Jocelyn Reahl and Leafia Sheraden Cox
Prof. Hilary Palevsky
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The Sun is a Deadly Laser: Assessing the Accuracy of the One-Dimensional Single-Layer Atmosphere Model Using a Data Science Approach

Background and Motivations

The Earth's climate is an extremely dynamic system that is controlled by a wide variety of variables, from the Earth's surface albedo to the Sun's incident solar flux on the Earth's surface. Earth's climate is frequently modeled using general circulation models (GCM's), which are climate models that utilize Navier-Stokes equations to model the general circulation of a planetary atmosphere or ocean on a rotating sphere. Although these models can generate detailed predictions of the Earth's weather and long-term climate, they require massive amounts of supercomputing power. From an educational perspective, these models' computing demands make GCM's inaccessible to interested undergraduates and professors that want to practice global climate modeling in the classroom on personal computers.

Luckily, other climate models exist, particularly the one-dimensional single-layer atmosphere model. The single-layer model's inherent assumptions of the Earth's atmosphere as a single, non-circulating column of air and of the Earth as a perfect blackbody make the model's calculations simple enough to be performed on a personal computer. Although this model is typically used to estimate the surface and skin temperatures of a single column of air, the model can be expanded into a rough global climate model by dividing the Earth's surface into a grid and defining each grid space as a single column of non-circulating air that has no lateral transport of heat between columns.

The authors are aware that the single-layer model and this highly idealized global model are extremely inaccurate compared to even rudimentary GCM's. We are not interested in defining a new, simpler alternative to a GCM; rather, we want to assess the accuracy of our single-layer global climate model (SLGCM) by comparing the observed surface temperatures with our generated surface temperatures. In this study, we plan to use MIDAS global solar irradiance data from the NCAS British Atmospheric Data Centre together with global albedo observations from NASA's Earth Radiation Budget Experiment (ERBE) in a 5° x 5° gridded SLGCM to generate modeled surface temperatures for each grid space. Next, we plan to compare these modeled temperatures with observed temperatures from the HadCRUT4 dataset developed by the Climatic Research Unit (University of East Anglia) in conjunction with the Hadley Centre (UK Met Office).

Research Questions

This study seeks to understand how accurate the surface temperatures generated from our SLGCM are compared to observed surface temperatures. From this, we are also interested in understanding what regions on Earth, if any, have the largest difference between the observed and modeled temperatures ΔT. Since the MIDAS dataset records global solar irradiance over spatial and temporal timescales, we are also curious about how the difference between modeled and observed temperatures changes over seasonal and annual cycles. Finally, the methods outlined in this study provide a foundation for a future undergraduate climate modeling assignment.

Hypotheses

Since the SLGCM is an idealized climate model that is comprised of a grid of non-circulating and non-interacting columns of air, we expect the absolute value of the difference between the observed temperatures and our generated temperatures $|\Delta T|$ to be large because the model does not account for multiple other variables like atmospheric circulation, ocean circulation, and topography. Since the MIDAS solar irradiance observations are raw solar irradiance data, we expect that there should not be significant latitudinal differences in ΔT between low and high latitudes. However, we expect that there should be a large ΔT for coastal and oceanic regions since the climates of these areas are heavily influenced by oceanic circulation. We also expect annual changes in the mean solar irradiance incident on a given grid space to have a significant influence on the modeled surface temperatures, but to have a negligible effect on the observed temperatures.

Methods and Data Sources

Methods and SLGCM Calculations

For this SLGCM, we assume that the Earth's atmosphere is made up of a series of 5° x 5° columns of non-circulating air that do not thermally interact with each other. For simplicity, we also assume that the Earth is a perfect blackbody, with an emissivity ε of 1. We generate the ground temperature T_g of each grid space on a planetary surface using the following equation:

$$T_g = 2^{1/4}\left(\frac{q_s'(1-\alpha)}{4\sigma}\left(\frac{r_s}{R_p}\right)^2\right)^{1/4}$$

