User Manual for *SlugHeat:*

A software for processing data collected by a heat-flow measurement system

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Contents

1 Introduction

This is a tutorial for setting up and processing data collected by a heat-flow measurement system used in the sedimented seafloor using the MATLAB program, *SlugHeat*. This tutorial corresponds with the 2022 update of *SlugHeat*. Full long-files that record all data collected by the heat-flow probe, including multiple penetrations, should first be run through *SlugPen* (a parsing software corresponding to *SlugHeat*) to generate individual data files for each penetration separately, which can then be run through *SlugHeat*. To use the parsing software, *SlugPen*, see `*SlugPen tutorial*`

Processing steps in *SlugHeat* include defining input parameters, calculating equilibrium temperatures of sediment with depth, calculating *in-situ* thermal conductivity values of sediment with depth, and calculating heat flow at the seafloor. *SlugHeat* also includes multiple optional uncertainty assessments including an analysis to test sensitivity of results with varying layer properties and analysis of uncertainty in the linear regressions that are used to calculate heat flow. There are numerous opportunities for inspection and modification of data and results before, during, and after processing. All processing results and input parameters are saved to text files, MAT files, and optional Excel files.

Included in this tutorial is an outline of the steps through a general workflow in *SlugHeat* for a single penetration. The example penetration `ExamplePen_SlugHeatTutorial` will be used. For more details regarding the *SlugHeat* code, see `*SlugHeat pseudo-code*`. For more details regarding the *SlugHeat* processing methods and theory, see `*SlugHeat methods paper*`

2 System requirements

1. MATLAB Version 2020b or later (Version 2022b or later is preferred)
2. Correct directory in MATLAB Path. This directory must include all of the following functions and folders to run *SlugHeat* correctly:
   (a) Main application (`SlugHeat`)
   (b) All functions (as `.m` files), including:
      - `cbValueChange.m`
      - `ChiSquaredFit.m`
      - `DiscardSensorsNoHP.m`
      - `FrictionalDecay.m`
      - `GetFiles.m`
      - `HeatFlowAnalysis.m`
      - `HeatFlowRegression.m`
      - `HeatPulseDecay.m`
      - `InitializeProcessing.m`
      - `InitializeProgram.m`
      - `PlotCheckboxes.m`
      - `PlotFrictionalDecay.m`
      - `PlotHeatFlowAnalysis.m`
      - `PlotHeatPulseDecay.m`
      - `PlotHeatFlowRegression.m`
      - `plotLayout.m`
      - `PlotRawData.m`
      - `PrintBullardResults.m`
      - `PrintFricResults.m`
      - `PrintHeaderResults.m`

    - `PrintHeatPulseResults.m`
    - `PrintNewPar.m`
    - `PrintParametersResults.m`
    - `PrintStatus.m`
    - `ReadCalFile.m`
    - `ReadParFile.m`
    - `ReadPenFile_withPulse.m`
    - `ReadPenText_withPulse.m`
    - `ReadTAPFile.m`
    - `ReadTAPText.m`
    - `RemoveSensors.m`
    - `ResetAll.m`
    - `SensitivityAnalysis.m`
    - `SplitDecays.m`
    - `TempCorrection.m`
    - `updateLabels.m`
    - `xAlign.m`
    - `xAlignHPD.m`

(c) Default input files:
    - PAR file (`SlugHeat22.par`)
    - MAT file (`SlugHeat22.mat`)

(d) Auxiliary applications (as `.mlapp` files)
    - `BottomWaterAuxApp.mlapp`
    - `SetParams.mlapp`
    - `SetUpSensAnalysis.mlapp`
    - `UserBWTAuxApp.mlapp`
    - `DiscardData.mlapp`

(e) Graphics subfolder (`images`), including:
    - `arrow.png`
    - `slugheatLogo.png`
    - `UCSC-HydrogeologyLogo.jpg`
    - `x.png`

3 System set up

1. Add current directory and all subdirectories to MATLAB path

To set up the system, you must first ensure that you are in the correct directory, with all functions and subdirectories needed to run *SlugHeat* (listed in section above). It is best to also add these functions and subdirectories to your MATLAB path. There are a few ways to do this once you are in the correct directory and in the MATLAB Command Window, as follows.

To *temporarily* add current directory to MATLAB path:
In MATLAB Command Window:

```
>> addpath(genpath(pwd))
```

To *permanently* add current directory to MATLAB path:
In MATLAB toolbar at top right of application:

(a) Select *'Set Path'* in MATLAB toolbar

(b) Select *'Add with Subfolders...'*

(c) Open current directory

(d) Press *'Save'*

To check that correct directory and all subfolders are in your MATLAB path:
In MATLAB Command Window:

```
>> path
```

2. Launch *SlugHeat*

Once you ensure all necessary functions and subdirectories are in your current working directory or in your MATLAB path, you can launch the program.

In MATLAB command window:

```
>> SlugHeat
```

The *SlugHeat* application immediately displays all tabs used for processing, though no data is loaded in or plotted yet (Figure 1).

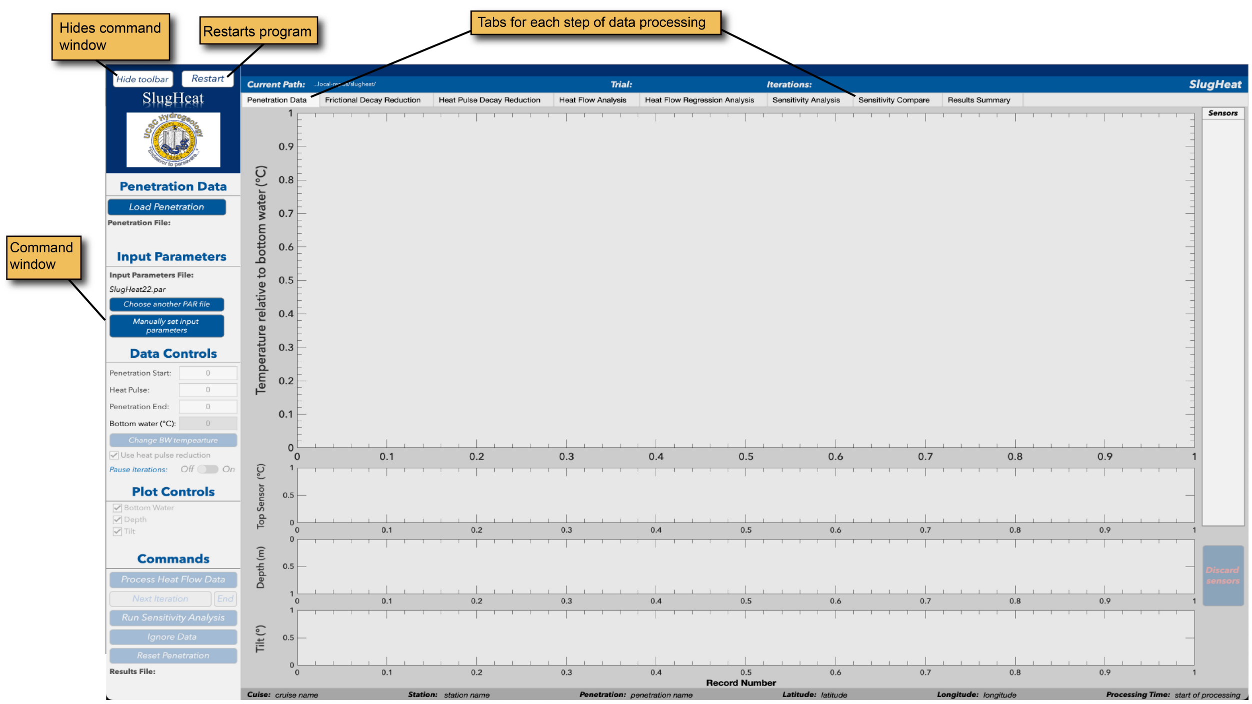


Figure 1: *SlugHeat* application launched. No penetration data is loaded in yet. Left hand side shows command window for data and plot control.

Command Window:
The command window on the left-hand side of the screen shows all penetration and processing information and controls. This includes input parameters, penetration information, data and plot controls, and processing commands. To close this window, press *Hide toolbar* at top left of screen. To re-open this window, press the *arrow* on the left of screen. *Restart* button will begin *SlugHeat* from

beginning, resetting all plots and data to default properties before a penetration is loaded in. Each box on this command window defines data or plot controls, as follows:

Penetration Data:
Defines penetration data to be processed, including the name of the PEN file loaded in. See Figure 5 **(box 1)**

Input Parameters:
Controls parameters for data processing and calibration of temperature sensors, including files where default parameters are obtained. See Figure 5 **(box 2)**

Data Controls:
Controls processing specs such as timing of events that were defined in *SlugPen* (start of penetration, end of penetration, and firing of the calibrated heat pulse), bottom water temperature, and the use of a calibrated heat pulse to determine *in-situ* thermal conductivity. User can modify as needed. See Figure 5 **(boxes 3, 4, & 5)**

Plot Controls:
Controls which plots displayed and which are hidden. See Figure 5 **(box 6)**

Commands:
All commands for processing data (*detailed in subsequent sections*). See Figure 9

Tabs:
The rest of the screen to the right of the command window shows each tab for plotting, inspecting, modifying data, and analyzing heat flow results (Figure 1). Tabs include results from each major step in the heat flow data processing, including: *Penetration Data*, *Frictional Decay Reduction*, *Heat Pulse Decay Reduction*, *Heat Flow Analysis*, *Heat Flow Regression Analysis*, *Sensitivity Analysis*, and *Results Summary.*

4 Load in penetration data

Next, load in data recorded by the heat-flow probe from an individual penetration. This could be via:

- PEN (*.pen)* file: a penetration (PEN) file is a text file that defines all recorded temperatures as well as timings of significant events during the penetration, such as start and end of the penetration and the firing of a calibrated heat pulse. This might also include metadata such cruise, station, penetration, location, instrument specifications, and power of heat pulse used (in J).
- TAP (*.tap)* file: a temperature and pressure (TAP) text file is a text file that defines all recorded tilt and pressure (i.e., depth) measurements from a single penetration. This often corresponds with a PEN file.
- MAT (*.mat)* file: a MATLAB (MAT) file is a binary file that stores workspace variables. Data from a MAT file consists of all information generally recorded by both a PEN and a TAP file, such as temperatures, tilt, and pressures for an entire penetration. Data stored in this MAT file is already formatted for MATLAB and therefore does not require tedious reading in of text files.

