Lab Manual

The Physics of Climate Change

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Contents

Lab 1

Measurement, Uncertainty, and Temperature

Equipment List

- Leslie Cube
- Glass Thermometer
- IR Thermometer "gun" (2)
- Stopwatch
- Ruler
- Computer

Overview

In this weekly lab you will primarly work in pairs, with your "partner" at the same table, but feel free to discuss things with the "group" of four at your adjoining tables. We will also share data with the entire class, usually using google surveys and sheets. You will turn in your own individual lab assignment, with copies of all data and graphs, in a single pdf document uploaded to the Blackboard "assignment" for that week.

1.1 Introduction and Definitions

Today we will conduct our first measurements of physical phenomena, mostly temperature measurements, and understand the necessity of the uncertainty and units associated with those measurements.

> A **physical measurement** contains three equally important parts: the numerical **value**, the **uncertainty** (also referred to as *error*) in that value, and the **units** in which these are measured.

Some examples are:

- The human body temperature is 37.0 ± 0.5 °C.
  (Uncertainty represented as "plus or minus" makes a range of values. Both the value and uncertainty are in "degrees celsius".)

- A college basketball game has 40 minutes ± 0.1 seconds of playing time.
  (The final minute clock measures to tenths of a second. The units can be different between the value and uncertainty.
- The Sun is 93 million miles away
  Here the uncertainty is expressed *implicitly* as "plus or minus a few of the last digit given", so plus or minus a few million miles

Let's make a precise definition of the uncertainty/error in a measurement:

> Given a particular measurement, the **uncertainty** is a statement of the range of values in which another scientist is likely[1] to make the same measurement.

There are a number of sources/components of this uncertainty:

- **Instrumental Uncertainty**: A measurement device generally has a smallest unit division shown. For an analog device — like a ruler with millimeter marks, or a thermometer with degrees — where we might hope to measure between the smallest markings, we can specify the instrumental uncertainty as such (e.g., half of a millimeter on a ruler, or 0.3°C on a thermometer). For a digital device, we can say that the instrumental uncertainty is "plus or minus a few of the last digit" (e.g., ± 0.03 seconds on a standard stopwatch).
- **(Manufacturing) Instrumental Uncertainty**: Sometimes although an instrument shows a precise demarcation, it is clear from looking at multiple "identical" instruments that they were not manufactured to that precision (e.g., multiple identical thermometers read slightly different values). The range of manufacturing uncertainty can be assessed by using multiple copies of the same device.
- **Methodological Uncertainty**: Sometimes our uncertainty is limited more by the way we make a measurement than by the instrument itself. For example, although a stopwatch has instrumental uncertainty in the hundreths of a second, our human reaction time is no better than a few *tenths* of a second, so our methodological uncertainty would be ± 0.3 s. This can be assessed by making repeated measurements.
- **Natural Variation** Almost always, the object of measurement does not have an infinitely precise value (e.g., the "temperature outside right now" depends on where exactly you measure it, and at which moment in time; the "diameter of a rock" that is not spherical). This uncertainty can sometimes be limited by a more precise specification of the measurement (e.g., "the temperature in the shade, outside Padnos, at 10:40 am"; or "the largest diameter of the rock"). And, like the methodological uncertainty, it can be assessed by repeated measurements.

1.2 Experiments

1.2.1 The time of my name

- Have your partner recite their full name to you at a steady relaxed pace. Measure the amount of time this takes using the stopwatch. You can try this multiple times. Then

[1] More precisely, if we say that the uncertainty is the *standard deviation* over repeated measurements, then 68% of all measurements fall in that range

switch and recite your own name for them.

Questions

1. Write down the name, and then your time measurement with uncertainty and units.

2. Briefly explain how you arrived at the uncertainty value, making mention of all "sources" of uncertainty.

1.2.2 "Seeing" the uncertainty I: Room Temperature

One table has been set up with an array of thermometers. Since they are all localized in the same place, they should be making approximately the same measurement: the temperature of the air at that table right now.

