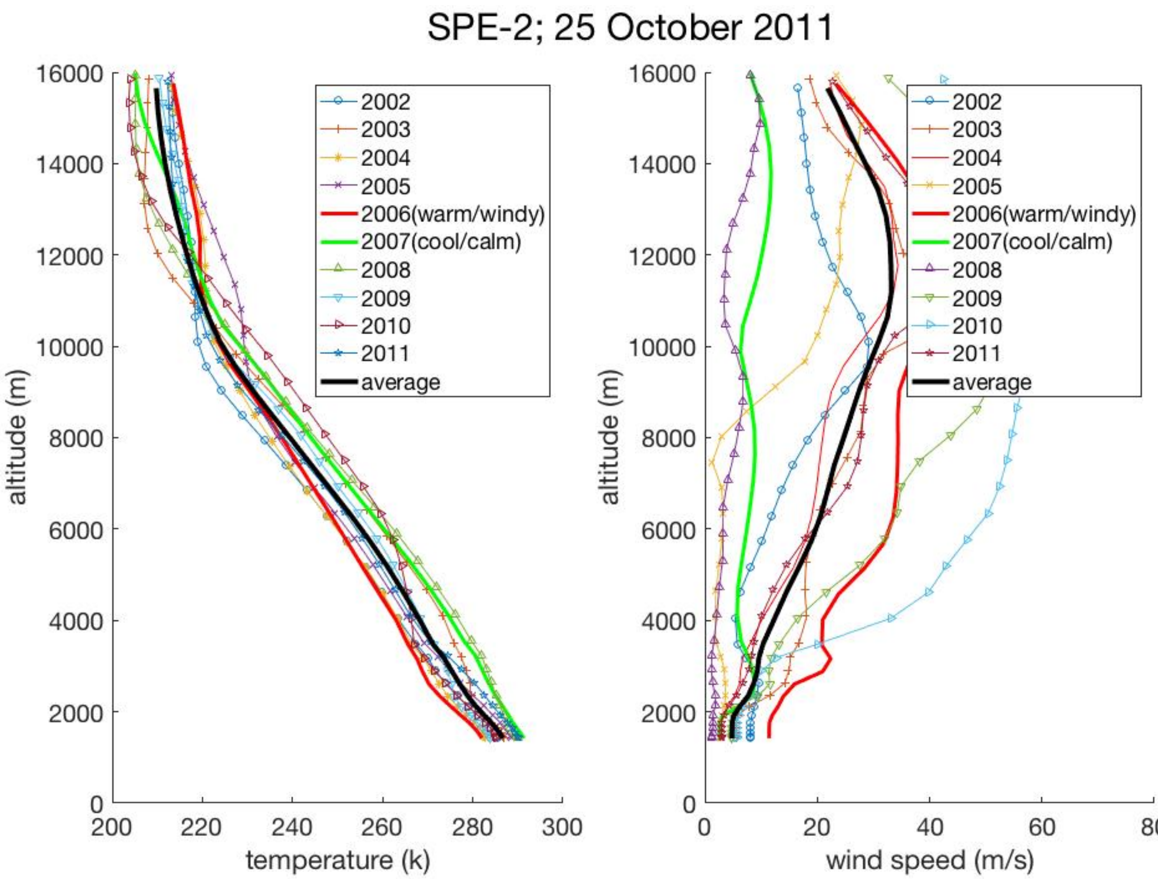

Figure 2.2. Temperature and wind speed profile on the SPE-2 date.

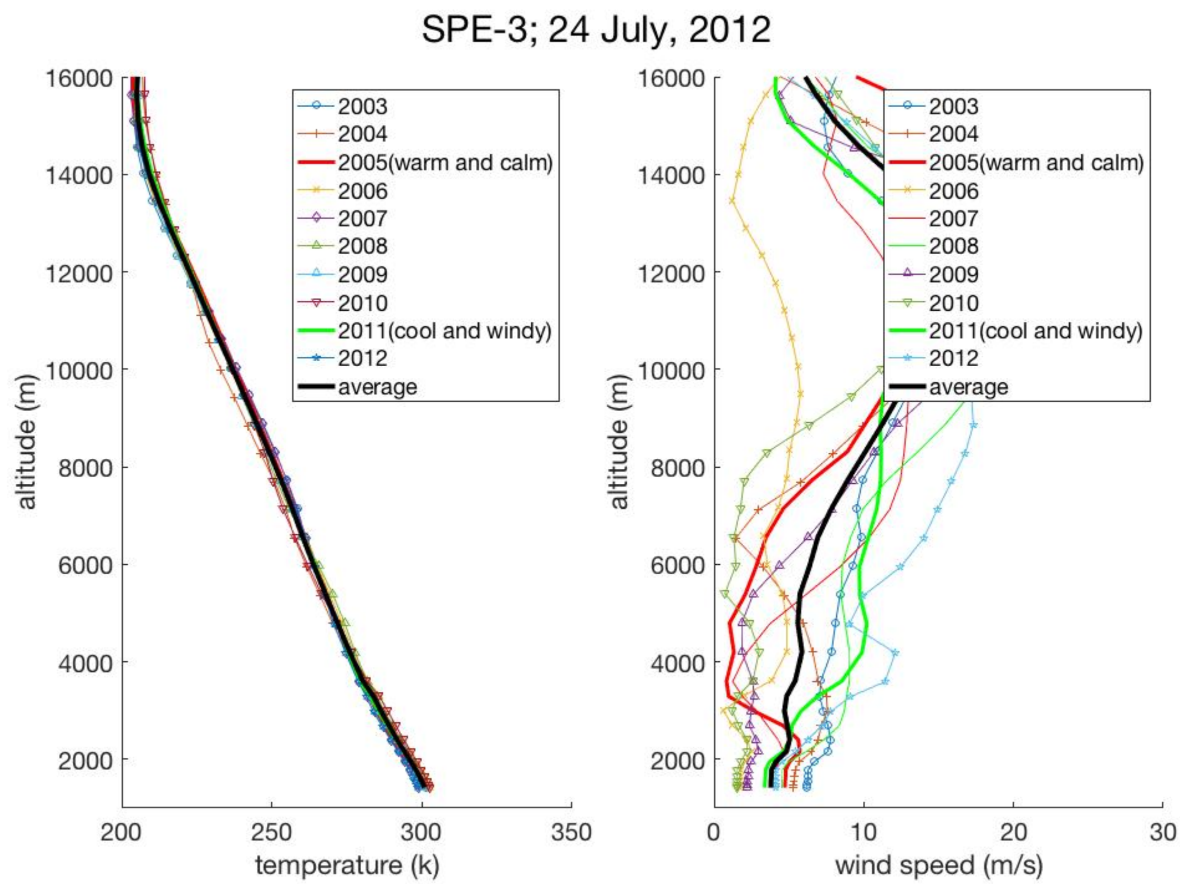

Figure 2.3. Temperature and wind speed profile on the SPE-3 date.

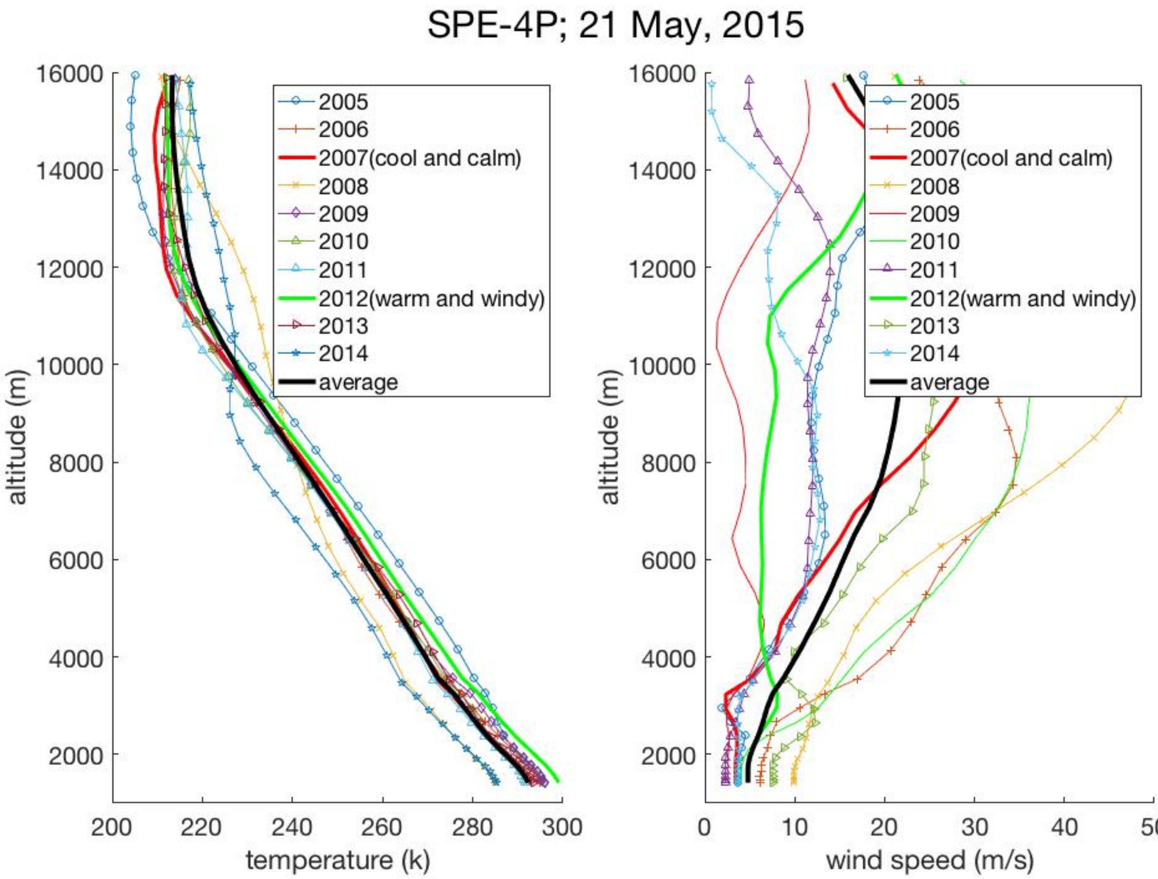

Figure 2.4. Temperature and wind speed profile on the SPE-4P date.

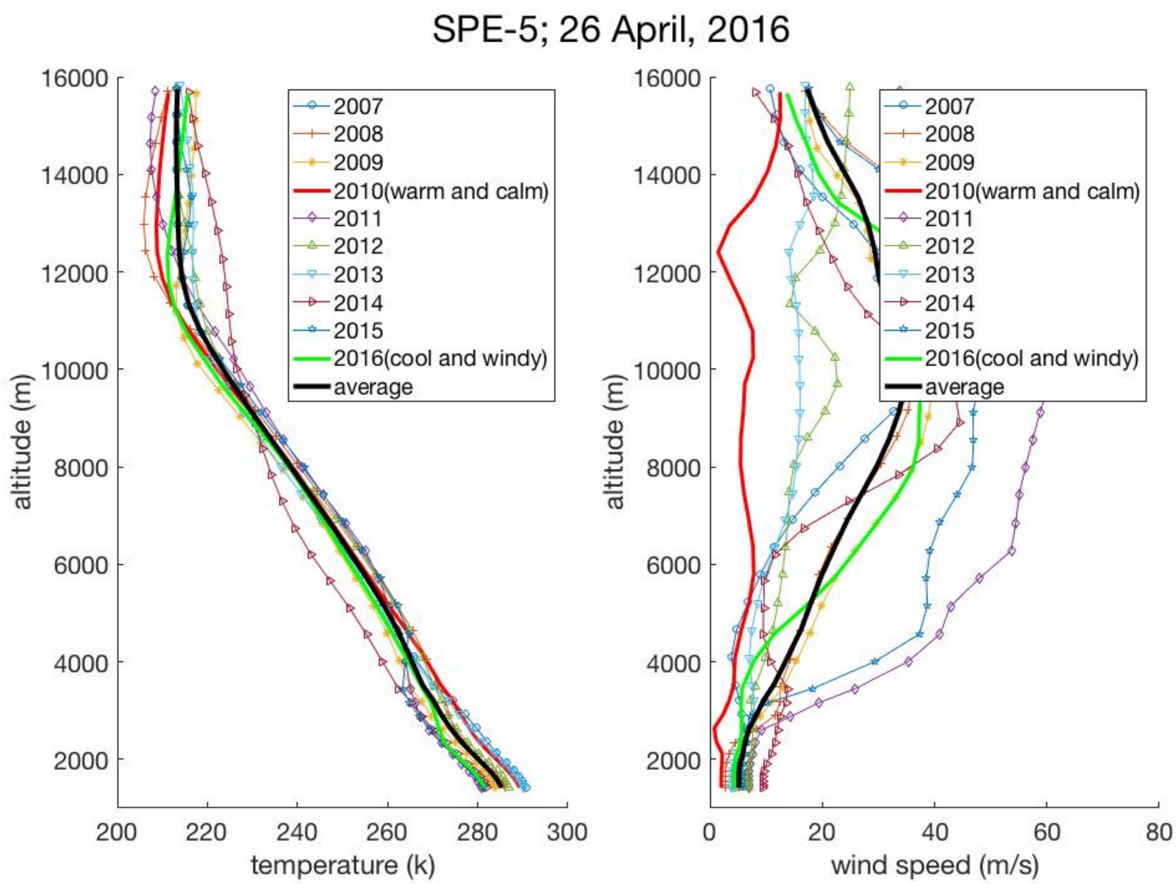

Figure 2.5. Temperature and wind speed profile on the SPE-5 date.