Though PEN, TAP, and MAT files are all created in *SlugPen*, the minimum requirement for processing data in *SlugHeat* is a PEN file or a MAT file. *SlugHeat* will first ask you to select a PEN file that defines the penetration. Corresponding TAP and MAT files for that penetration will also be loaded in automatically if they exist in the same directory. If they do not exist, *SlugHeat* can still process temperature data recorded by a PEN file alone. In this example, penetration `ExamplePen_SlugHeatTutorial` is loaded using PEN, TAP, and MAT files (See Figure 3).

IMPORTANT: If your PEN file was *not* created in the 2022 version of *SlugPen*, you *must* check format of the PEN file. File format has likely changed and must be corrected to match the format required by *SlugHeat*. Any data or metadata that is missing or unknown will be recorded as '-999' in the PEN, MAT, and TAP files. To see example format, see Figure 2

General format for .pen file header:

```
Station #   Penetration #   'Cruise'        Datum
Lat         Lon             Av. Depth       Av. Tilt
Logger ID   Probe ID        Num. Sensors    Pulse power (J)
        Pen record
        HP record
                    Cal1        Cal2        Cal3        Cal4     ......
        Record #    T1          T2          T3          T4       ......
```

Example .pen file:

```
   0    1 'TutorialCruise' datum
418880 2063970   2234   2.00
  5301    203     11      -999
    13
    77
         2.584    2.634    2.583    2.567    2.548    2.591    2.616    2.589    2.602    2.548    2.594    2.695
     1   2.584    2.633    2.581    2.565    2.545    2.587    2.613    2.588    2.602    2.549    2.594    2.694
     2   2.584    2.633    2.582    2.565    2.545    2.588    2.614    2.589    2.603    2.548    2.594    2.694
     3   2.584    2.633    2.582    2.564    2.545    2.588    2.615    2.589    2.602    2.548    2.594    2.694
     4   2.584    2.634    2.583    2.566    2.546    2.590    2.615    2.589    2.602    2.548    2.594    2.695
     5   2.584    2.634    2.583    2.567    2.547    2.590    2.615    2.590    2.602    2.548    2.594    2.696
     6   2.584    2.634    2.583    2.567    2.548    2.591    2.616    2.589    2.602    2.548    2.594    2.695
     7   2.580    2.629    2.579    2.560    2.543    2.585    2.610    2.582    2.597    2.543    2.587    2.702
```

Figure 2: *SlugHeat* example PEN file formatted correctly. PEN files that do not match this format cannot be loaded into the 2022 version of *SlugHeat*.

Steps for loading in data are as follows:

1. **Press *'Load Penetration'* button** to load in data from a single penetration.
   - Note: If you do not see the pop-up window, you may need to click anywhere on the screen after pressing *'Load Penetration'* button or look on other screens, if applicable. The pop-up window should become visible.
2. **Select a PEN file** in the pop-up window (Figure 3), which defines data from a single penetration.
   - Note: If you are using a PEN file *without* a corresponding MAT file and you wish to include a TAP file as well, the TAP file must be in the same folder as your PEN file.

- Note: If the PEN, TAP, and MAT files were created in the updated 2022 version of *SlugPen*, the power of the heat pulse (J), as recorded directly by the instrument, will be loaded in directly from the PEN or MAT file. If there is not recorded pulse power in the PEN file (i.e., it is set to -999), the power of the heat pulse will be instead be the default input parameter loaded in by the PAR file.

Once the unprocessed penetration data is loaded in, four time series are plotted on the first tab (*Penetration Data* tab). These time series are shown in Figure 4: **(a)** temperature relative to bottom water; **(b)** temperature recorded by the top (bottom water) sensor that rests atop the data logger; **(c)** depth below seafloor; and **(d)** tilt of the probe relative to vertical. Time is displayed as record numbers, which begin at zero at the start of the penetration and increment with each measurement made by the probe. In plot **(a)**, each line color is a separate temperature sensor (thermistor), which line the probe and therefore vary with depth. Sensors with higher numbers are shallower and sensors with lower numbers are deeper (i.e, T1 is the deepest). The number of sensors could vary with different probe constructions. Data processing to calculate heat flow does not require top sensor, depth, or tilt measurements, but all are useful in data interpretation and are therefore recorded and plotted.

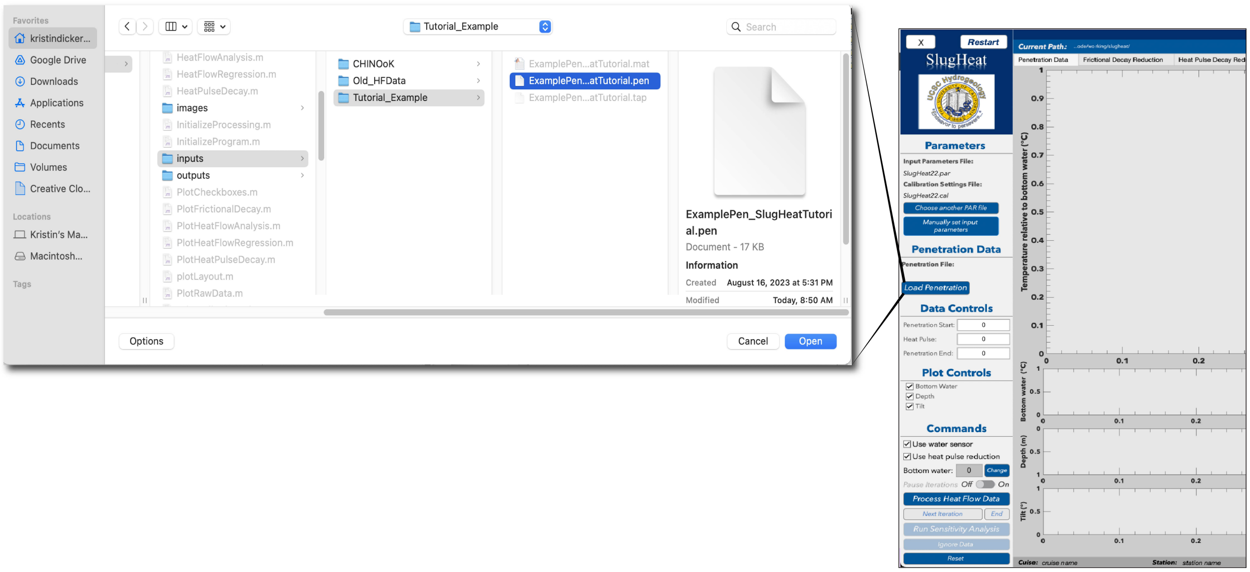


Figure 3: *SlugHeat* example pop-up window to select a PEN file that will be used to load the penetration into the program.

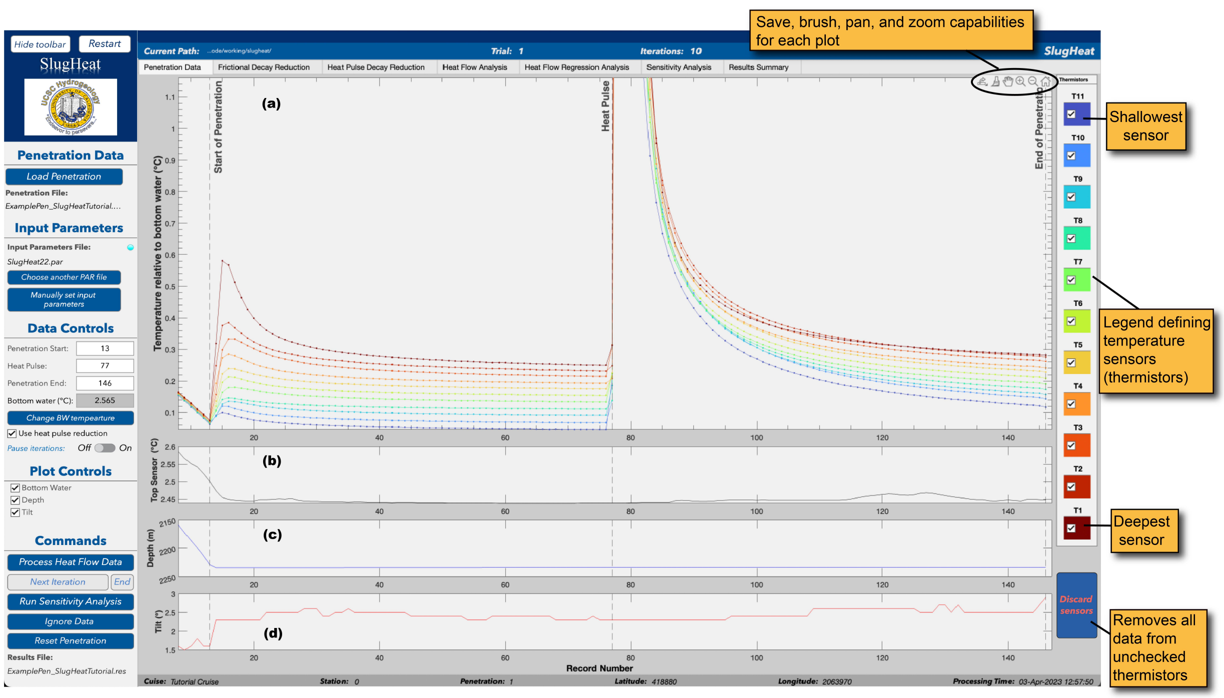


Figure 4: *SlugHeat* example *Penetration Data* tab where data has been loaded in but has not been processed. **(a)** Temperature relative to bottom water ($^{\circ}C$) vs. Record Number; **(b)** Top Sensor temperature ($^{\circ}C$) vs. Record Number; **(c)** Depth (m) vs. Record Number; and **(d)** Tilt ($^{\circ}$) vs. Record Number. Vertical lines indicate timing of start of penetration, heat pulse firing, and end of penetration. Yellow boxes indicate notable plot and data controls on main window. Example penetration used: `ExamplePen_SlugHeatTutorial`