- Take a careful clear photo of the array of thermometers, then return to your desk and write down each of the temperature measurements on a sheet of paper.
- Considering the range of measurements you have, put labeled tick marks on the axis below such that the values will be spread out across the line. Use a ruler to make equal spacing of tick marks. At the far right, label that axis (e.g., "Temperature (C)").
- Place a dot on/near the axis for every measurement of temperature. You can "scatter" these a bit above/below the axis for clarity.

Questions

1. Express the full measurement with value, uncertainty, units. Estimate the uncertainty using your graphical display of points.

2. What is the instrumental uncertainty for this thermometer?

3. What do you think is the primary source of the uncertainty? Mention each type of uncertainty source.

1.2.3 "Seeing" the uncertainty II: Body Temperature

Here each of you will make a measurement of your body temperature using the Infrared (IR) thermometer "gun" on the palm of your hand. Note the picture on the side of the IR thermometer gun describing its "beam" of measurement (imagine a spot being projected onto the thing you are measuring, and make sure the spot is contained within the object). You will produce a two-picture plot, using a provided code (see Blackboard) and the Google CoLab implementation of python programming language.

1. What is the instrumental uncertainty associated to the IR thermometer?

2. Do you observe any natural variation of temperature across your hand?

3. Write down your measurement (with value, uncertainty, and units) here, and then submit it to the google survey (see Blackboard).

- Copy the column of "values" data for the whole class in the linked spreadsheet (see Blackboard) into your own spreadsheet and save as a csv file.
- In a web browser, go to `colab.research.google.com` and open a "New Notebook".
- Paste in the code provided on blackboard for *Scatter and Histogram Plot*.
- To run the code, either press the "play" button, or press shift-enter/shift-return. It will prompt you for your csv file to upload.
- This will produce a plot on the screen.
- Notice that there are generic axis labels and titles. Find the place in the code where they have been entered and edit them to make them specific to your particular data.
- To save and print your plot, you can either right-click and save to a file or screenshot to a file. Print this plot so that you can add it to your submission.

1.2.4 Leslie Cube

- Fill up the Leslie cube with hot/warm water at the sink and then replace the rubber stopper. Fill a small beaker with cold water.
- Place the glass thermometer first in the cold water, and then insert it into the Leslie cube such that its bulb is in the middle of the cube.

1. Record the glass thermometer measurements of the temperature in the cold water and in the Leslie cube.

2. Describe how quickly the thermometer came to equilibrium with the cold water and with the hot water.

3. Take and record temperature measurements of <u>each side</u> of the Leslie cube using the IR thermometer gun.

1.2.5 Temperatures of other objects

- Using the IR thermometer gun, record measurements of temperature (with value, uncertainty, units for each) for some of the following objects:
  - The surface of the table you sitting at.
  - Something else in the room.

  - Outside: Something that might be in equilibrium with the air temperature (shaded spot).
  - Outside: Something that is probably not in equilibrium with the air temperature.
  - Outside: The sky (try both clear and clouded spots).
- Record your temperature measurements below and also report them to the google survey posted on Blackboard.

1. Record your temperature measurements here.

Summary Questions

Brief answers are fine, but please write in complete sentences.

1. State the temperature measurements you made for the Leslie cube, including each type of side and the direct glass thermometer measurement. Speculate on why you found different values, if you did.

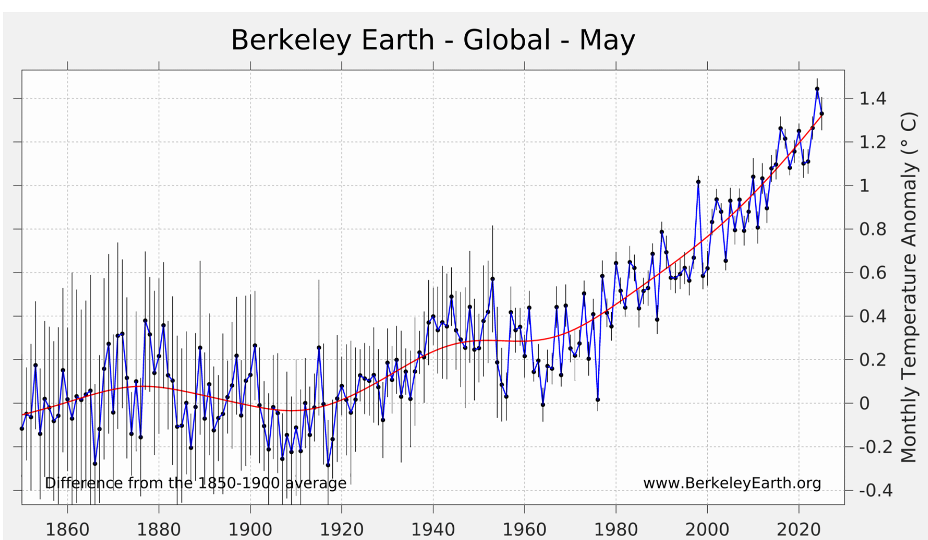
2. Looking at either the hand-temperature data or the other plot you made with the entire class data: how did your own estimated uncertainty (for your measured value) compare to the "spread" of the data taken by all students? Should these agree? Why or why not?