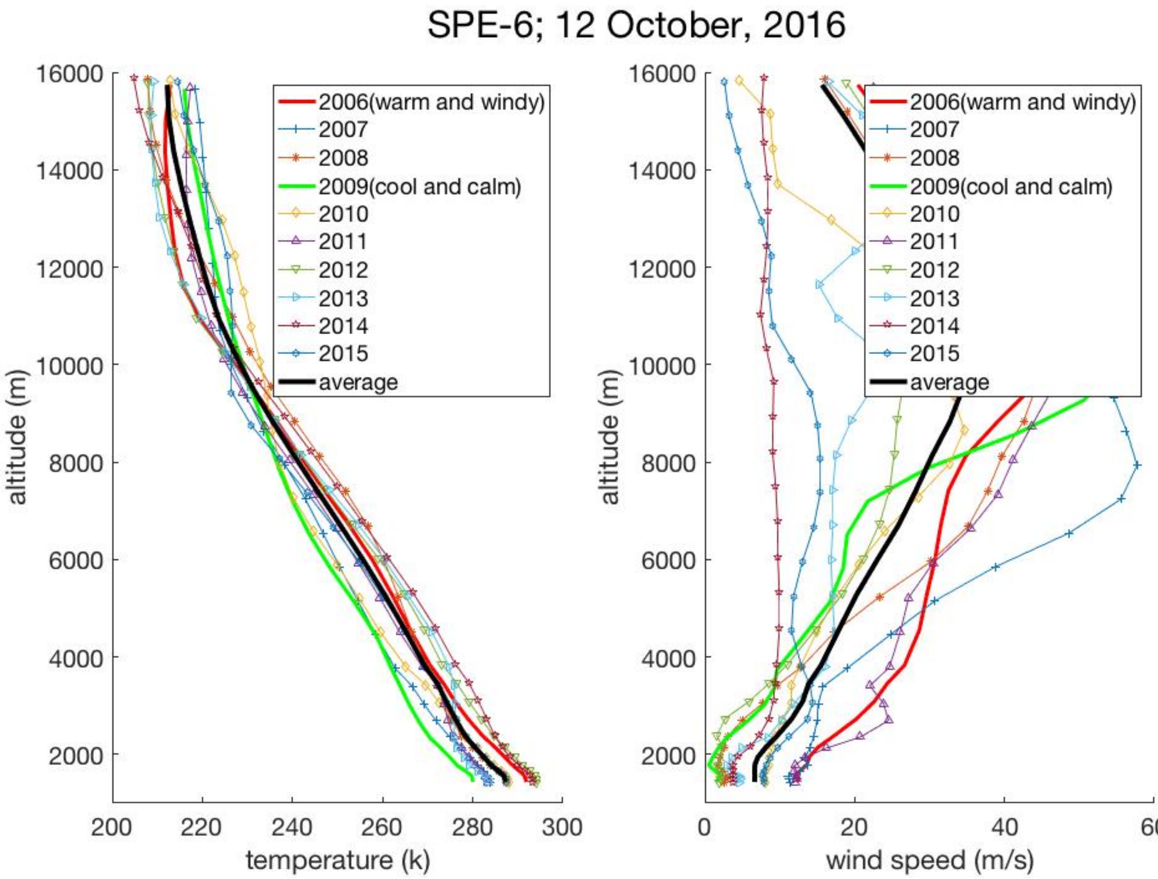

Figure 2.6. Temperature and wind speed profile on the SPE-6 date.

Table 2.1. 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 windy
SPE-4P	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

Chapter 3

Results

In this section, we present the results of the Atmospheric Predictions using the methods previously outlined. Figures 3.1 - 3.18 show the logarithm peak pressure on the left panel (normalized to the peak pressure and corrected for radial distance from the source) and the computed Green's functions in the right panel. The thirty-two acoustic sensors are circled in white or red, and labeled according to station number. This station number corresponds to the labeled station numbers in the right panel. The origin of the SPE event is apparent by the high peak amplitude pressure located at $[x,y] \approx [942, 4920]$m in the local coordinates (also denoted by the white square). Note that the Green's functions have been convolved with a 6Hz Gaussian wavelet for display purposes. For each SPE event, we show the results for the ten-year average predictions as well as the two extrema predictions.

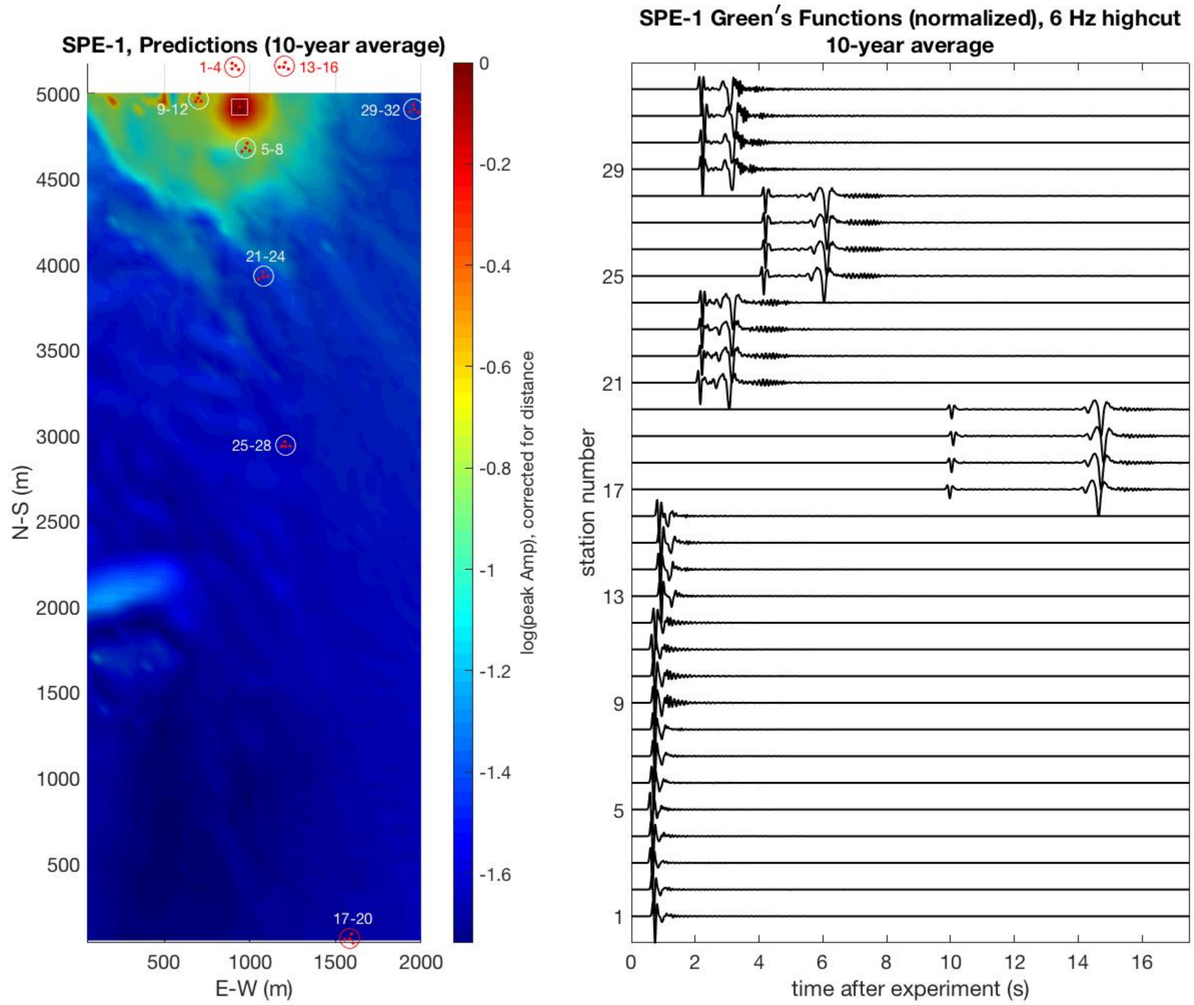

Figure 3.1. SPE 1 Predictions, ten-year average. The left panel shows the logarithm of the peak pressure, corrected for the radial distance from the source and the right panel shows the computed Green's functions convolved with a 6Hz Gaussian wavelet. Note that the station numbers on the right panel correspond to the labels in the left panel. The SPE event occurred at the local coordinates (942,4920)m which corresponds to latitude 37.221207N, longitude 116.0608674W. 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.

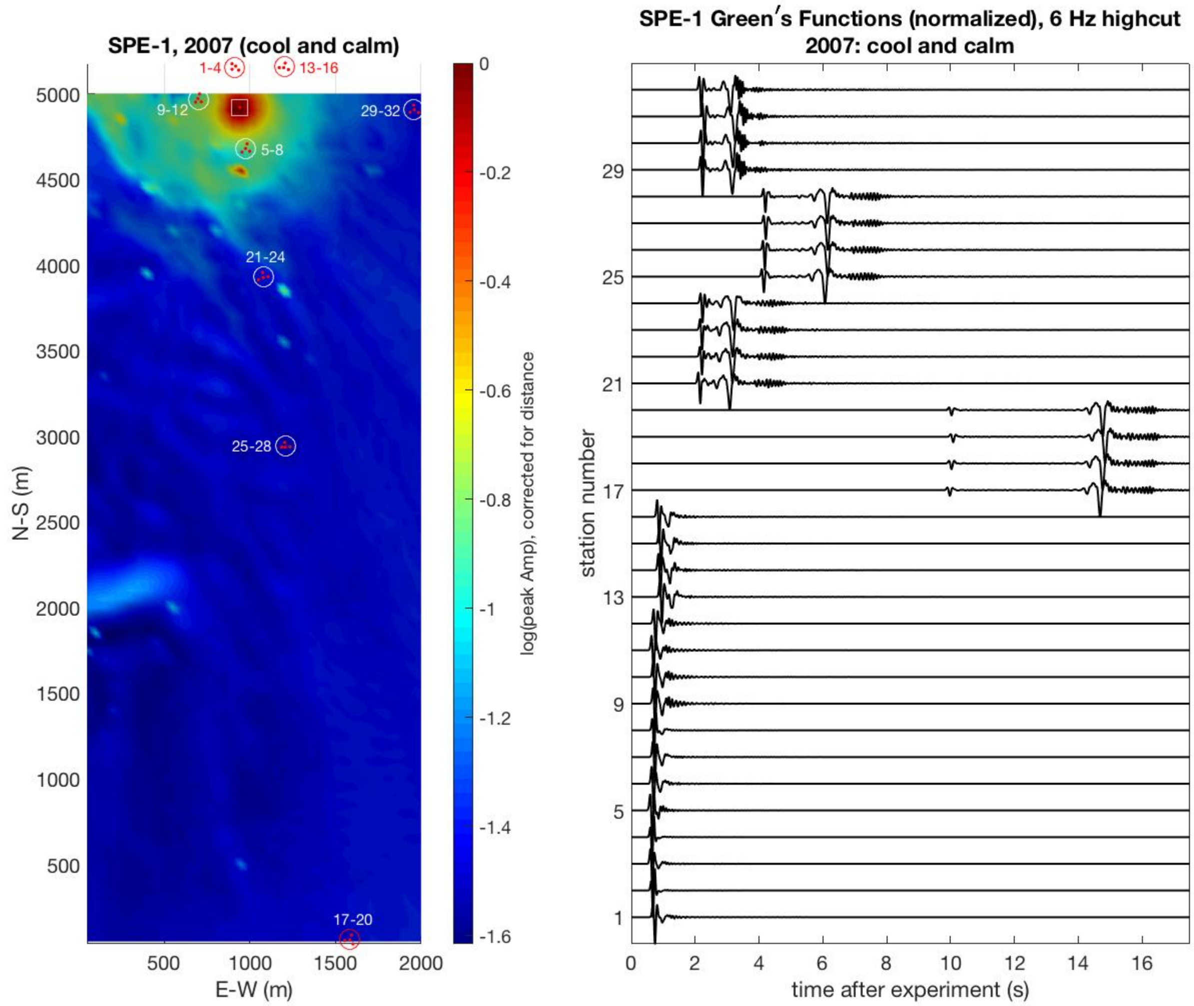

Figure 3.2. SPE 1 Predictions: 2007, cool and calm.