Display and plot controls

Once plotted, all displays are modifiable in the following ways:

(a) **Plot zoom, pan, and save**: Each plot has pan, zoom, and save capabilities. Save options include copying as an image or vector graphic. These capabilities can be used by hovering mouse over the top right corner of each plot. All plots on the *Penetration Data* tab are linked with the same x axis (Record Number), so panning and zooming on one plot will be mirrored on all other plots on this tab. See Figure 4

(b) **Plot display:** Checkboxes in the *Plot Controls* box in the command window indicate which plots are shown. Unchecked plots are hidden from display (Figure 5 **(box 6)**).

(c) **Temperature data display:** Checkboxes in the thermistors legend on the right-hand side of the screen indicate which thermistors' data will be displayed. Data from unchecked thermistors will be hidden from display, but are not removed from data file. Therefore, data from unchecked thermistors will still be used in subsequent calculations unless otherwise noted by user (described in next section). See Figure 4

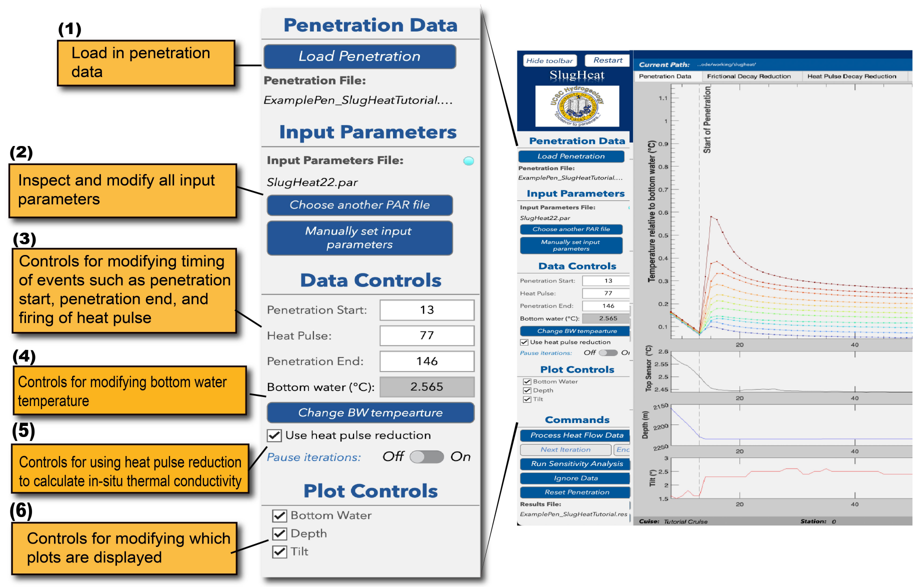


Figure 5: *SlugHeat* controls for modifying data, input parameters, and plot display before processing. Yellow boxes indicate notable pre-processing data and display controls. Example penetration used: `ExamplePen_SlugHeatTutorial`

5 Set input parameters

Once the program is launched and penetration data is loaded in, the input parameters for data processing and calibration of temperature sensors must be defined. To see default parameters and modify as needed, use the *Input Parameters* box on the command window (Figure 5 **(box 2)**).

1. **Check default parameters**

   – The default parameters for processing are read in automatically when the main program is launched using the default parameters text file (PAR file): `SlugHeat.par`

   – To check *all* default input processing parameters and calibration parameters before processing data, either (1) check `SlugHeat.par` in a separate text editor or (2) press *'Manually set input parameters'* button on the *SlugHeat* command window which will launch an auxiliary application within *SlugHeat* to view and adjust all input parameters. See Figure 6.

2. **Adjust input parameters, if needed** (two optional ways to do this):

   (a) **Press *'Manually set input parameters'* button** on top of command window to left of application, launching auxiliary application where individual input parameters can be adjusted manually. **Press *'Update Parameters'* button** to update modified values. See Figure 6.

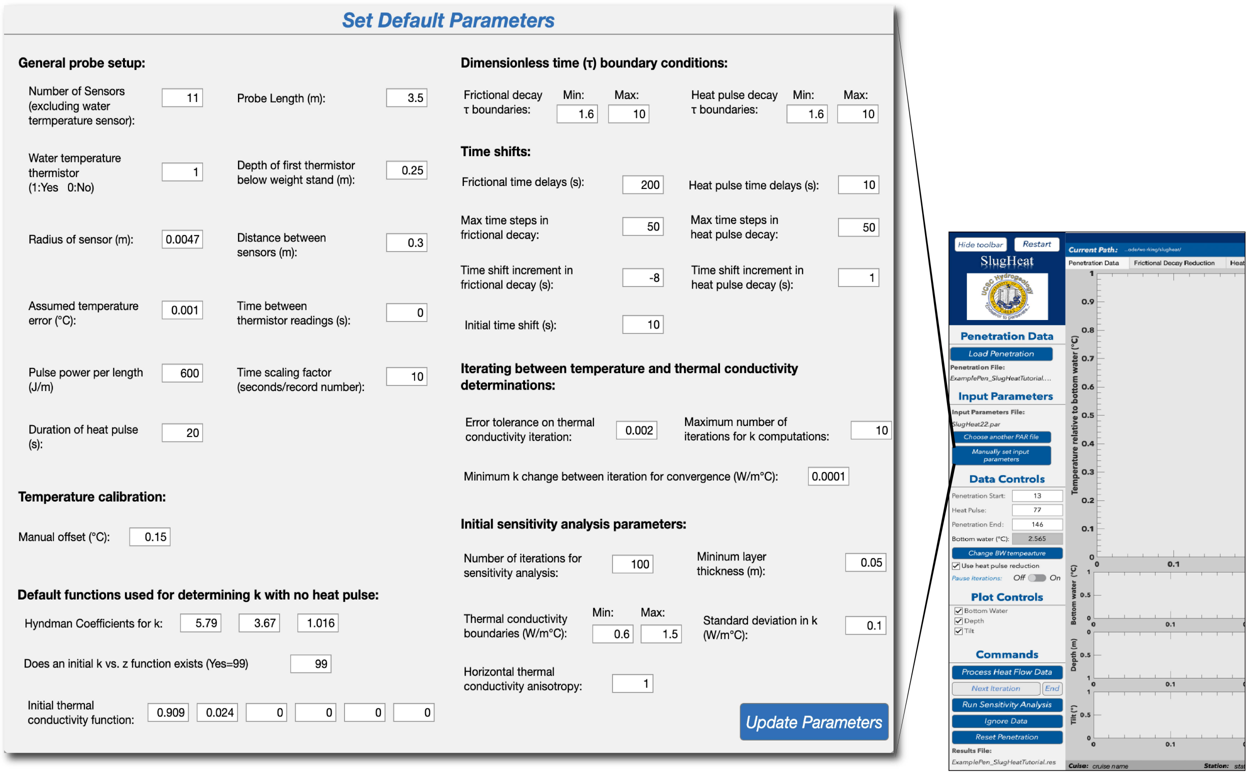


Figure 6: SlugHeat auxiliary application to inspect and modify input parameters

   (b) **Press *'Choose another PAR file'* button** and select another text file to be used instead of the default `SlugHeat.par` text file. This is often a PAR file saved from a previously processed penetration. See Figure 7

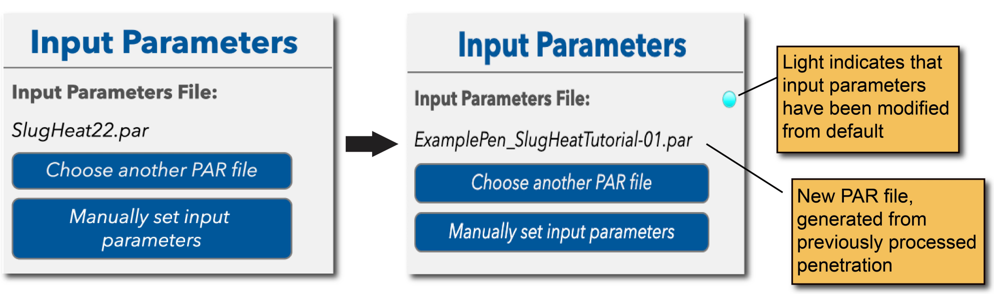


Figure 7: *SlugHeat* option for changing input parameters text file from default `SlugHeat.par` to a PAR file created while processing another penetration (in this example, new input parameters file is `ExamplePen_SlugHeatTutorial_01.par`). The blue light at the top right of second box indicates that parameters have been modified or a new input PAR file has been used.