3. Two students make a measurement of the distance from the Bookstore to the Clock Tower. They are reported as follows

$$199.65 \text{ m} \pm 0.3 \text{ m}$$
$$202 \text{ m} \pm 3 \text{ m}$$

(i) On the axis below, draw tick marks over a wide enough range to plot both measurements *and their ranges of uncertainty*. (ii) Plot the two measurements using a point for the "value" and a horizontal bar to show the uncertainty. (iii)Are these "the same" measurements to within uncertainty or not? Explain.

4. Shown below is a summary of the Global Average Temperature over most of human recorded history. The uncertainties for each data point are indicated by bars. Speculate on how these uncertainties might have been determined, how they change over time, and why.



Lab 2

Global Average Temperature

Equipment List

- Ruler
- Meter Stick
- IR Thermometer "gun"
- Masking Tape
- incandescent lamp
- Computer

Note: When you arrive at your table, clear a space on your table that is approximately half the area and mark it off with masking tape. Then turn on the lamp so that it it pointing down at one portion of that empty space. You are "pre-heating" the table for measurements we will make below.

2.1 Introduction and Definitions

Today we consider the *Global Average Temperature*, which we have seen is the primary measure used to specify tha degree of global climate change over time. Specifically, we will perform some experiments and analyses to mimic the process by which this quantity is calculated. Obviously, there are many details that are used by professional climatologists that will will ignore, but we will focus on the two most important ideas: *area-weighted average* and *temperature anomalies*.

The **global average temperature** at a given moment in time, is defined to be (and calculated as) the weighted average of the temperature at every point on Earth, with weight for a given point being the area fraction assigned to that point. For example, if we restricted ourselves to just the United States, we could *estimate* the "US average temperature" as:

$$T_{\mathrm{US,avg}} = T_{\mathrm{MI}}\frac{A_{\mathrm{MI}}}{A_{\mathrm{USA}}} + T_{\mathrm{IN}}\frac{A_{\mathrm{IN}}}{A_{\mathrm{USA}}} + T_{\mathrm{IL}}\frac{A_{\mathrm{IL}}}{A_{\mathrm{USA}}} + \cdots$$

where you can see that the temperature value assigned to a state is weighted by the fraction of area (measured, e.g., in square kilometers) that state has in the total area of the US. This can be written equivalently as

$$T_{\mathrm{US,avg}} = \frac{T_{\mathrm{MI}}\,A_{\mathrm{MI}} + T_{\mathrm{IN}}\,A_{\mathrm{IN}} + T_{\mathrm{IL}}\,A_{\mathrm{IL}} + \cdots}{A_{\mathrm{USA}}}$$

This is a *weighted average* because the sum of all the factors in the numerator, $A_{\mathrm{MI}}+A_{\mathrm{IN}}+A_{\mathrm{IL}}+...$, adds up exactly to the value in the denominator (or, in the first question, the sum of all the weights, e.g., $\frac{A_{\mathrm{MI}}}{A_{\mathrm{USA}}}$, add up to one). The calculation above would only be an estimate of the average temperature, because we have used only 50 points (one for each state) instead of "all" points in the US. To improve our estimate[1], we could use multiple points per state (perhaps using a thermometer in each major city). Today we will perform a number of calculations to demonstrate this technique.