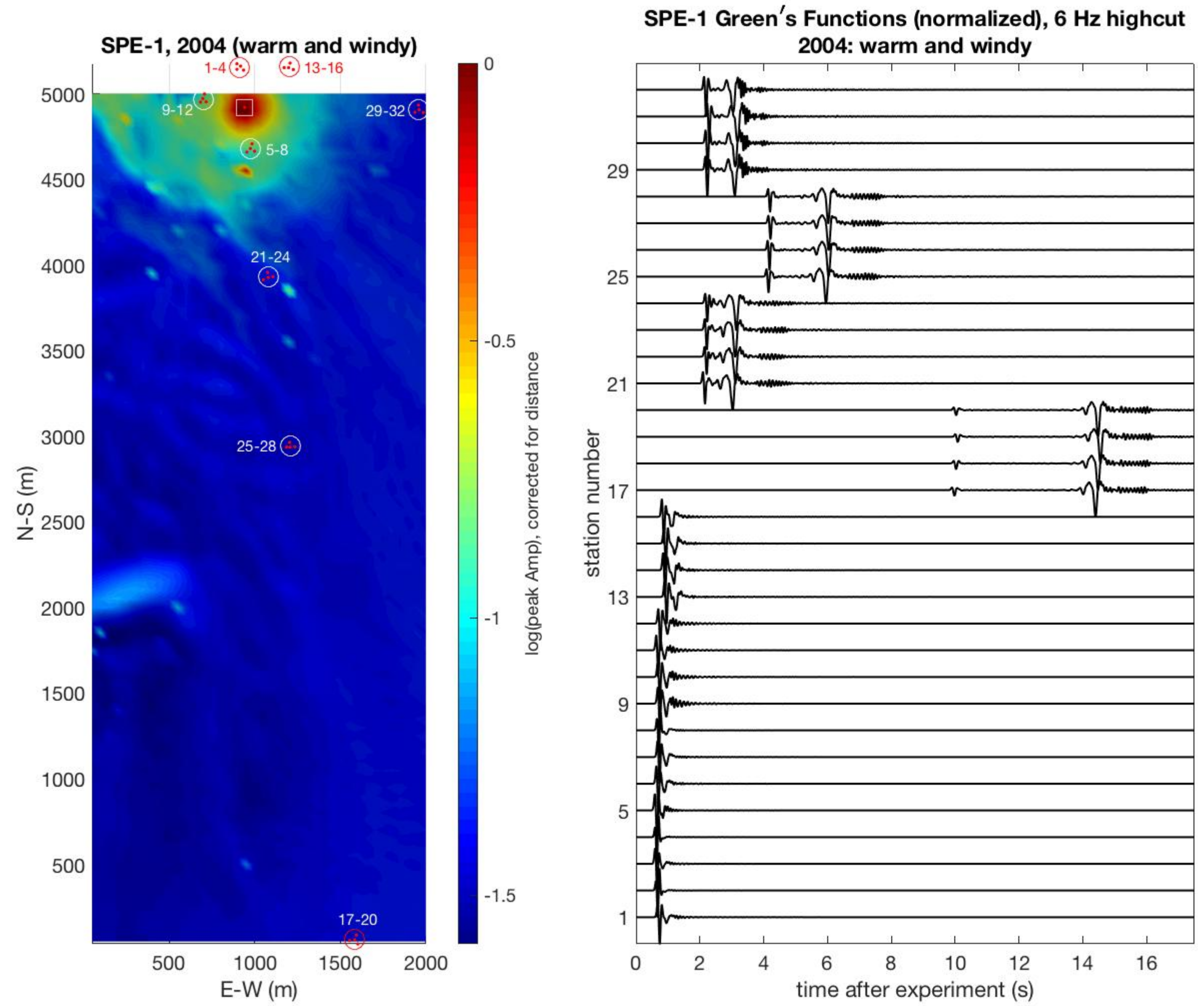

Figure 3.3. SPE 1 Predictions: 2004, warm and windy.

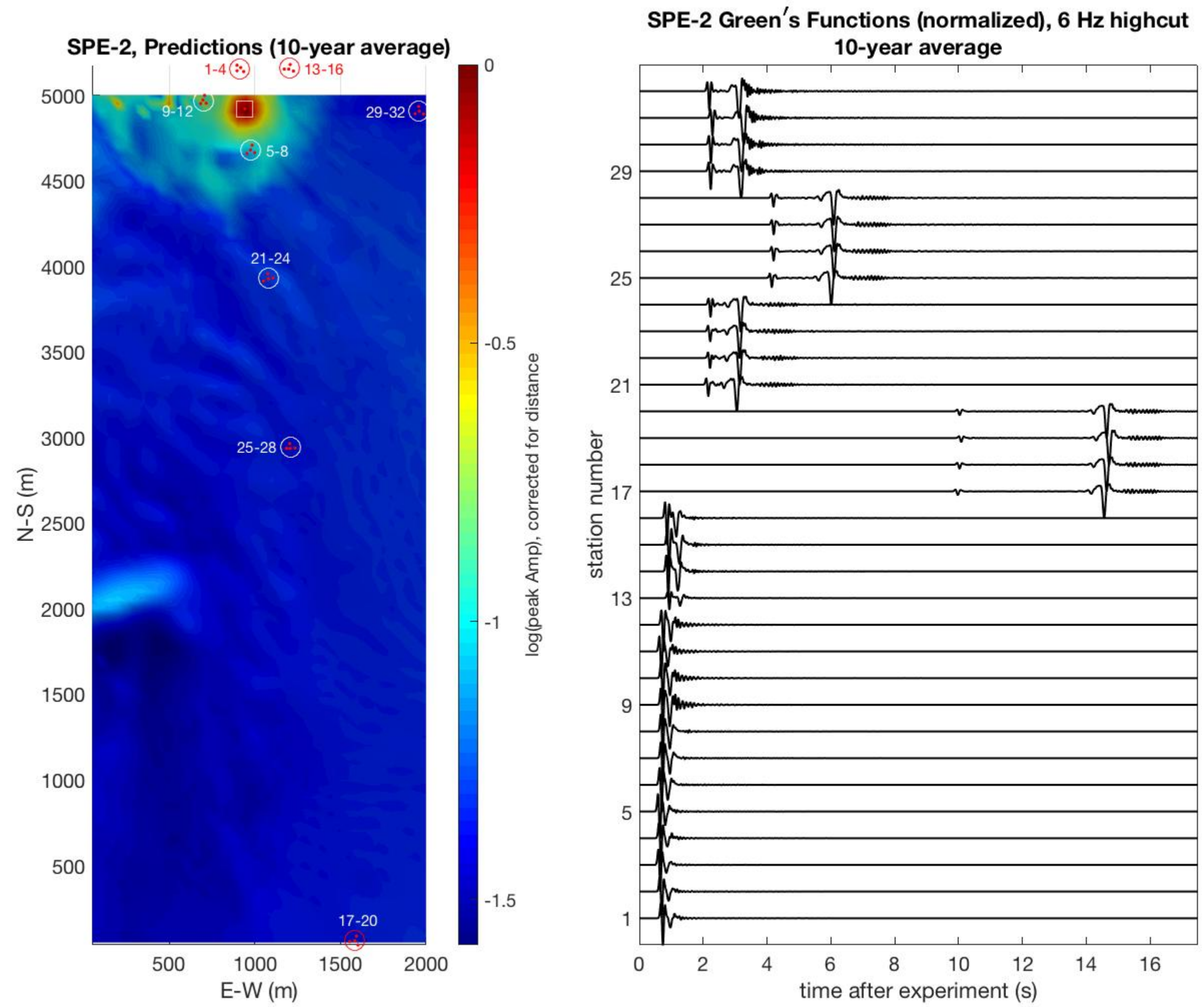

Figure 3.4. SPE 2 Predictions: ten-year average.

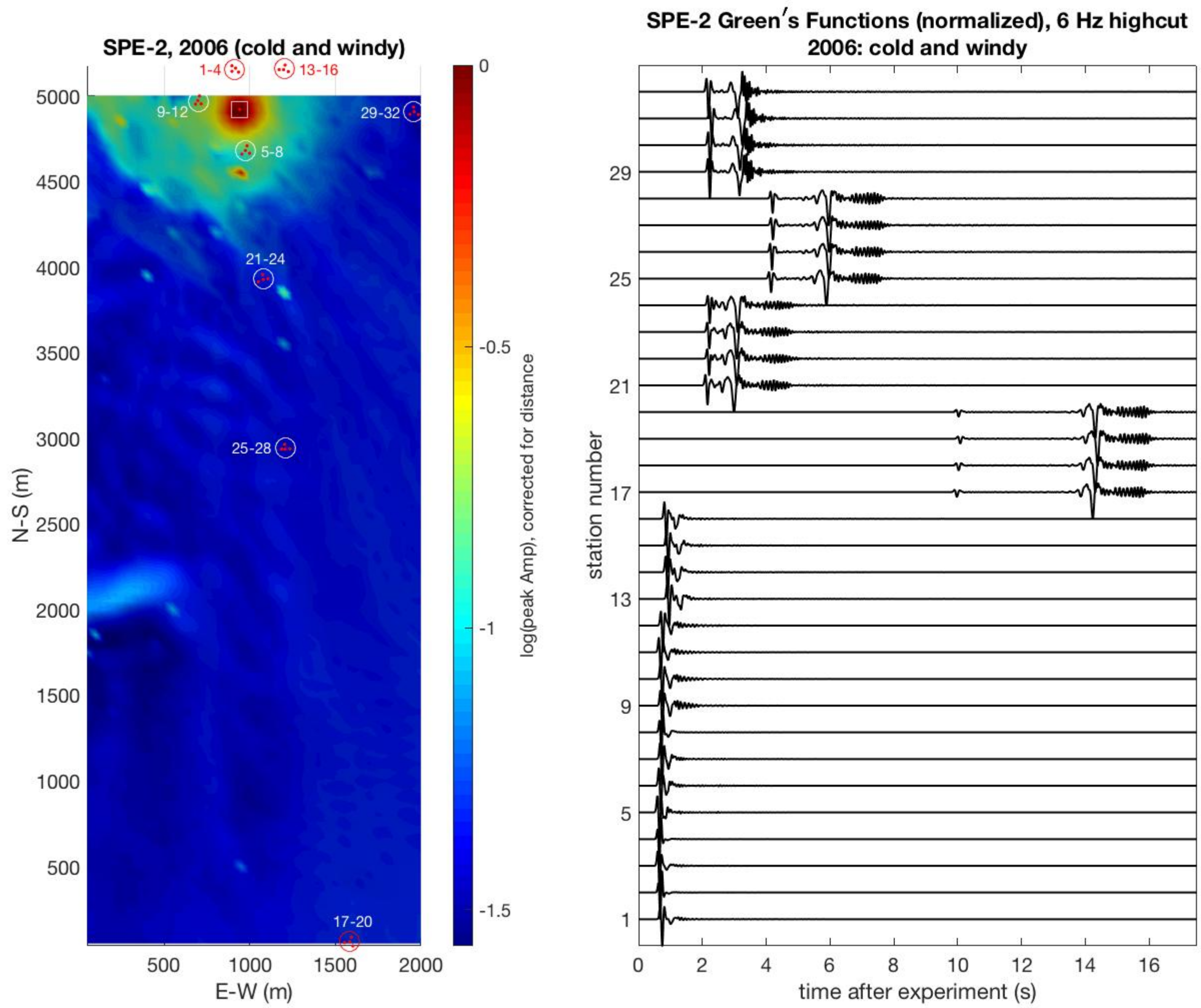

Figure 3.5. SPE 2 Predictions: 2006, cool and windy.