6 Pre-processing data controls

Along with plots and displays, data are modifiable before processing in the following ways:

(a) **Timing of events:** Using the *Data Controls* box in the command window, timings of significant events, such as start of penetration, heat pulse firing, and end of penetration (shown with dashed vertical lines on the plots to right) can be modified by changing the corresponding record number in the text edit box to a new record number. If changed, plots will update accordingly. These record times and corresponding measurement values will be used in processing calculations. See Figure 5 **(box 3)**

(b) **Bottom water temperature:** All calculations using temperatures recorded by the heat-flow probe are done using temperatures relative to bottom water. When the data is loaded in, bottom water is initially assumed as the average of all temperatures recorded by the sensor that sits atop the data logger and does not penetrate the sediment (referred to as 'top sensor' in this tutorial) during penetration. To modify this value, **press *'Change BW temperature'* button** next to bottom water edit field in the command window under the *Commands* box (Figure 5 **(box 4)**). This will launch an auxiliary application where bottom water can be varied (Figure 8). A new bottom water temperature can be defined using:

   – The temperature recorded by a specific sensor at a specific record number, or

   – Manually inputting a temperature in the bottom water temperature text edit field at the bottom of this auxiliary application

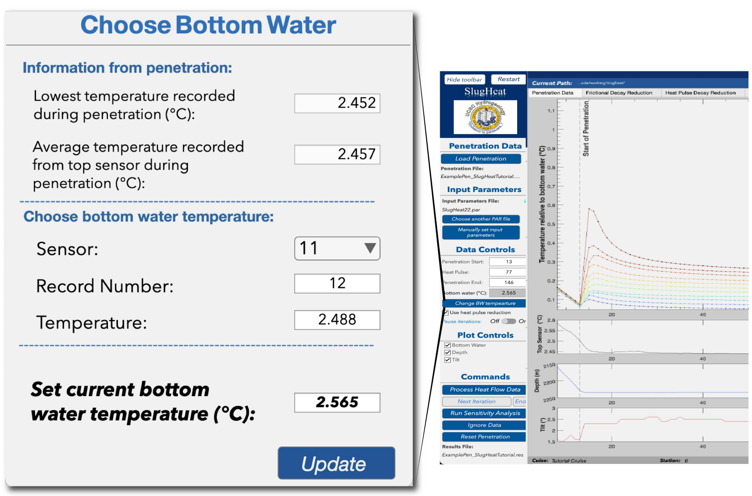


Figure 8: *SlugHeat* auxiliary application for changing bottom water temperature. This includes information from the penetration such as the lowest temperature recorded by the probe during penetration and the average temperature recorded from the top sensor (which is the initially assumed bottom water temperature).

When bottom water is changed, plots will update and all temperatures will be relative to this new bottom water temperature.

(c) **Sensors used:** Though checkboxes in the thermistors legend initially only control the *display* of data from each sensor, the data from individual sensors can be fully removed from the data set before processing. This is useful if there is a faulty sensor or the probe does not fully penetrate. To do this, **uncheck boxes for the sensors** which you would like to remove and **press *'Discard Sensors'* button** below the thermistors legend (Figure 4). When the data is processed, all measurements made by these sensors will be ignored. Checkboxes on the thermistors legend will be shaded and disabled for removed sensors.

(d) **Ignore the heat pulse decay reduction:** If there is no heat pulse fired, *SlugHeat* will automatically ignore the heat pulse decay reduction. However, if there is a heat pulse and you would like to *ignore* the heat pulse decay reduction anyway, you must **uncheck the *'Use heat pulse reduction'* checkbox** before processing (Figure 5 **(box 5)**. If the heat pulse decay reduction is ignored, *in-situ* thermal conductivity values will not be calculated. Instead, *SlugHeat* will use an assumed thermal conductivity vs. depth function to determine heat flow. This is defined in the default input parameters.

7 Processing to calculate equilibrium temperatures with depth, *in-situ* thermal conductivity values with depth, and heat flow

When input parameters and data have been checked and modified as needed, the data can be processed to determine heat flow. Processing penetration data includes determining equilibrium temperatures of the sediment, *in-situ* thermal conductivity of the sediment, and heat flow. Equilibrium temperatures and thermal conductivity values for each sensor are determined iteratively. Once convergence criteria (specified as a default input parameter) has been reached, iterations end and values are established for each sensor (and therefore at the depths of each sensor in the sediment). These values are then used to calculate heat flow at the seafloor. Processing steps are described briefly below.

1. **Press *'Process Heat Flow Data'* button** in the *Commands* box of the command window (Figure 9 **(box 8)**).

   - **Option to pause between iterations:** *SlugHeat* will immediately begin to iterate between calculations for equilibrium temperatures of the sediment and *in-situ* thermal conductivity of the sediment at the depth of each sensor. Generally, only the final iteration is plotted unless otherwise noted by the user. To pause calculations and plot results from each iteration, **switch the *'Pause Iterations'* control switch on the command window to *'On'***. This will plot results from each iteration to allow mid-processing data inspection. To continue to next iteration, you must **press *'Next Iteration'* button** each time (Figure 9 **(box 9)**). This control switch can be turned on and off at any time. Iterations will continue until convergence criteria is met or a maximum number of iterations is reached. To calculate heat flow using equilibrium temperatures and thermal conductivity values from any iteration, even before convergence criteria has been reached, **press *'End'* button** instead of moving on to the next iteration. Values determined in the latest iteration when this button is pressed will be used to determine heat flow.

2. **Migrate to other tabs**, including *Frictional Decay Reduction* tab, *Heat Pulse Decay Reduction* tab, and *Heat Flow Analysis* tab. These allow investigation into results for each processing step, including:

   (a) ***Frictional Decay Reduction:*** This tab shows results from the frictional decay reduction, where the thermal response following the penetration is extrapolated to infinite time to calculate **equilibrium temperatures** of the sediment at the depth of each sensor. Penetration leads to an increase in temperature due to both an increase in temperature of the sediment relative to bottom water as well as a frictional heating caused by the penetration itself. This frictional heating must be removed to determine equilibrium temperatures of the sediment. Each plot represents a step in these calculations. See Figure 10.

   (b) ***Heat Pulse Decay Reduction:*** This tab shows results from the heat pulse decay reduction, where the thermal response following the firing of a calibrated heat pulse from the probe into the surrounding sediment is extradpolated to infinite time to calculate ***in-situ* thermal conductivity** of the sediment at the depth of each sensor. Each plot represents a step in these calculations. See Figure 11.

   (c) ***Heat Flow Analysis:*** This tab shows results from the heat flow analysis, where the calculated equilibrium temperatures and *in-situ* thermal conductivity values with depth are used to calculate **heat flow**. Each plot represents a step in these calculations. See Figure 12.

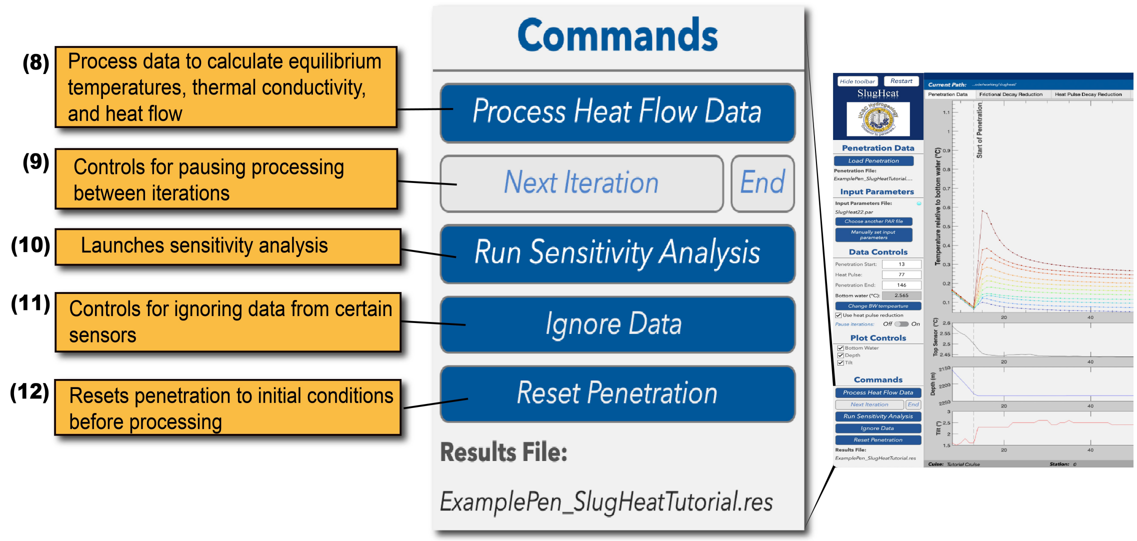


Figure 9: *SlugHeat* processing commands. Yellow boxes indicate notable processing data and display controls. Example penetration used: `ExamplePen_SlugHeatTutorial`