However, it is not actually the average temperature that is used to track climate change, but what is called the **global average temperature anomaly**. The average temperature anomaly is calculated as follows. (1) A *reference time range* is chosen (usually a span of a decade or more, e.g., 1950–1980), over which temperatures will be averaged to determine a (local) reference temperature value. (2) At each thermometer location, the *local reference temperature* is calculated as an average over the reference time range. (3) The temperature anomaly (over time) at a given thermometer is calculated by subtracting off the local reference temperature from all temperature values. (4) An area-weighted average of the temperature anomalies is calculated over the entire Earth.

2.2 Experiments and Activities

2.2.1 Temperature Anomalies

Recall Figure 2.1 from the Dessler textbook, showing the temperature over time for two Texas cities, and then their respective temperature anomalies:

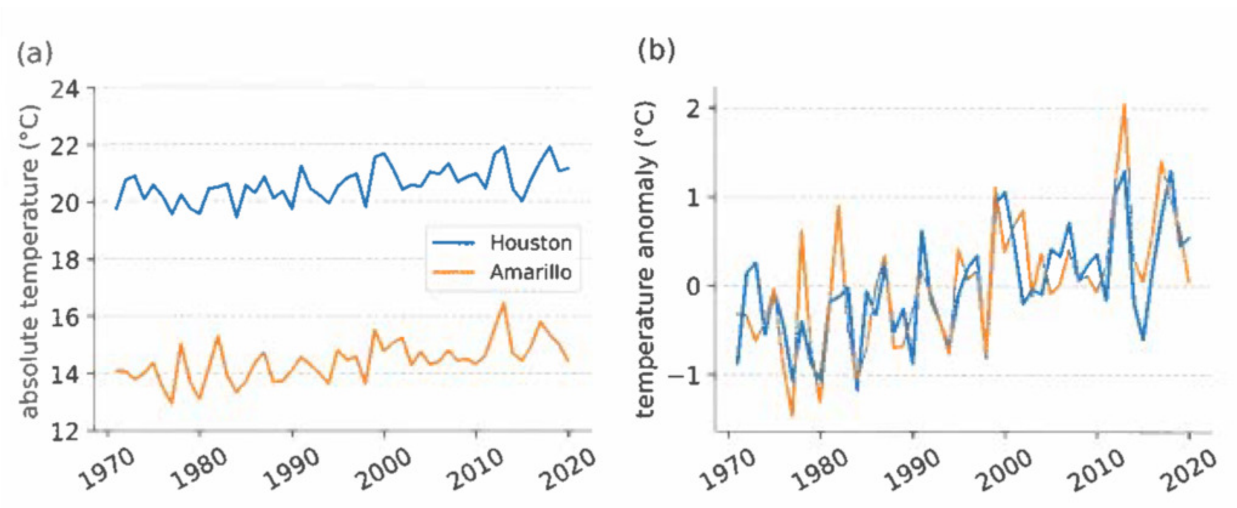
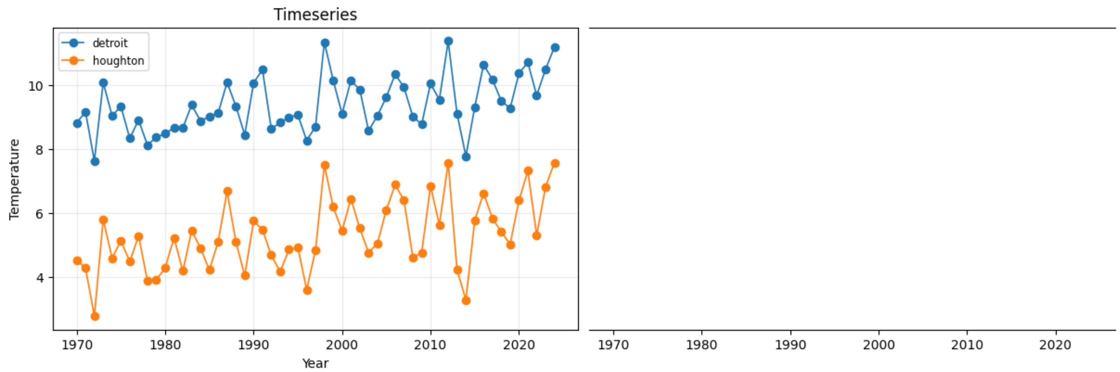


Figure 2.1 (a) Annual temperatures (°C) in Houston, TX (Bush-IAH station) and Amarillo, TX (Amarillo International Airport station). (b) Temperature anomalies (°C) at these stations, relative to the 1980–2010 average. Data are derived from breakpoint-adjusted monthly station data from Berkeley Earth (http://berkeleyearth.org/data/, retrieved May 21, 2020).