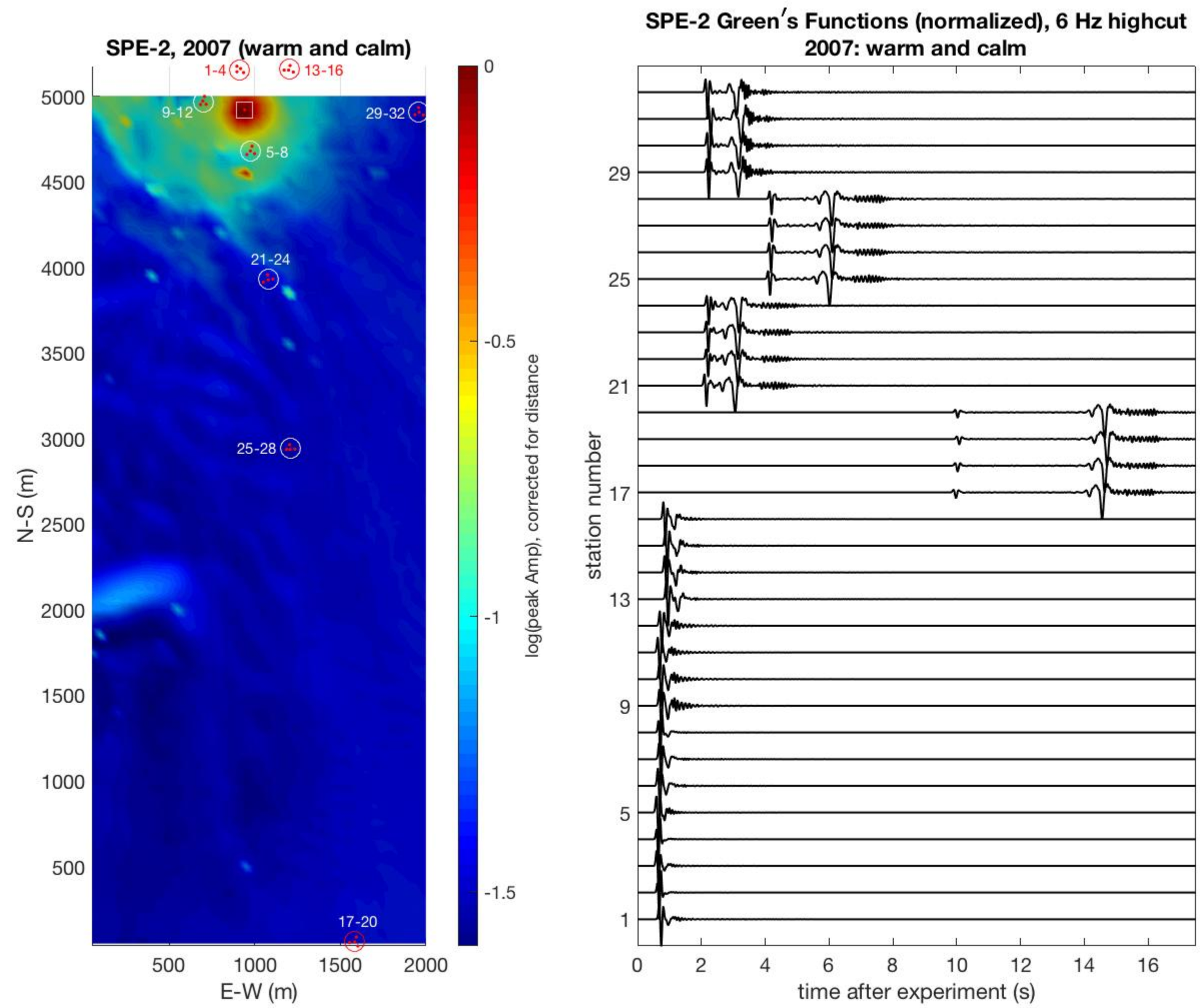

Figure 3.6. SPE 2 Predictions: 2007, warm and calm.

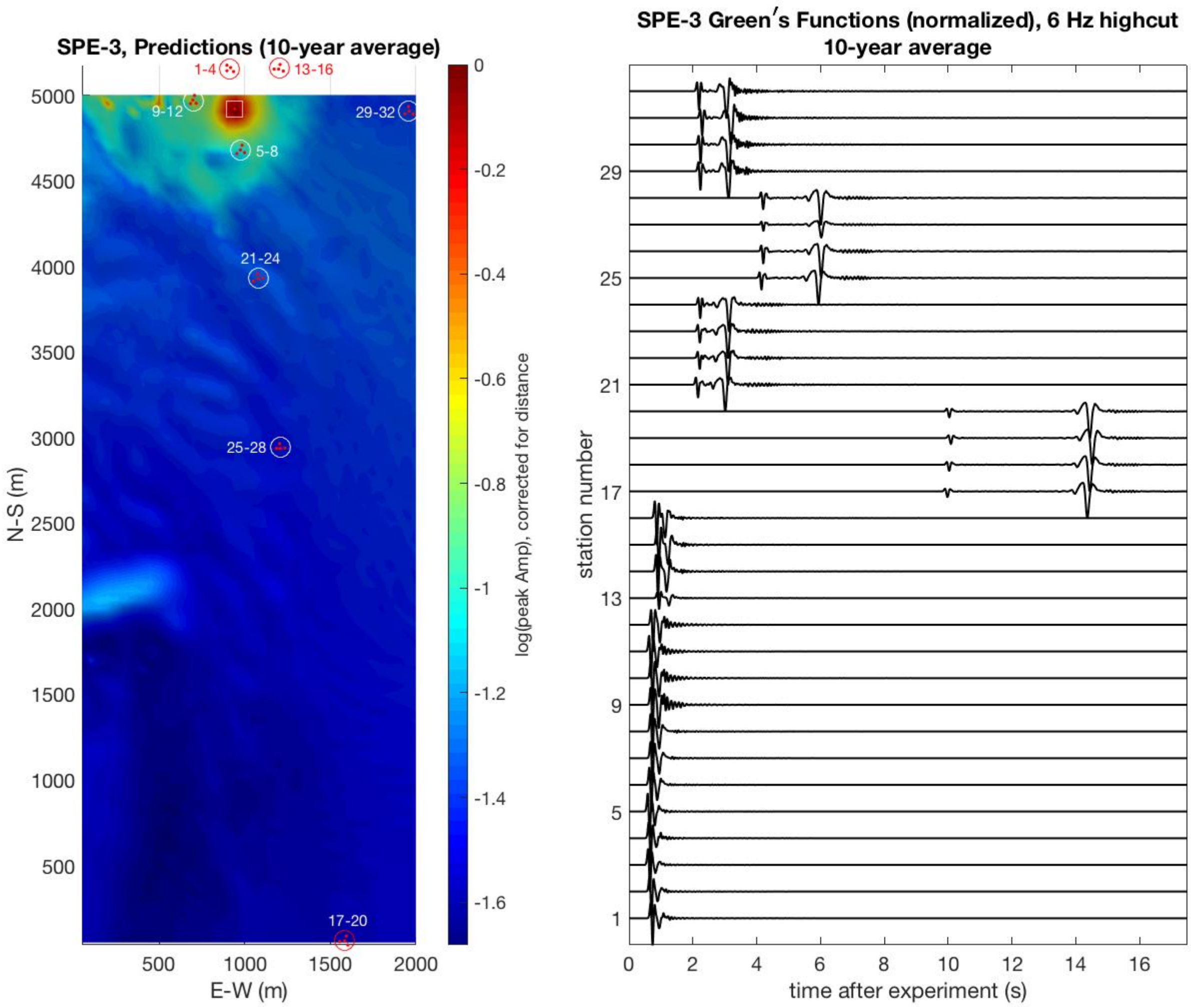

Figure 3.7. SPE 3 Predictions, ten-year average.

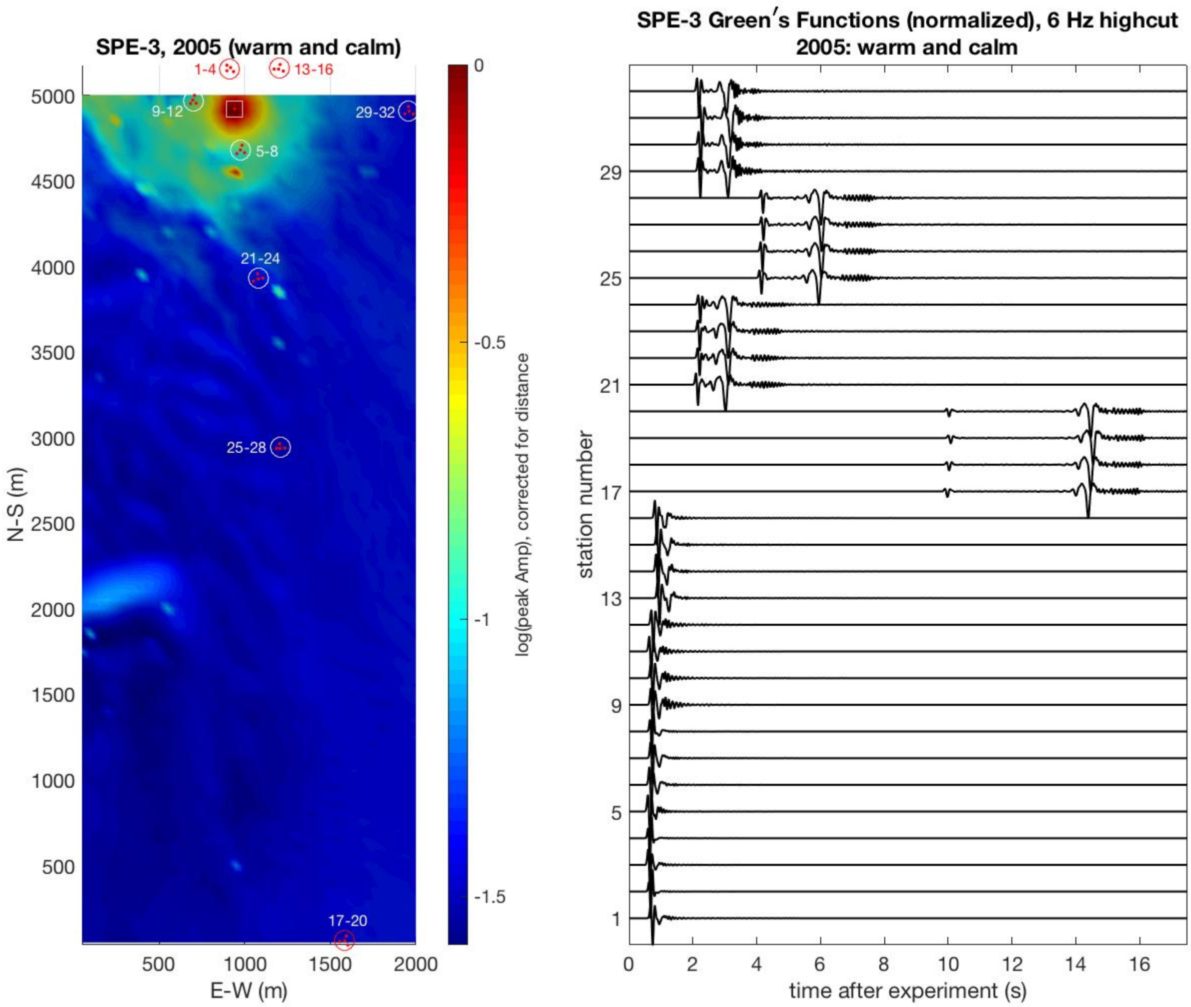

Figure 3.8. SPE 3 Predictions; 2005, warm and calm.