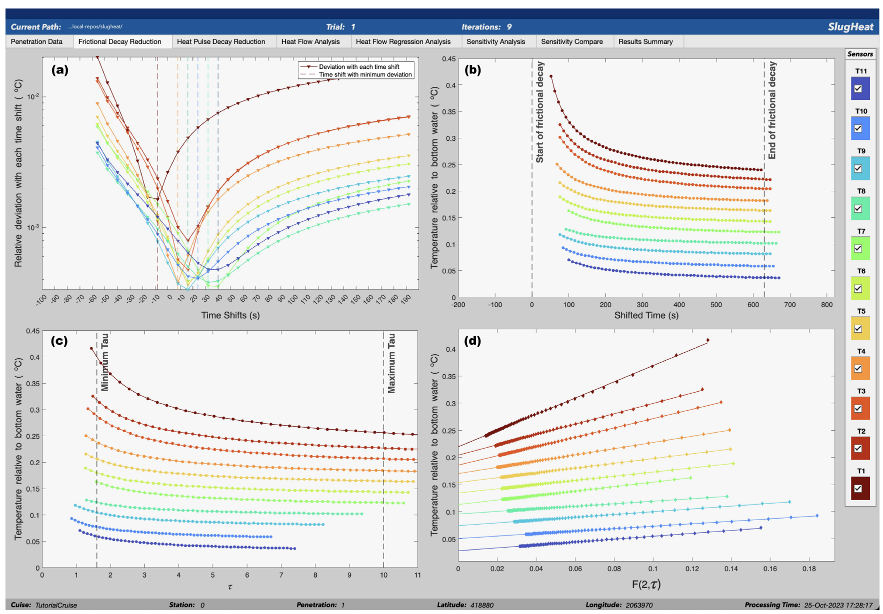


Figure 10: *SlugHeat* example *Frictional Decay Reduction* tab for determining equilibrium temperatures. Frictional heating caused by the penetration is removed by extrapolating temperatures to infinite time. Plots include **(a)** Temperature ($^{\circ}C$) vs. Time (s); **(b)** Temperature ($^{\circ}C$) vs. Dimensional time, τ; **(c)** Temperature ($^{\circ}C$) vs. the cylindrical decay function $F(\alpha, \tau)$; and **(d)** Residual misfit from the linear regression used in the previous plot ($^{\circ}C$) vs. Time Shifts (s). Vertical lines indicate the lowest residual misfit for each sensor.

8 Post-processing data controls, data analysis, and reprocessing

SlugHeat provides several options for modifying and reprocessing data. This is useful to see effects of certain sensors, various input parameters, and more on heat flow results.

1. **Optionally modify input parameters and/or specify data to be ignored when reprocessed**:
   (a) To modify input parameters, see Section 5.
   (b) To remove results from specific sensors for heat flow determinations, **press the *'Ignore Data'***

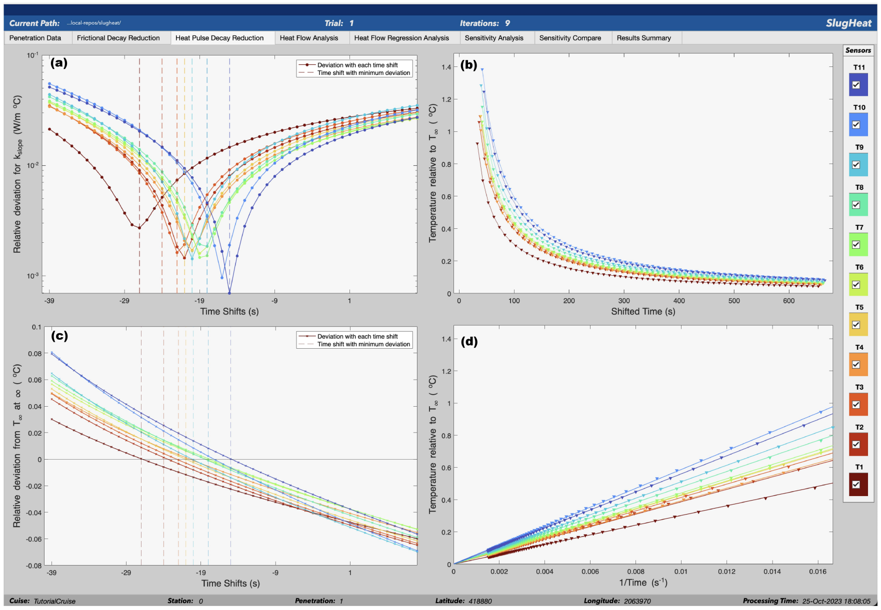


Figure 11: *SlugHeat* example *Heat Pulse Decay Reduction* tab for determining *in-situ* thermal conductivity. This is calculated using the thermal response following a calibrated heat pulse from the probe into the surrounding sediment. Corrected temperatures are temperatures above estimated equilibrium temperatures of the sediment. Plots include **(a)** Corrected temperature ($^{\circ}C$) vs. Time (s); **(b)** Residual misfit from the linear regression used in the previous plot vs. Time shifts (s) ; **(c)** Corrected temperature ($^{\circ}C$) vs. 1/Time (s); and **(d)** The temperature rise above equilibrium temperatures at infinite time (which should be zero) ($^{\circ}C$) vs. Time Shifts (s). Vertical lines in **(b)** and **(d)** indicate the lowest residual misfit for each sensor.

button under the *Commands* box of the command window (Figure 9 box **(11)**). This will launch an auxiliary application (Figure 13) where data from individual sensors can be ignored. Equilibrium temperature and *in-situ* thermal conductivity values were calculated for each sensor in previous processing steps (*Frictional Decay Reduction* and *Heat Pulse Decay Reduction*, respectively). In this auxiliary application, either equilibrium temperatures, *in-situ* thermal conductivity values, or both can be ignored for any sensor. Values from unchecked sensors will be ignored in any subsequent processing.

2. **Reprocess**: After checking boxes for data to include and unchecking data to ignore, **press the *'Ignore unchecked data and reprocess for heat flow'* button** to update data to be used for subsequent processing. Heat flow will automatically be recalculated, ignoring all unchecked estimations.

   – Note: If input parameters were changed, all processing calculations will be redone. This includes all iterations between equilibrium temperature and *in-situ* thermal conductivity calculations for all sensors as well as heat flow determinations. If no input parameters were changed but data from certain sensors were ignored using the *Ignore Data* function, this does ***not*** recalculate equilibrium temperatures or *in-situ* thermal conductivity determinations. Instead, values for each sensor from the final iteration from the most recent processing will be used, but values calculated from ignored sensors are simply *unused* when determining heat flow.

Ignored data will be shown with an 'X' through its corresponding sensor marker on the Depth vs. Temperature and Depth vs. Thermal conductivity plots (Figure 13). A sensor whose thermal conductivity values are ignored cannot be incorporated in the heat flow determination at all, however, a sensor whose equilibrium temperature alone is ignored but whose thermal conductivity value is used can still be incorporated in the heat flow assessments because it will affect the thermal gradient. Therefore, sensors whose equilibrium temperature alone is ignored will still be plotted on the Cumulative thermal resistance vs. Temperature relative to bottom water plots, but sensors whose thermal conductivity is ignored will not be plotted at all on this plot. See Figure 13 for example: T11 equilibrium temperature is ignored but this sensor is still

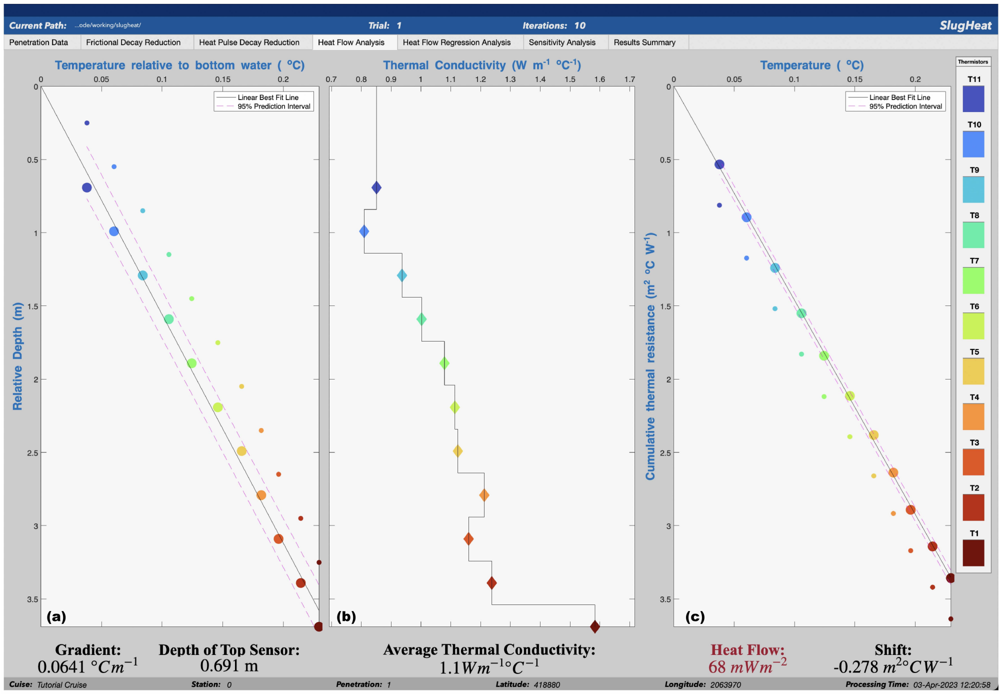


Figure 12: *SlugHeat* example *Heat Flow Analysis* tab for determining heat flow for a particular penetration. This is calculated using the equilibrium temperatures with depth, calculated in the *Frictional Decay Reduction* and the *in-situ* thermal conductivity values with depth, calculated in the *Heat Pulse Decay Reduction*. Plots include **(a)** Depth below seafloor (m) vs. Temperature relative to bottom water ($°C$); **(b)** Depth below seafloor (m) vs. *In-situ* thermal conductivity (W/m$°C$); and **(c)** Cumulative thermal resistance ($m^{2°}C/W$) vs. Temperature relative to bottom water ($°C$). For plots **(a)** and **(c)**, small markers indicate estimated results for each sensor, and large markers indicate results with a depth correction so that temperature relative to bottom water is zero at the seafloor. Solid black lines are linear best fit lines through depth-corrected results. Dashed pink lines indicate 95% confidence interval for the linear best fit line. Key calculations are shown below each plot. The slope of the linear best fit line in **(c)** is heat flow.

plotted on **(c)**, whereas T10 thermal conductivity is ignored, so this sensor is not plotted on **(c)**.