[1]Technically: when the global average temperature is calcuated, the discrete temperature measurements at weather stations are used to produce a continuous "function" of temperature at every point on earth by interpolation between the stations; then that continuous function is "integrated" (calculus) over the total area.

Use the similar graph below, for two Michigan cities. (i) Determine a reference time period (ii) Estimate the refernece temperature for each (iii) Make an anomaly temperature timescale at right, and plot the values at three years for each city.



2.2.2 The approach to an average

Find the dataset of your own collected temperature measurements (submitted by you and your classmates to the google form this past week) in the "Results" link on Blackboard. For each of the two types of temperatures (air and sky) perform the following analysis:

- Copy the data from the spreadsheet of all data into your own Google sheet (or Excel spreadsheet).
- Clean the data column to make sure it contains only one numerical value per row. Save the single column of cleaned data as a csv file.
- Find the "Scatter-Histogram-Average" code on Blackboard. Copy the blocks of code into a new Google Colab notebook. (This step does not need to be done twice).
- Run the code blocks. The last block will prompt you to upload your csv file and then make a plot.

2.2.3 Global average temperature (of your table)

Perform a sequence of area-weighted averages of the temperature of your table in the previously marked off region, by completing the following steps:

1. Measure the total area that you have marked off and record this value.
2. Choose one point in the total area and measure the temperature using your IR thermometer gun. This is **Estimate 1**.
3. Using masking tape, partition your total area into 3–4 smaller areas. Measure the area of each one and record their values. Also draw a picture to show the way you have partitioned and to give names to the sub-areas (e.g., A_1, A_2, etc).
4. Measure and record the temperature at one point in each of the sub-areas. Create a table with columns [name, area (units), Temperature (units)].
5. Using the method described above (average US temperature), calculate an area-weighted temperature from your data. This is **Estimate 2**.

6. Subdivide your table even further, such that you have about twice as many sub-areas. Repeat steps 3–5 to calculate **Estimate 3**.

2.2.4 Global average temperature (of the Earth land surface)

We will now attempt to find the global average temperature anomaly for the Earth. Find the "Get annual temperature data for one location" code on Blackboard, and import the code blocks into a new Google Colab notebook. We will make three estimates:

- **Estimate 1:** Using only one location on Earth (your choice).
- **Estimate 2:** Using one location on each continent (again, your choice per continent).
- **Estimate 3:** Using about twice as many locations, spread out across the Earth.

In each trial you will take the following steps:

1. Use the "Get annual temperature data" code to download an annual average temperature dataset for one or more location over the 1970–2024 time range.
2. Choose a time range over which to determine the local reference average (e.g., 1970–1990).
3. Open this csv file (in Google sheets or Excel), and highlight the cells in that reference time range to find the reference average value.
4. Use the spreadsheet tools to make a new temperature anomaly column, in which the reference average is subtracted off from the temperature.
5. In Estimates 2 and 3, where you have multiple locations, create a new spreadsheet with a single date column at left and then a temperature anomaly column for each location.

To make the global average calculation, we will need to edit this file in a few additional steps:

- Look up online the surface area of each continent in square kilometers and record them. To make these values more understandable, let's convert each into units of "Michigan mitten". The lower peninsula of Michigan has an area of almost exactly 100,000 square kilometers. So you can divide each continental area by that value to obtain the area in "mittens".
- In your multiple location spreadsheet, add two blank rows at top. For each anomaly column, put the name in the first row, and the area (in mittens) in the second row. In the first column (of dates) you can leave the first two rows blank.
- Locate the "Get weighted average of timeseries" code on blackboard and import the blocks into Colab. It will allow you to import your csv file. If you use the format prescribed above (two extra rows above the temperature vs time data) then it should produced a weighted temperature anomaly graph.