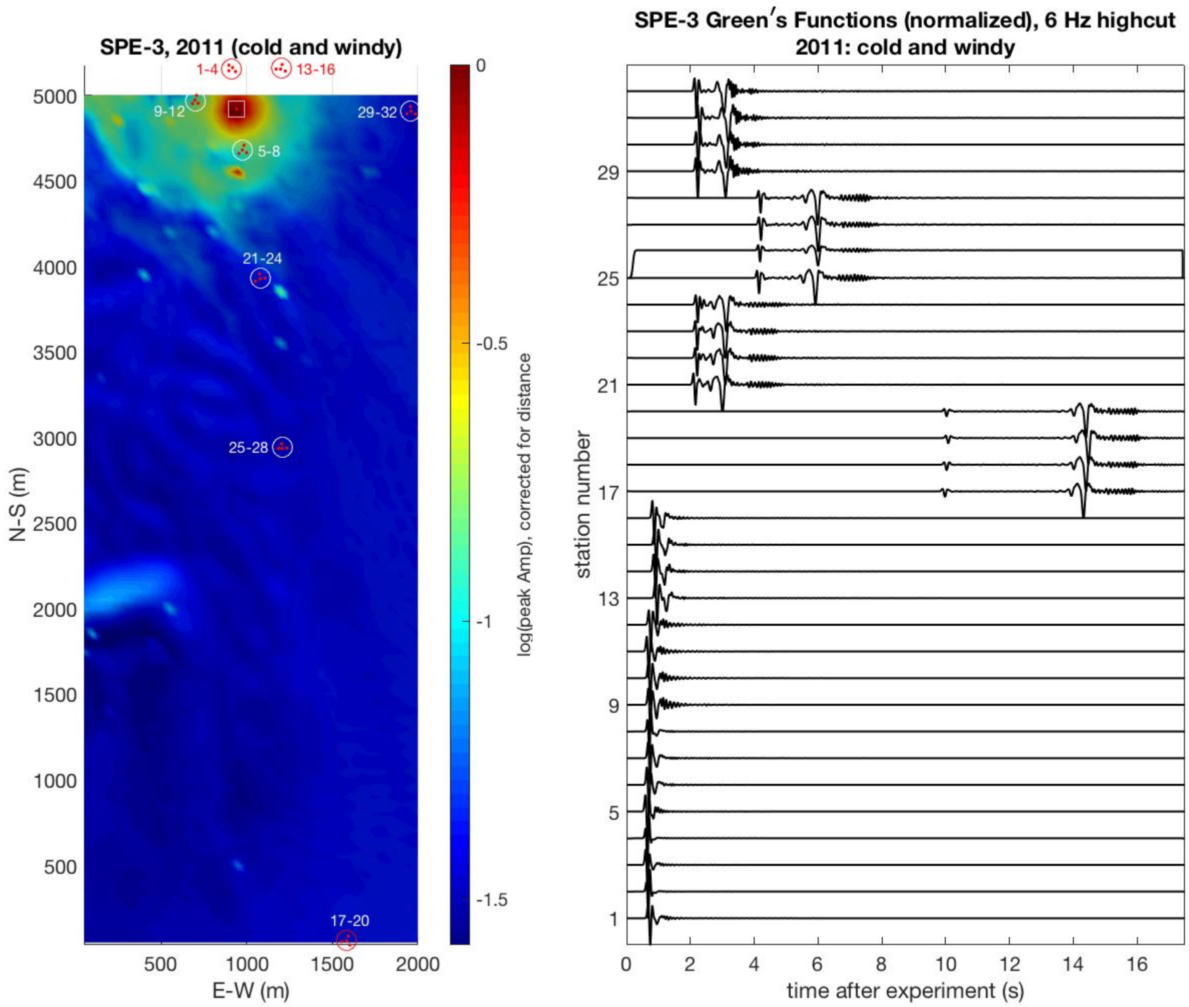

Figure 3.9. SPE 3 Predictions; 2011, cool and windy.

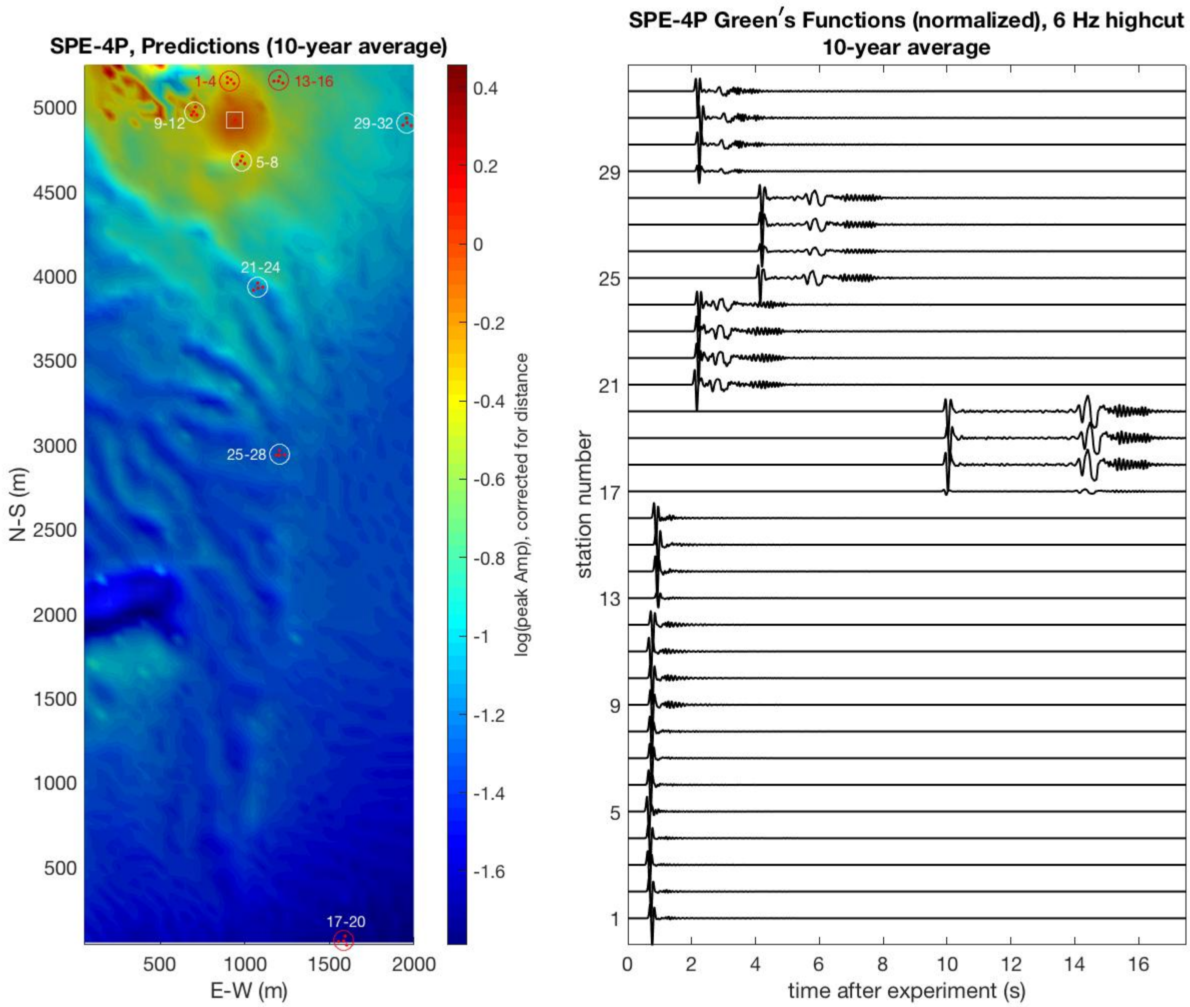

Figure 3.10. SPE 4P Predictions, ten-year average.

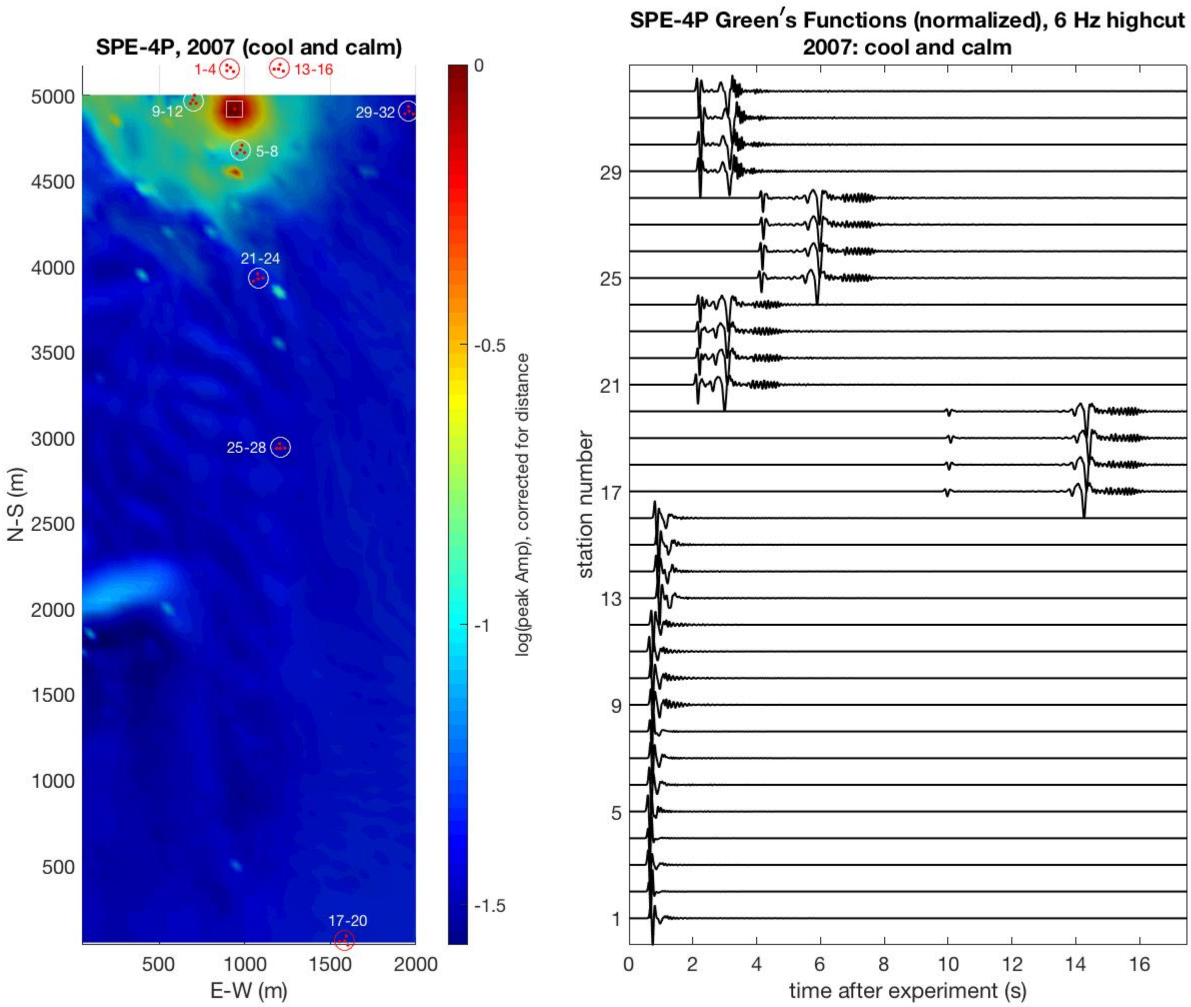

Figure 3.11. SPE 4P Predictions; 2007, cool and calm.

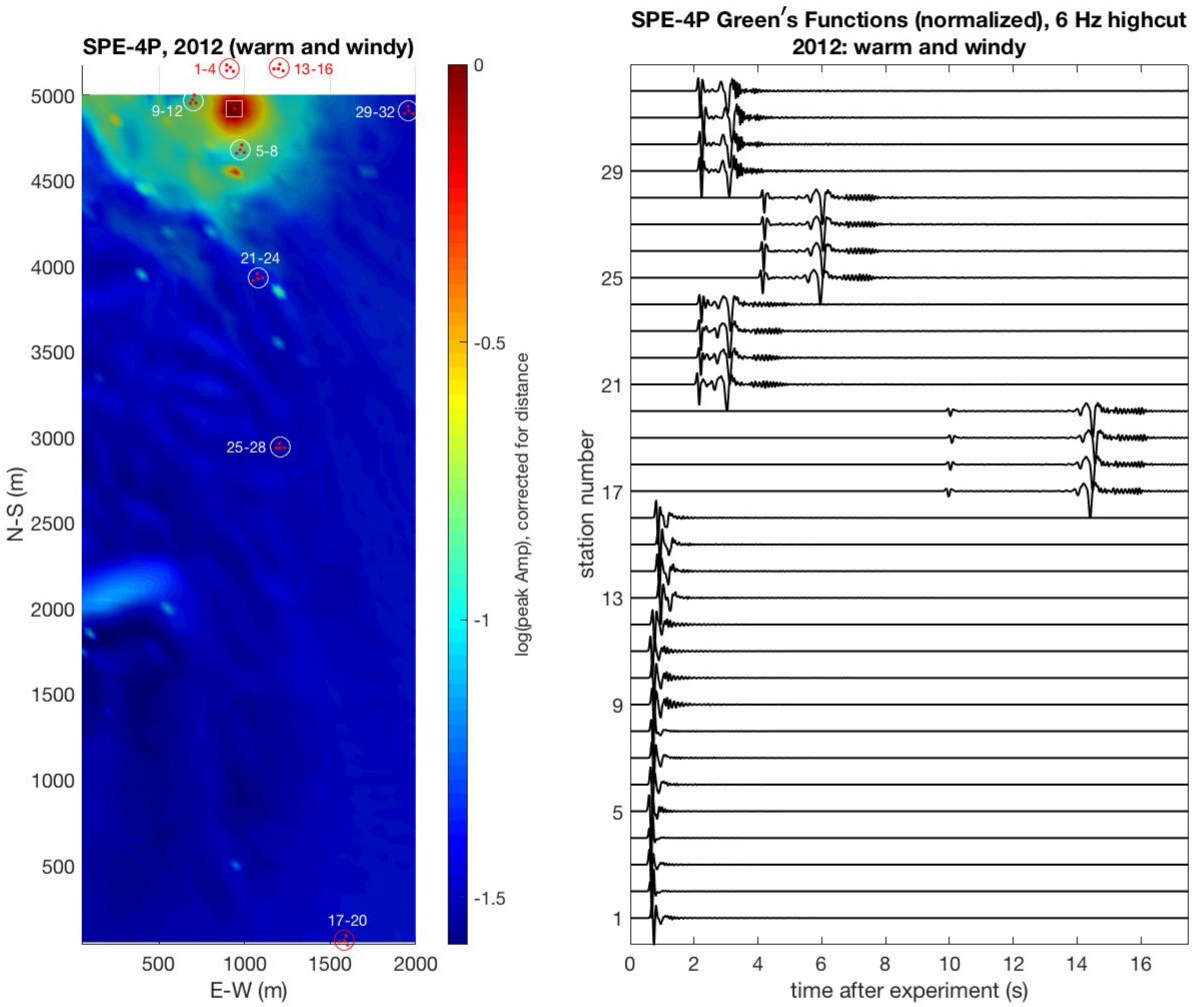

Figure 3.12. SPE 4P Predictions; 2012, warm and windy.