Ignored data are not lost entirely. To reintroduce previously ignored data, simply **press the *'Ignore Data'* button** again to relaunch the corresponding auxiliary application, and recheck data from sensors you would like to include. This will update which equilibrium temperatures and *in-situ* thermal conductivity values are used in subsequent heat flow determinations, even those previously ignored.

9 Heat flow regression analysis using "scatter"

SlugHeat offers multiple ways to estimate sensitivity of results to various input parameters and calculations.

Firstly, to consider the number of sensors used in all analyses, as significant error could arise when measuring in disturbed sediment, **navigate to the *Heat Flow Regression Analysis* tab**. Uncertainty in the heat flow linear regression (Figure 12c) is assessed using a parameter called "scatter" (Villinger and Davis, 1987):

$$\xi = \sqrt{\frac{\chi^2}{N-1}} \tag{1}$$

where
ξ is "scatter" from the regression model,
χ^2 is based on the minimized misfit to the regression estimate, and
N is the number of sensors used

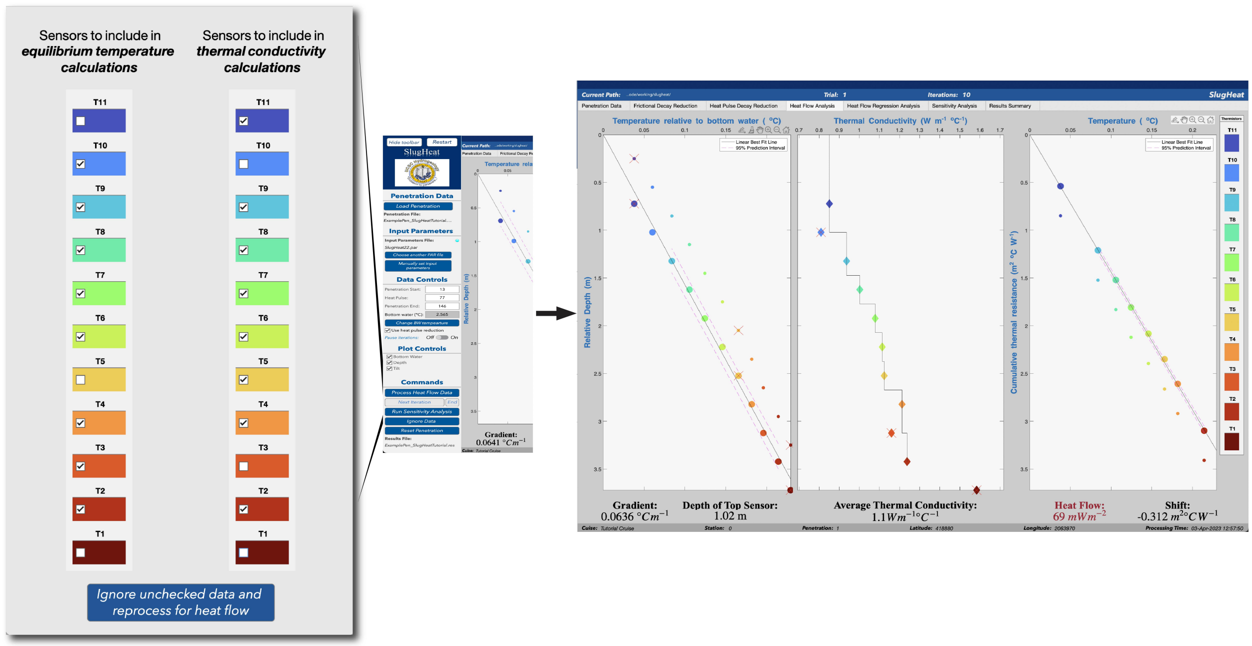


Figure 13: *SlugHeat* auxiliary application for ignoring data from certain sensors in heat flow determinations (left of arrow). This app is launched with the *Ignore Data* button under the *Commands* box in the command window. Plot to right of arrow shows results from a heat flow analysis where data from certain sensors are ignored. All data with an 'X' is not included in heat flow determinations for this analysis. In this example, equilibrium temperatures calculated for sensors T1, T5, and T11 are ignored and *in-situ* thermal conductivity values determined for sensors T1, T3, T10 are ignored. Use of application is detailed in text.

"Scatter" (ξ) increases with the misfit from the heat flow linear regression, therefore, can be used to assess uncertainty in heat flow. It is analyzed for each heat-flow measurement by systematically removing data from the shallowest subseafloor sensors, to see how this influences values of both ξ and heat flow. Results are presented with plots of ξ vs. N (number of sensors retained) and heat flow vs. N (Figure 14, top plot) as well as normalized ξ vs. N and heat flow uncertainty (σ_{HF}) vs. N (Figure 14, bottom plot).

10 Heat flow sensitivity analysis

SlugHeat also includes an optional sensitivity analysis to assess the impact of varying thermal conductivity and/or the thicknesses of sediment layers for which properties are inferred (Figure 12b). Once thermal conductivity values are determined for each sensor, thermal resistance is calculated based on the assumption that seafloor sediments comprise a series of horizontal layers, with layer boundaries located midway between sensor locations. The sensitivity analysis is based on randomly shifting the boundaries between layers, within limits, and varying the values of thermal conductivity assigned to each layer. With each shift in values, the program recalculates the heat flow. This processes is typically repeated $\geq$100 times (each time is a 'realization'), generating an ensemble of heat flow results for each probe penetration from which multiple metrics are calculated (mean, median, range, standard deviation).

To run the sensitivity analysis,

1. **Press the '*Run Sensitivity Analysis*' button** (Figure 9 box **(10)**): This will launch an auxiliary application for generating layer property distributions to be analyzed (Figure 15). Use this auxiliary application to specify and visualize property distributions before running the analysis.

2. **Define properties to be tested:** This includes the number of realizations to be run and layer thickness and thermal conductivity properties to vary each realization. Adjust property distributions

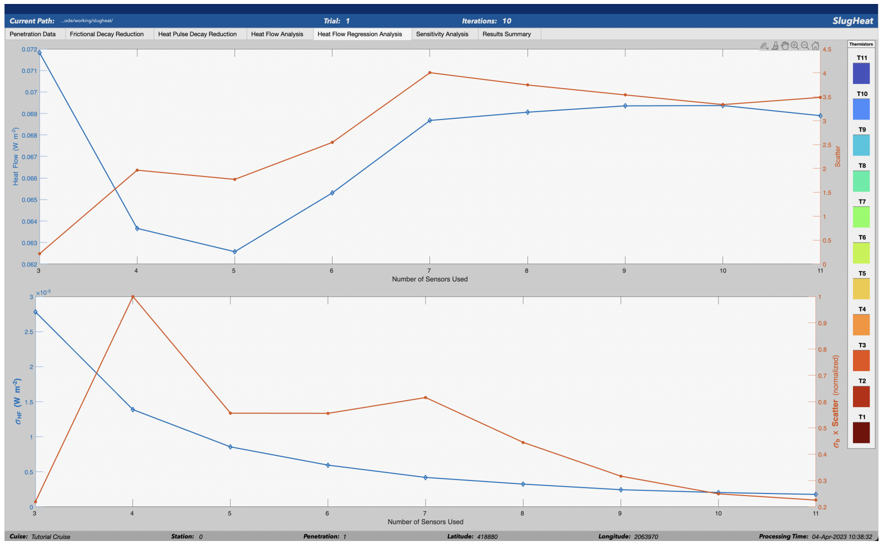


Figure 14: *SlugHeat* example *Heat Flow Regression Analysis* tab. Top plot shows number of sensors used vs. heat flow (blue line) and number of sensors used vs. scatter (ξ) (orange line). Bottom plot shows number of sensors used vs. heat flow uncertainty (σ_{HF}) (blue line) and number of sensors used vs. normalized scatter (orange line).

using the text edit boxes in the auxiliary application. Properties to vary for *each sensor* include:

(a) **Layer thickness:** Layer thicknesses are defined by a uniform distribution and is varied such that no layer boundary is closer than a prescribed distance from a sensor. User can define minimum thickness.