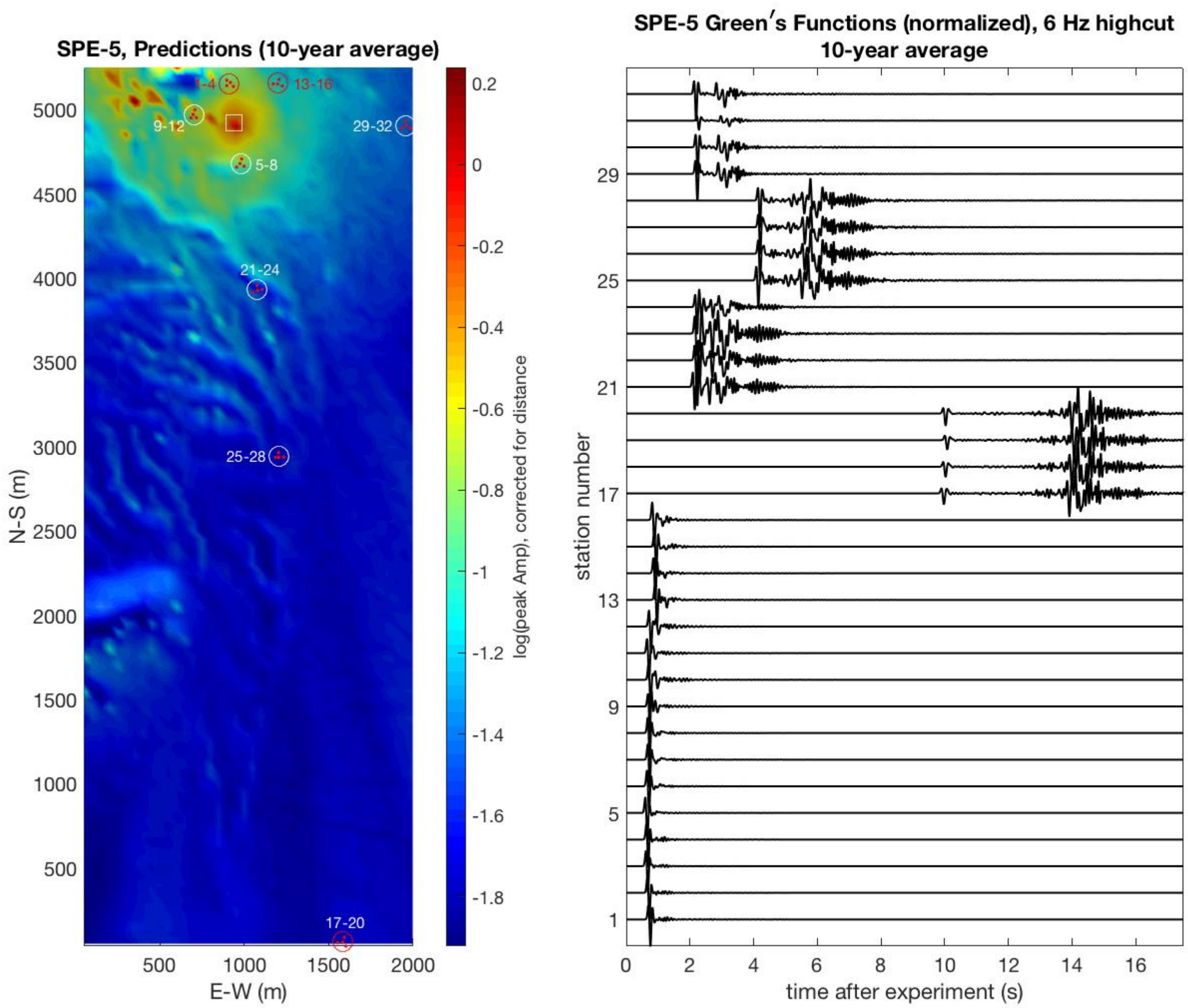

Figure 3.13. SPE 5 Predictions, ten-year average.

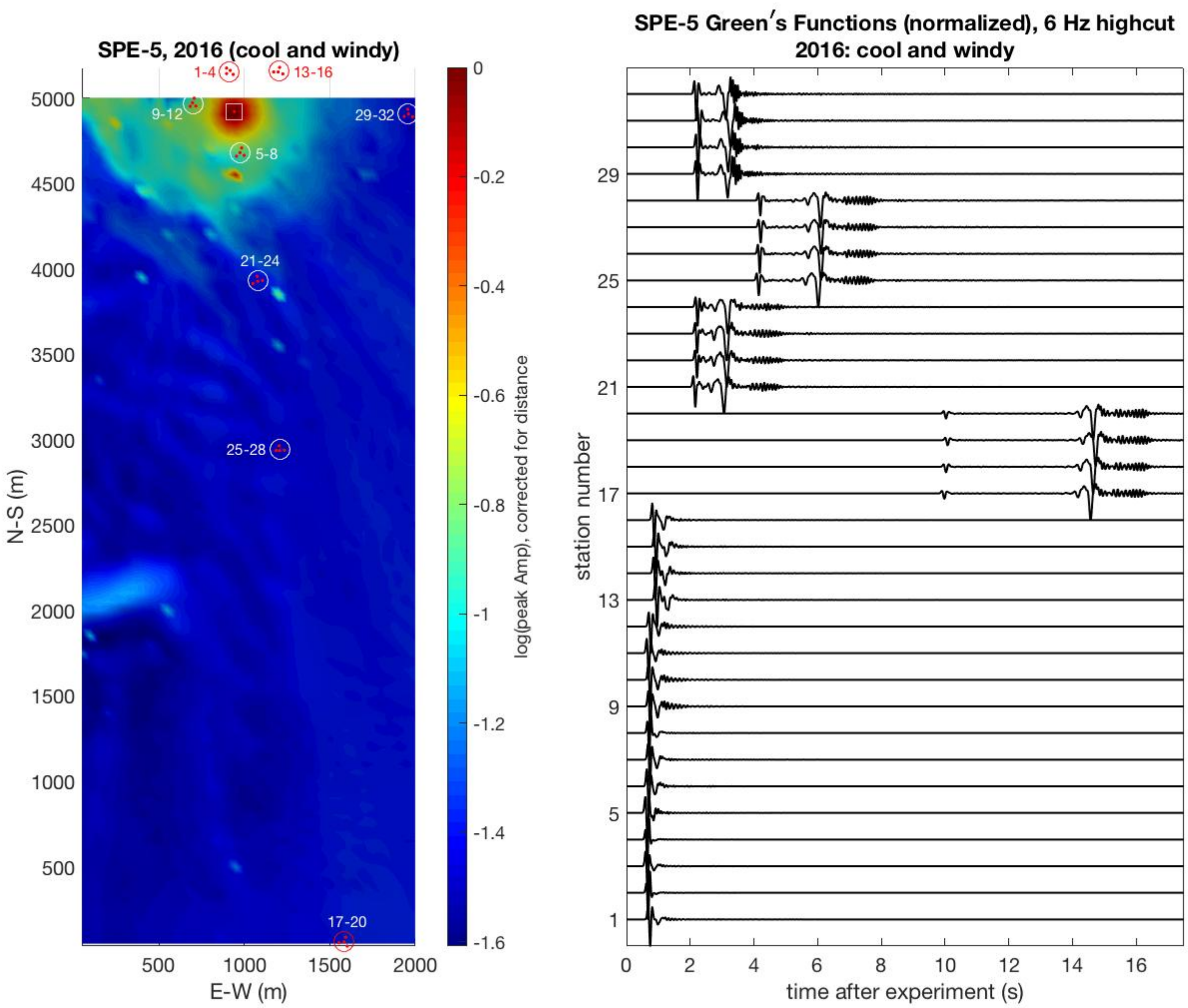

Figure 3.14. SPE 5 Predictions; 2016, cool and windy.

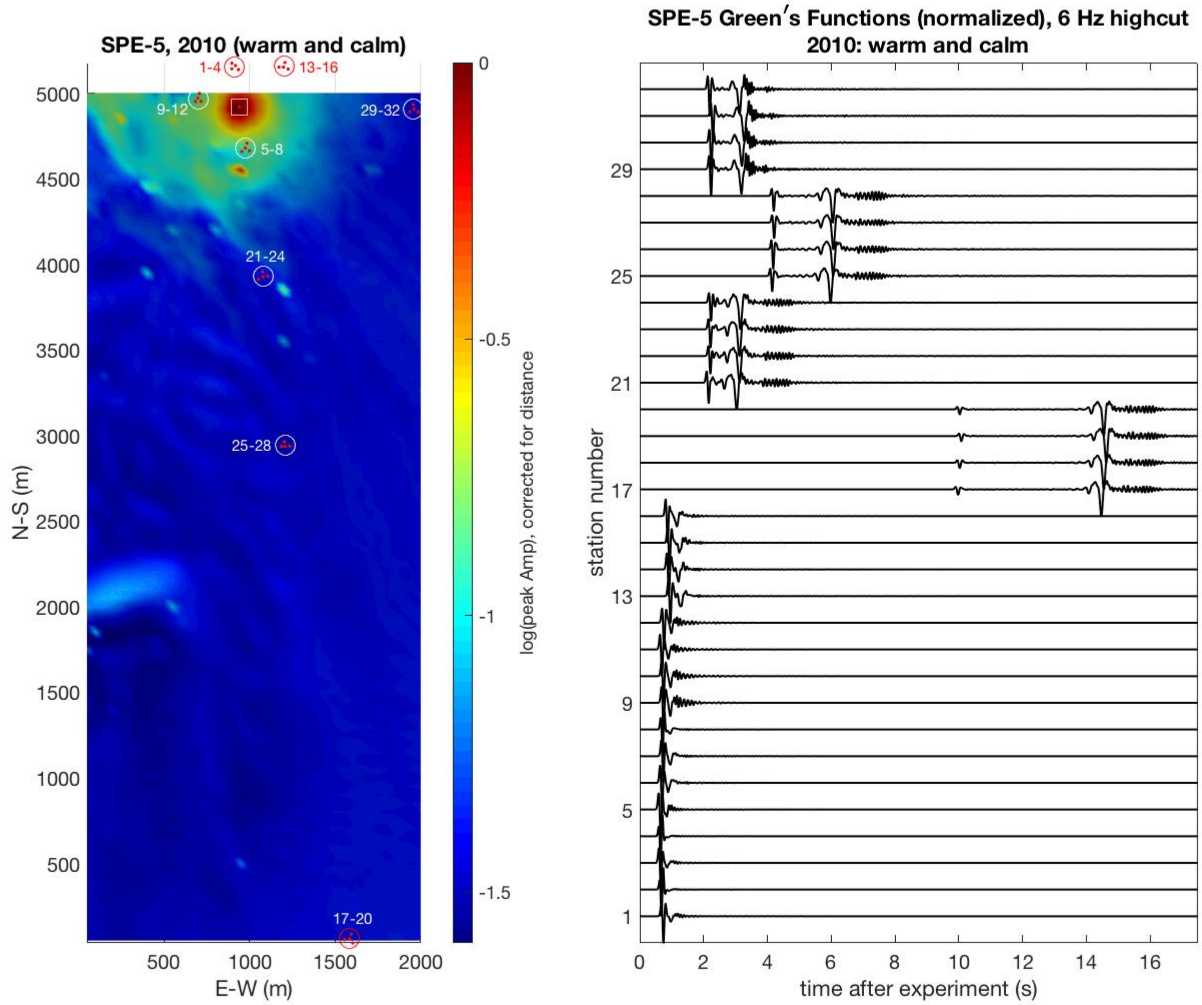

Figure 3.15. SPE 5 Predictions; 2010, warm and calm.

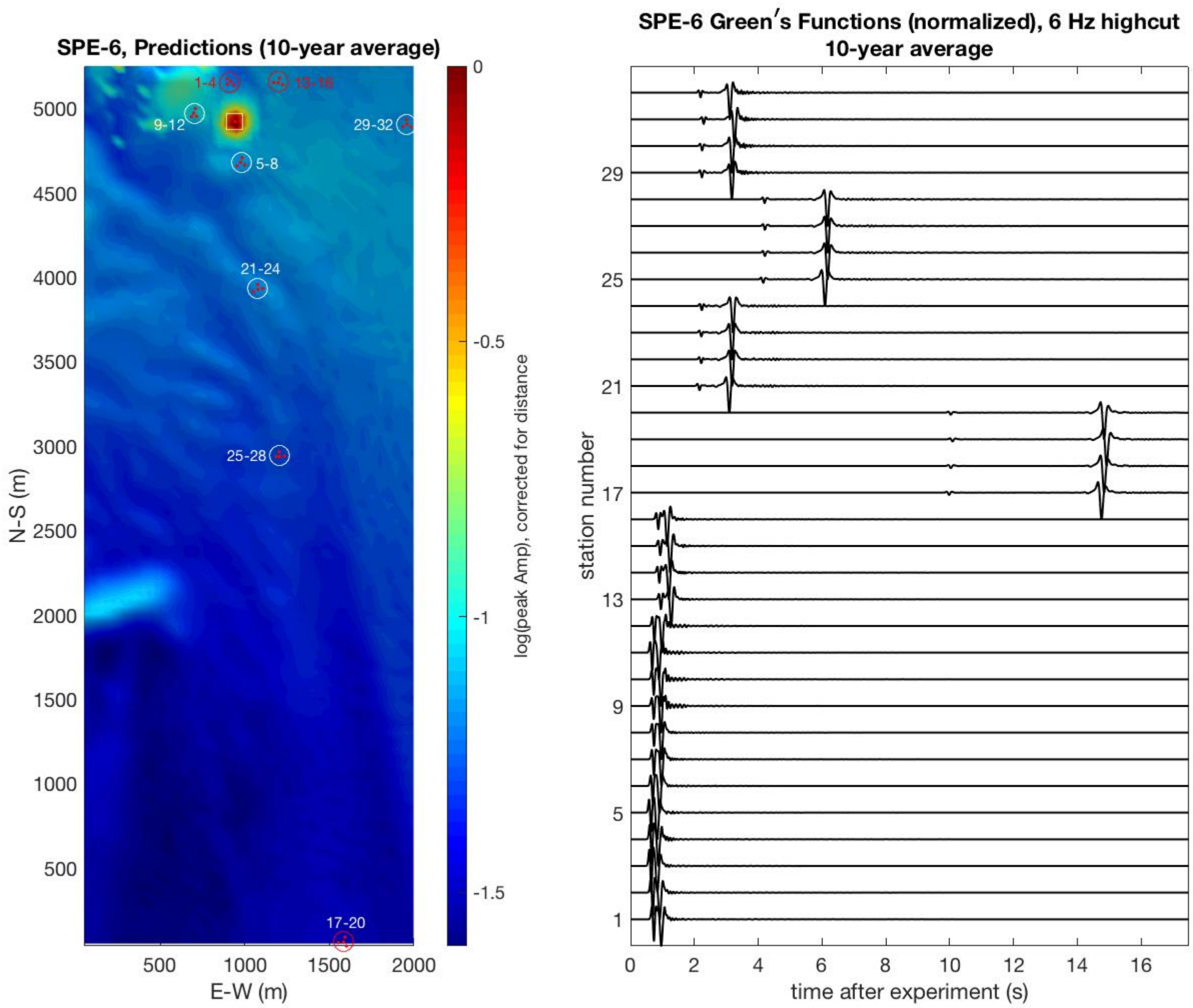

Figure 3.16. SPE 6 Predictions, ten-year average.

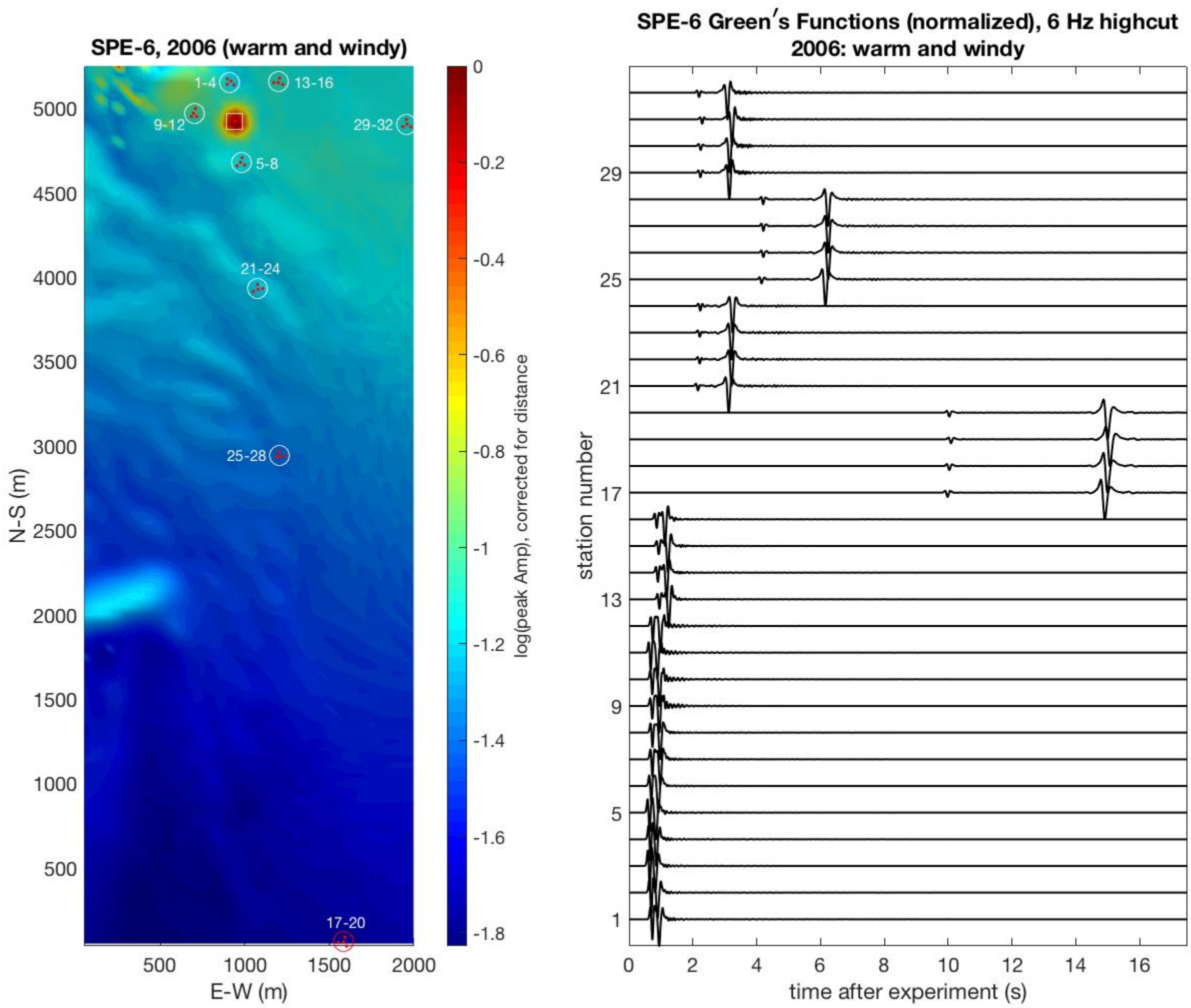

Figure 3.17. SPE 6 Predictions; 2006, warm and windy.

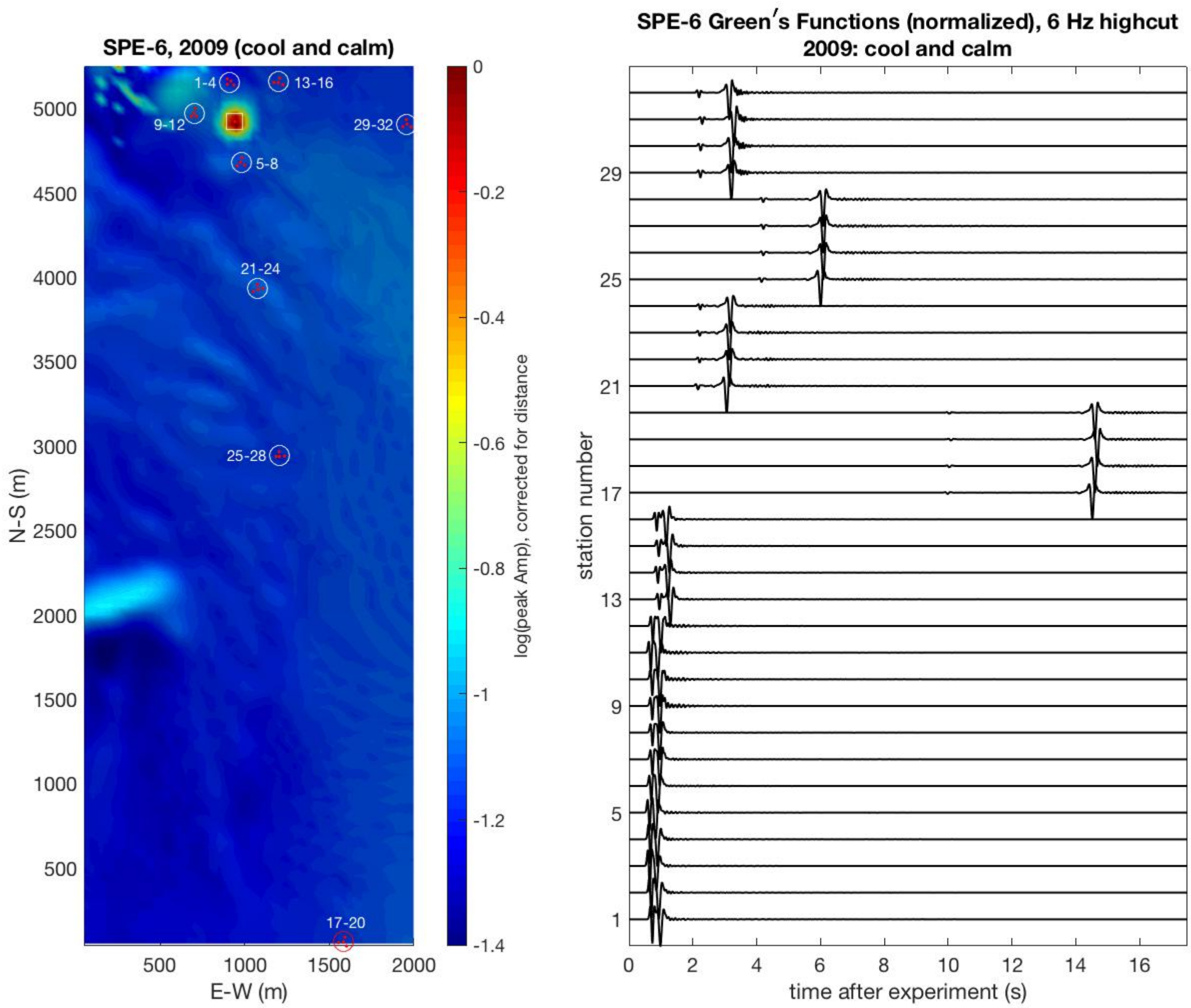

Figure 3.18. SPE 6 Predictions; 2009, cool and calm.

Chapter 4

Summary

The goal of the Atmospheric Predictions that we present here are 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 method we developed is to use roughly one hour of atmospheric data that's 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.

In the previous chapter, we show the average and extrema atmospheric models for all the SPE events. We also show the Green's functions for all thirty-two of the receiver stations, where the Green's functions have been convolved with a Gaussian wavelet (center frequency of 6 Hz) for display purposes. In order to better illustrate the effects of the differing atmospheric models on the Green's functions estimates, 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 the extrema in the atmospheric models whereas the station farthest from the experiment point would be the most effected. This is due to the differing travel paths: the longer the ray path of a given acoustic arrival, the more it will be influenced by bulk atmospheric properties.

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. 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.