(b) **Thermal conductivity:** Thermal conductivity values can be held constant (select 'None' in *Distribution of Thermal Conductivity Values* options of auxiliary application). If held constant, values calculated in the heat pulse decay reduction will be used (See Section 7) or an assumed function of thermal conductivity vs. depth will be used if no heat pulse reduction was done, and only layer thickness will change each realization. To vary thermal conductivity values with each realization, generate a distribution of values for each sensor to be tested. The default average of each distribution is either the *in-situ* measurement determined using the heat pulse or the value determined by the the assumed depth function, but the user may adjust this as needed for each sensor. Thermal conductivity values are varied to follow either a truncated Gaussian or Gamma distribution with lower and upper limits set based on *a priori* knowledge. For example, thermal conductivity of seafloor sediment can't be lower than that for seawater ($\sim$ 0.6 W/m°C) and is typically bounded at the upper limit based on regional data (perhaps 1.5 - 2.0 W/m°C for most shallow marine sediment types). Distribution and truncation parameters can be set equally for all sensors or set individually, if desired. In the auxiliary application (Figure 15), the text edit boxes in the *Variable thermal conductivity values and layer thickness values* section define these distributions. The two plots on the right-hand side represent a Gaussian distribution (top plot) or Gamma distribution (bottom plot) of thermal conductivity values to be tested and update as the user changes key parameters. The Gaussian distribution plot is highlighted in green because it is currently selected. In this example, sensor 5 is plotted. Varying any parameters on this app will vary those that define sensor 5. Sensor number can be changed with drop-down menu at bottom right-hand corner of the application. Table defines all parameters currently set for all sensors. Alternatively, all sensor parameters can be updated together using the *'Update All Sensors to Current Parameters'* button or the *'Reset All Sensors to Default'* button. If the *'Run Sensitivity Analysis'* button is pressed, the sensitivity analysis will be run using parameters currently defined in this auxiliary application.

3. **Press the *'Run Sensitivity Analysis'* button** once the number of realizations and properties to be varied each realization are defined. This will close the application and begin the sensitivity analysis.

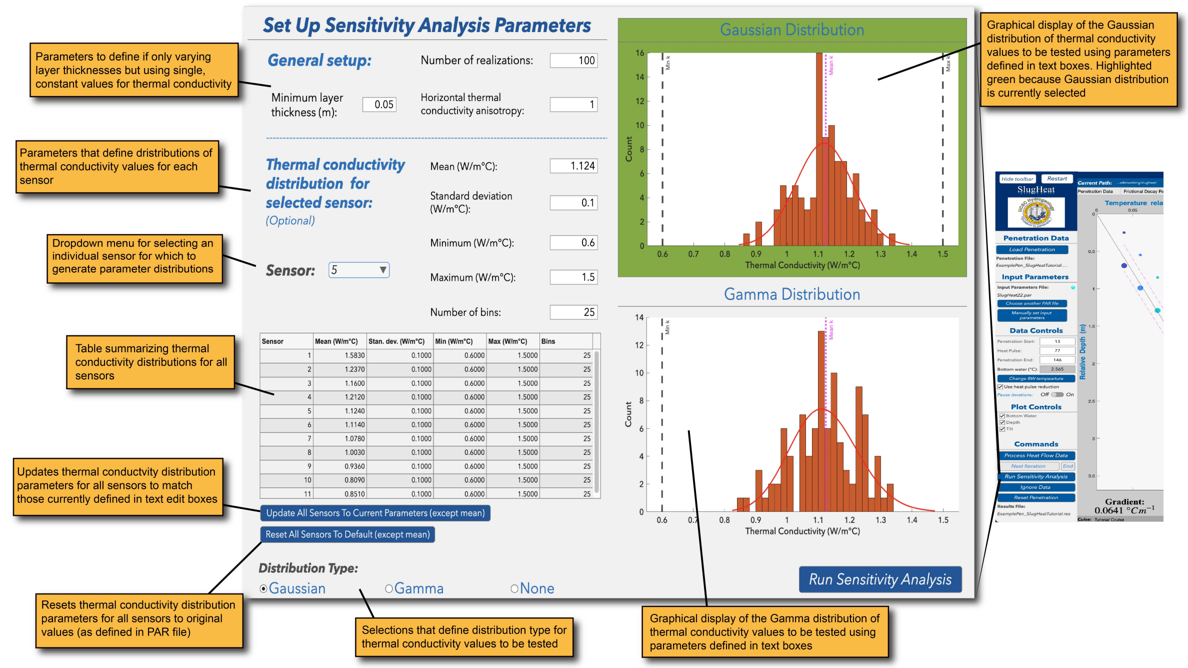


Figure 15: *SlugHeat* auxiliary application for defining parameters to be tested in a sensitivity analysis, including number of realizations to be run, minimum layer thickness, and thermal conductivity distributions. Thermal conductivity distributions for each sensor are displayed on right-hand side of this application, including plots that display distributions and a table that defines all parameters set for all sensors. Details in text. Yellow boxes indicate notable distribution controls and plots. Example penetration used: `ExamplePen_SlugHeatTutorial`

An example sensitivity analysis run using properties defined in Figure 15 is shown in Figure 16. Results displayed include the heat flow standard deviation for each realization of properties (Figure 16 **(a)**), the distribution of possible heat flow values for each sensor (Figure 16 **(b)**), and a heat flow analysis plot for each realization (Figure 16 **(c)**). The ensemble of results from all realizations are then used to calculate a median, mean, and standard deviation, the latter of which is typically considerably larger than inferred from the statistical fit of the initial heat flow analysis plot.

11 Results and outputs

All results are saved to summary tables and output in multiple formats, including MAT files, text files, and even Excel sheets. All plots can be saved individually as needed using the plot controls in the upper right-hand corner of the plot.

Summary Tables

Key results are summarized on the final tab of *SlugHeat*. To inspect and compare results from all analyses during a single program session (i.e., since the time *SlugHeat* was launched), **navigate to the *Results Summary* tab**. Here, there are two summary tables, which define notable input parameters and results not only from various penetrations but also for each trial of a single penetration. A penetration that is analyzed multiple times with varying input parameters or used/ignored data will have multiple trials. Comparing and contrasting results from different penetrations or different trials can help with heat flow interpretations. The two summary tables shown on this tab include:

(a) **Heat flow results summary table:** Here, results from all heat flow analyses since the start of the session are summarized. This includes key input parameters, such as penetration and trial number, use of a heat pulse, bottom water temperature, sensors used/ignored, and more. Also shown are key

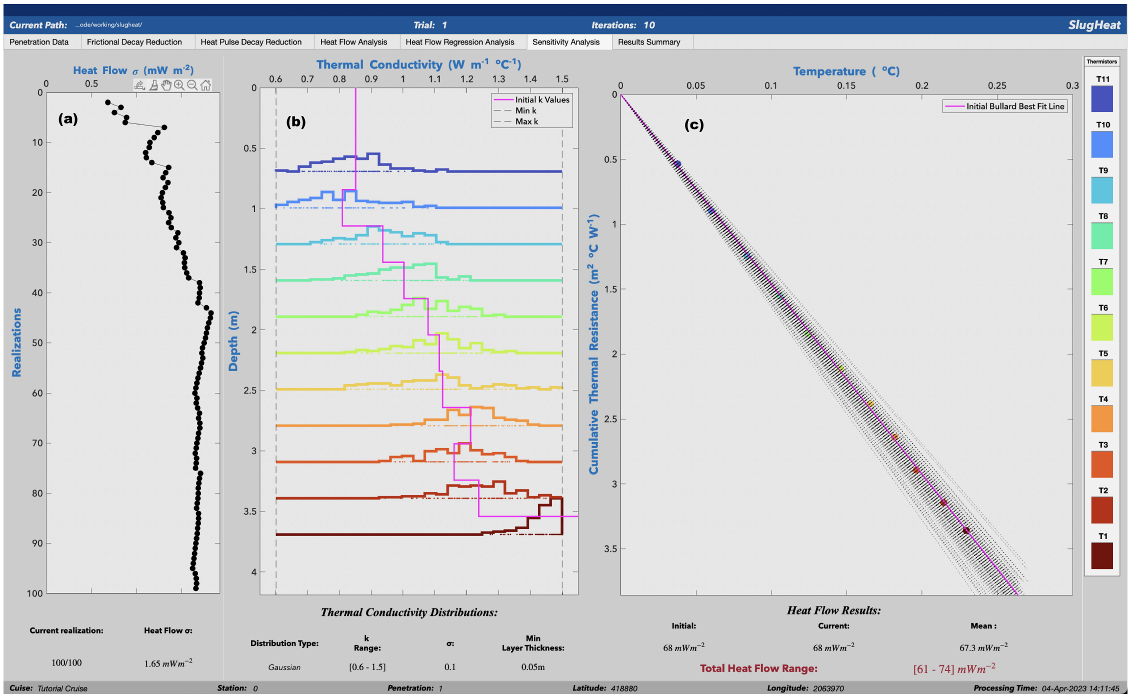
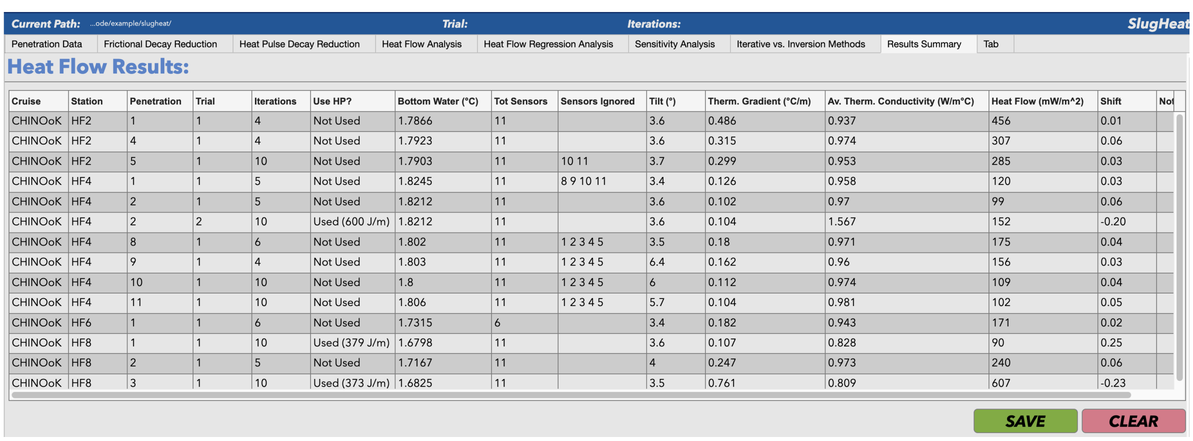