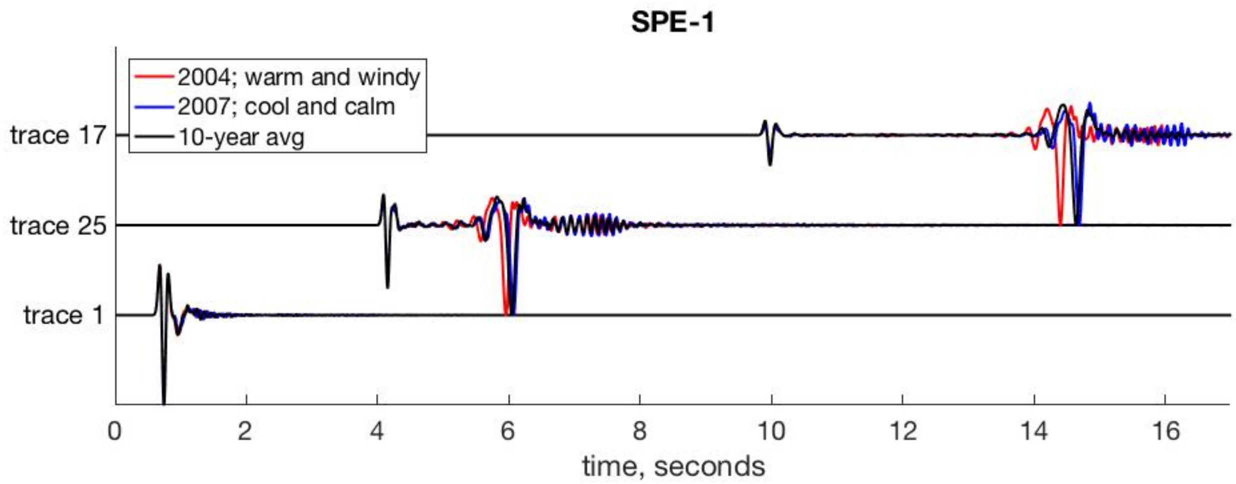

Figure 4.1. SPE-1 Green's functions for stations 1, 25, and 17. Note that for station 1, which is the closet station to the experiment site is virtually identical for all three atmospheric models, whereas station 17, which is the farthest station from the experiment site, is the most effected by variability in the atmospheric model.

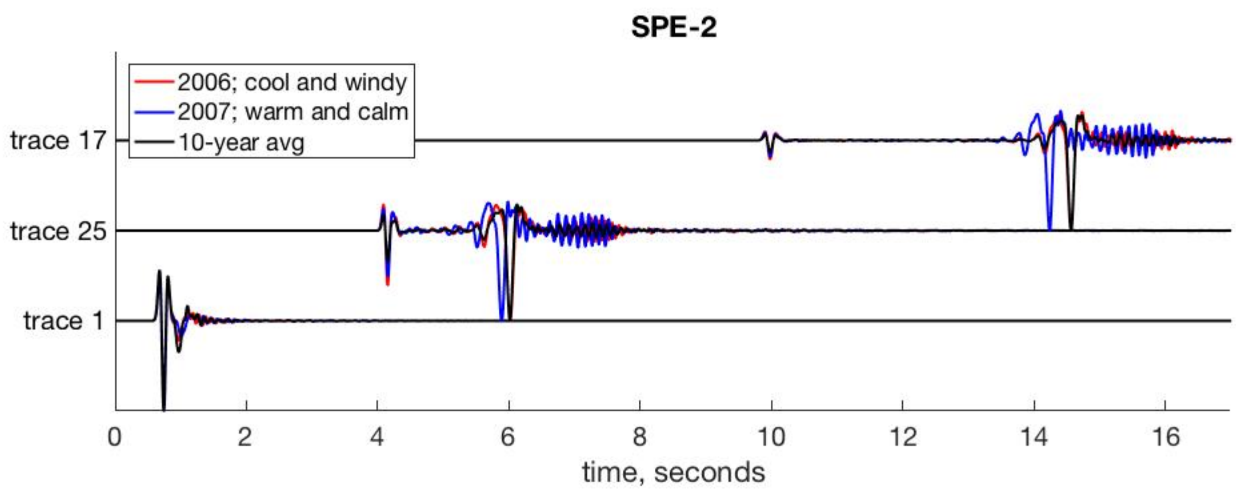

Figure 4.2. SPE-2 Green's functions for stations 1, 25, and 17.

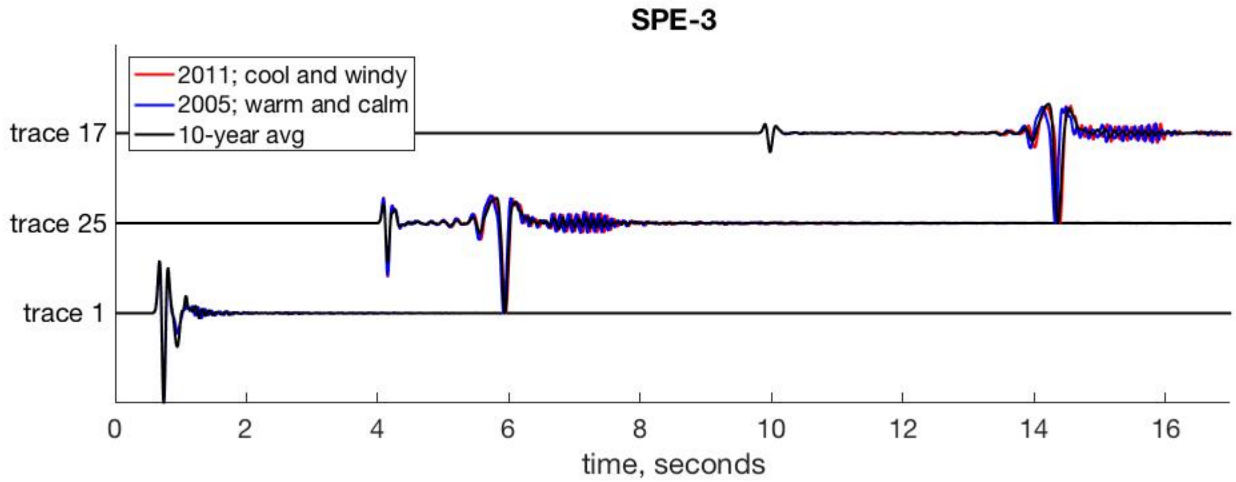

Figure 4.3. SPE-3 Green's functions for stations 1, 25, and 17.

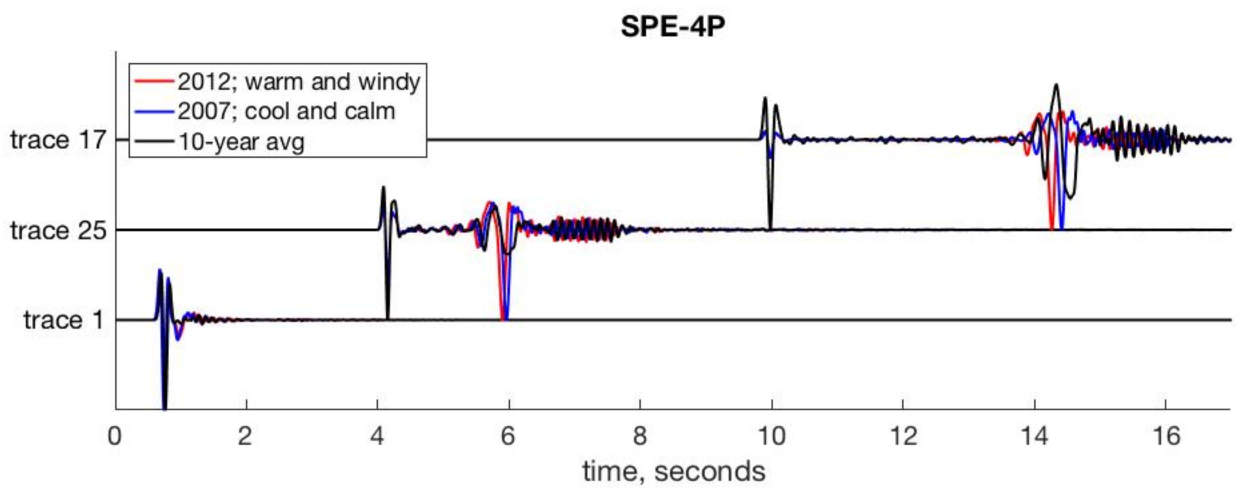

Figure 4.4. SPE-4P Green's functions for stations 1, 25, and 17.

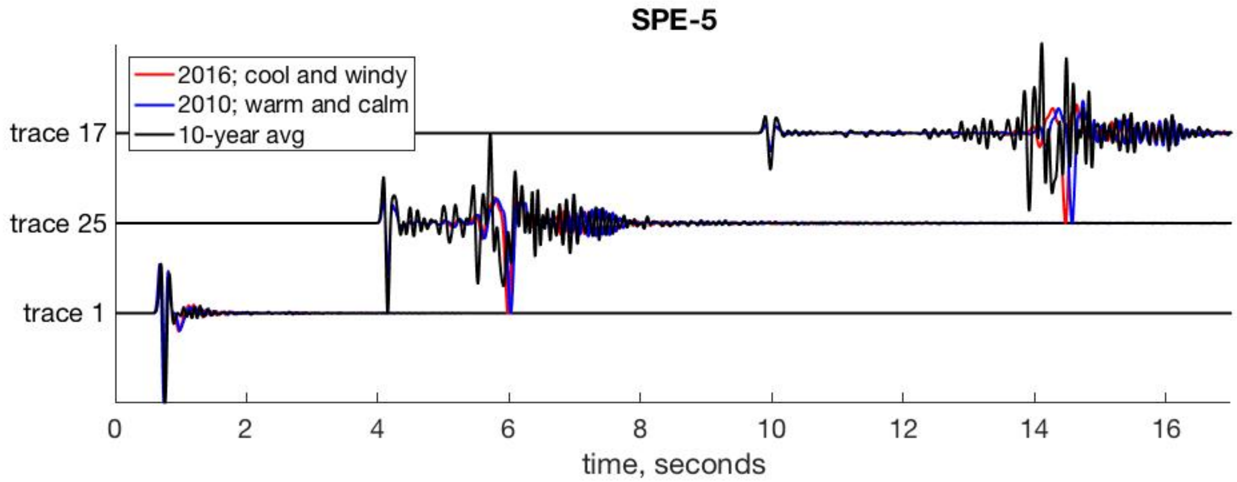

Figure 4.5. SPE-5 Green's functions for stations 1, 25, and 17.

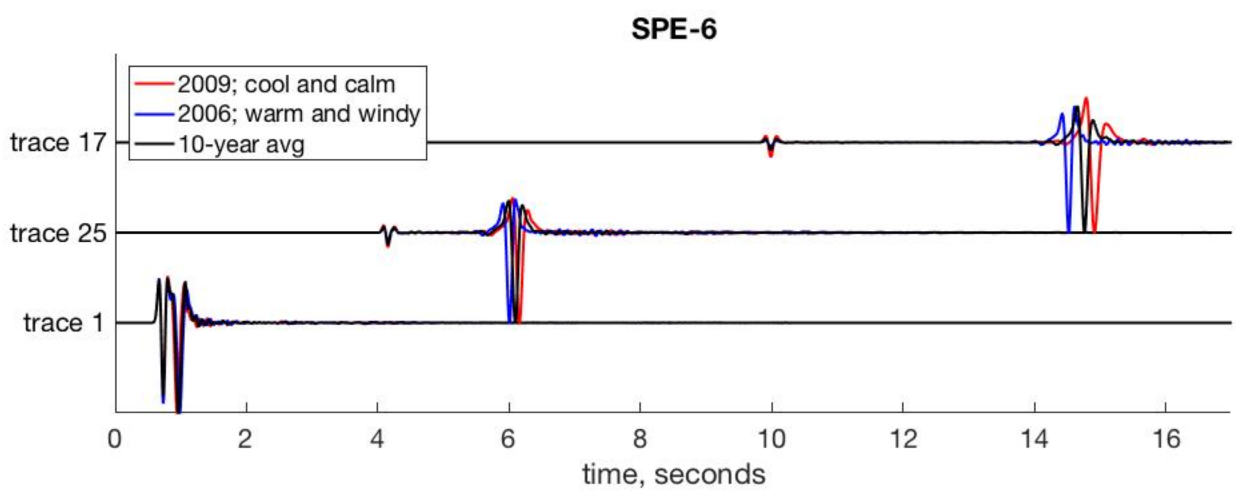

Figure 4.6. SPE-6 Green's functions for stations 1, 25, and 17.

Chapter 5

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