Figure 16: *SlugHeat* example *Sensitivity Analysis* tab with analysis results compiled for all realizations. **(a)** Heat flow uncertainty (σ_{HF}) vs. Realization; **(b)** Thermal conductivity ($W/m°$) vs. Depth below seafloor (m) where the initial thermal conductivity values (used in the original heat flow analysis during processing) are shown with the pink line. Each colored line depicts the distribution of thermal conductivity values for each sensor. Values for each realization are chosen randomly from these distributions. Dashed black lines indicate minimum and maximum values; and **(c)** Cumulative thermal resistance ($m^2/°W$) vs. Temperature relative to bottom water ($°C$) where the pink line represents results from the initial heat flow analysis. Each dashed line is a heat flow regression for a single realization. Key input parameters and results are defined below each plot.

results from that penetration and trial, including thermal gradient, average thermal conductivity, and heat flow. (Figure 17)

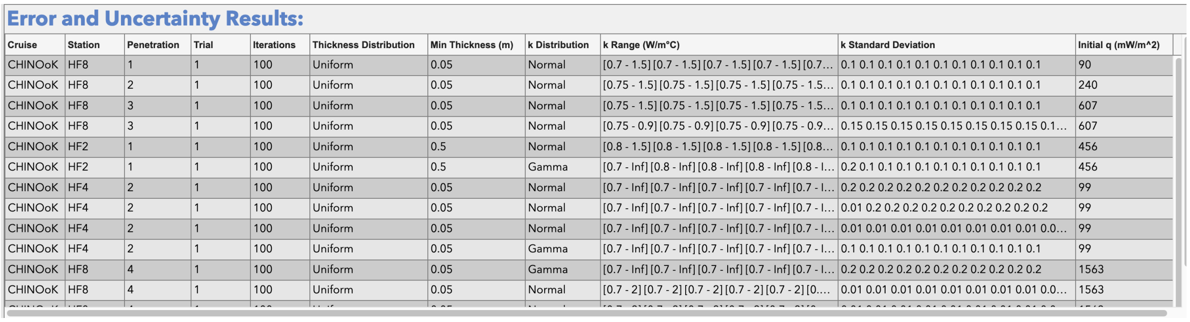


Cruise	Station	Penetration	Trial	Iterations	Use HP?	Bottom Water (°C)	Tot Sensors	Sensors Ignored	Tilt (°)	Therm. Gradient (°C/m)	Av. Therm. Conductivity (W/m°C)	Heat Flow (mW/m^2)	Shift	Not
CHINOoK	HF2	1	1	4	Not Used	1.7866	11		3.6	0.486	0.937	456	0.01	
CHINOoK	HF2	4	1	4	Not Used	1.7923	11		3.6	0.315	0.974	307	0.06	
CHINOoK	HF2	5	1	10	Not Used	1.7903	11	10 11	3.7	0.299	0.953	285	0.03	
CHINOoK	HF4	1	1	5	Not Used	1.8245	11	8 9 10 11	3.4	0.126	0.958	120	0.03	
CHINOoK	HF4	2	1	5	Not Used	1.8212	11		3.6	0.102	0.97	99	0.06	
CHINOoK	HF4	2	2	10	Used (600 J/m)	1.8212	11		3.6	0.104	1.567	152	-0.20	
CHINOoK	HF4	8	1	6	Not Used	1.802	11	1 2 3 4 5	3.5	0.18	0.971	175	0.04	
CHINOoK	HF4	9	1	4	Not Used	1.803	11	1 2 3 4 5	6.4	0.162	0.96	156	0.03	
CHINOoK	HF4	10	1	10	Not Used	1.8	11	1 2 3 4 5	6	0.112	0.974	109	0.04	
CHINOoK	HF4	11	1	10	Not Used	1.806	11	1 2 3 4 5	5.7	0.104	0.981	102	0.05	
CHINOoK	HF6	1	1	6	Not Used	1.7315	6		3.4	0.182	0.943	171	0.02	
CHINOoK	HF8	1	1	10	Used (379 J/m)	1.6798	11		3.6	0.107	0.828	90	0.25	
CHINOoK	HF8	2	1	5	Not Used	1.7167	11		4	0.247	0.973	240	0.06	
CHINOoK	HF8	3	1	10	Used (373 J/m)	1.6825	11		3.5	0.761	0.809	607	-0.23	

Figure 17: *SlugHeat Results Summary* tab example of heat flow summary table.

(b) **Sensitivity analysis results summary table:** Here, results from all sensitivity analyses since the start of the session are summarized. This includes penetration and trial, number of realizations, layer thicknesses and thermal conductivity distribution types, minimum layer thickness, thermal conductivity value range and standard deviation, and more. These property distributions may vary for each sensor.

Also summarized are key results of each sensitivity analysis, including initial, final, mean, total range, and standard deviation of heat flow. (Figure 18)



Error and Uncertainty Results:

Cruise	Station	Penetration	Trial	Iterations	Thickness Distribution	Min Thickness (m)	k Distribution	k Range (W/m°C)	k Standard Deviation	Initial q (mW/m^2)
CHINOoK	HF8	1	1	100	Uniform	0.05	Normal	[0.7 - 1.5] [0.7 - 1.5] [0.7 - 1.5] [0.7 - 1.5] [0.7…	0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1	90
CHINOoK	HF8	2	1	100	Uniform	0.05	Normal	[0.75 - 1.5] [0.75 - 1.5] [0.75 - 1.5] [0.75 - 1.5…	0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1	240
CHINOoK	HF8	3	1	100	Uniform	0.05	Normal	[0.75 - 1.5] [0.75 - 1.5] [0.75 - 1.5] [0.75 - 1.5…	0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1	607
CHINOoK	HF8	3	1	100	Uniform	0.05	Normal	[0.75 - 0.9] [0.75 - 0.9] [0.75 - 0.9] [0.75 - 0.9…	0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.1…	607
CHINOoK	HF2	1	1	100	Uniform	0.5	Normal	[0.8 - 1.5] [0.8 - 1.5] [0.8 - 1.5] [0.8 - 1.5] [0.8…	0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1	456
CHINOoK	HF2	1	1	100	Uniform	0.5	Gamma	[0.7 - Inf] [0.8 - Inf] [0.8 - Inf] [0.8 - Inf] [0.8 - I…	0.2 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1	456
CHINOoK	HF4	2	1	100	Uniform	0.05	Normal	[0.7 - Inf] [0.7 - Inf] [0.7 - Inf] [0.7 - Inf] [0.7 - I…	0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2	99
CHINOoK	HF4	2	1	100	Uniform	0.05	Normal	[0.7 - Inf] [0.7 - Inf] [0.7 - Inf] [0.7 - Inf] [0.7 - I…	0.01 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2	99
CHINOoK	HF4	2	1	100	Uniform	0.05	Normal	[0.7 - Inf] [0.7 - Inf] [0.7 - Inf] [0.7 - Inf] [0.7 - I…	0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.0…	99
CHINOoK	HF4	2	1	100	Uniform	0.05	Gamma	[0.7 - Inf] [0.7 - Inf] [0.7 - Inf] [0.7 - Inf] [0.7 - I…	0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1	99
CHINOoK	HF8	4	1	100	Uniform	0.05	Gamma	[0.7 - Inf] [0.7 - Inf] [0.7 - Inf] [0.7 - Inf] [0.7 - I…	0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2	1563
CHINOoK	HF8	4	1	100	Uniform	0.05	Normal	[0.7 - 2] [0.7 - 2] [0.7 - 2] [0.7 - 2] [0.7 - 2] [0.…	0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.0…	1563

Figure 18: *SlugHeat Results Summary* tab example of sensitivity analysis summary table.

Each results summary table can be saved or cleared. To save the summary table as a MAT file and Excel file in your current directory, **press the *'Save'* button below the summary table**.

Text File Outputs

The results summary tables on the final tab of the *SlugHeat* GUI are useful for highlighting key results of each analysis and quickly characterizing influential input parameters, penetration data, etc. However, there are numerous processing parameters and calculation results used in *SlugHeat* that are not shown in these summary tables. The entire catalog of processing parameters and results can be found in an output text file for each analysis. These files are automatically generated and saved to your current directory anytime heat flow data is processed. These are known as RES files. The RES file for the example penetration used in this tutorial would be `ExamplePen_SlugHeatTutorial.res`. Each time a penetration is loaded in to *SlugHeat*, a new RES file is created for that penetration and all trials for that penetration are recorded in this single RES file.

In addition to a RES file, a new PAR file will be generated. This not only defines all the input parameters used in this analysis, but it can then be used as an input PAR file in subsequent analyses in lieu of the default `SlugHeat.par` text file, if desired. This can be done by using the *'Choose another PAR file'* button before processing and selecting a PAR file that was generated as an output from another penetration (see Section 5).

To find the RES file for an individual penetration, **look in your current directory** for a subfolder called **outputs/**. In case of difficulty in locating any output files, pop-up windows launched when an analysis is finished will define where all output files are saved.