Where q_s' is the mean solar irradiance of the Sun on the grid space, α is the albedo of the grid surface, r_s is the radius of the Sun, R_p is the Sun-Earth distance, and σ is the Stefan-Boltzmann constant. Within the context of our datasets, the MIDAS Global Radiation Observations are equal to q_s' and NASA's ERBE albedo distribution is defined as α. The remaining variables are constant: we define r_s as $(695.508 \pm 0.026) \times 10^6$ m (Brown and

Christensen-Dalsgaard, 1998), R_p as 149.597 x 10^9 m (International Astronomical Union, 2012), and the Stefan-Boltzmann constant as 5.67 x 10^{-8} $W \cdot m^{-2} \cdot K^{-4}$ (Blevin and Brown, 1971).

To compare the generated surface temperatures T_g with the observed surface temperatures T_{obs}, we take the difference between the observed surface temperatures and the generated surface temperatures, ΔT. Negative values indicate that T_g is lower than T_{obs}, and positive values indicate that T_g is higher than T_{obs}.

MIDAS Global Radiation Observations

For this study, we use the Global Radiation Observations from the Met Office Integrated Data Archive System (MIDAS) collated by the National Center for Atmospheric Science in the United Kingdom (Met Office, 2006). The data includes monthly and yearly global solar irradiation measurements from stations around the world with additional hourly and daily measurements from UK based stations. The dataset extends from 1947 to 2019 with variation in data coverage between stations. The global solar irradiation amount is reported in kilojoules per square meter over the observation period. The global solar irradiance is measured as the total solar radiation flux from the whole sky, covering wavelengths from UV to near-infrared. It is measured using a pyranometer mounted horizontally, facing upwards. A pyranometer is a thermopile with an absorptive upper surface. The dataset is classified as restricted access and access was requested via the Center for Environmental Data Analysis.

NASA Earth Radiation Budget Experiment (ERBE) Albedo

For this study, we use the Earth Radiation Budget Experiment's (ERBE) spatial distribution of percent albedo data from 1986 to 1987 (Barkstrom and Smith, 1986; Barkstrom et al., 1990). The ERBE was launched from the Space Shuttle Challenger aboard NASA's Earth Radiation Budget Satellite (ERBS) in October 1984 (NASA, 1996). The ERBE was designed around three Earth-orbiting satellites (the ERBS and two NOAA satellites), and it had the primary goals of determining, for at least one year: the Earth's average monthly energy budget and its monthly variations, the seasonal movement of energy from the tropics to the poles, and the average daily variation in the energy budget on a regional scale (every 160 miles) (Barkstrom, 1984).

HadCRUT4 Observed Temperatures and Temperature Anomalies

To generate observed temperatures over the relevant period covered by the MIDAS dataset, we use the HadCRUT4 dataset of gridded global historical temperature anomalies relative to the mean temperature over a 1961-1990 reference period (Morice et al., 2012) as well as the mean monthly temperatures between 1961-1990 (Jones et al., 1999). The HadCRUT4 global temperature record is jointly compiled by the Climatic Research Unit (CRU) and the Met Office, and the dataset has been central to all five Intergovernmental Panel on Climate Change (IPCC) reports. Since HadCRUT4 data are presented in the form of temperature anomalies, we work backwards to calculate the observed data by calculating the average mean temperature over the 1961-1990 reference period and then adding the yearly temperature anomalies from the HadCRUT4 dataset to them to compute the yearly mean observed temperature T_{obs} for a 5° x 5° grid.

Preliminary Analysis and Results

Global Radiation Observations

Data were averaged and organized by station, month, and year by reading in the dataset and cross referencing a second dataset containing all MIDAS stations along with their latitudes and longitudes. This dataset does not have many stations in the southern hemisphere so we anticipate large gaps in the global map. As the dataset is extremely large, no global data has been plotted. Furthermore, the code used to analyse the daily and hourly Greater London data from station 712 is still undergoing troubleshooting and modification.

Albedo

A plot of the ERBE percent mean albedo between November 1986 and January 1987 is shown in Figure 1. Since this dataset does not have any values for albedo above +70° latitude, the scope of our study is constrained to the region below +70° latitude.

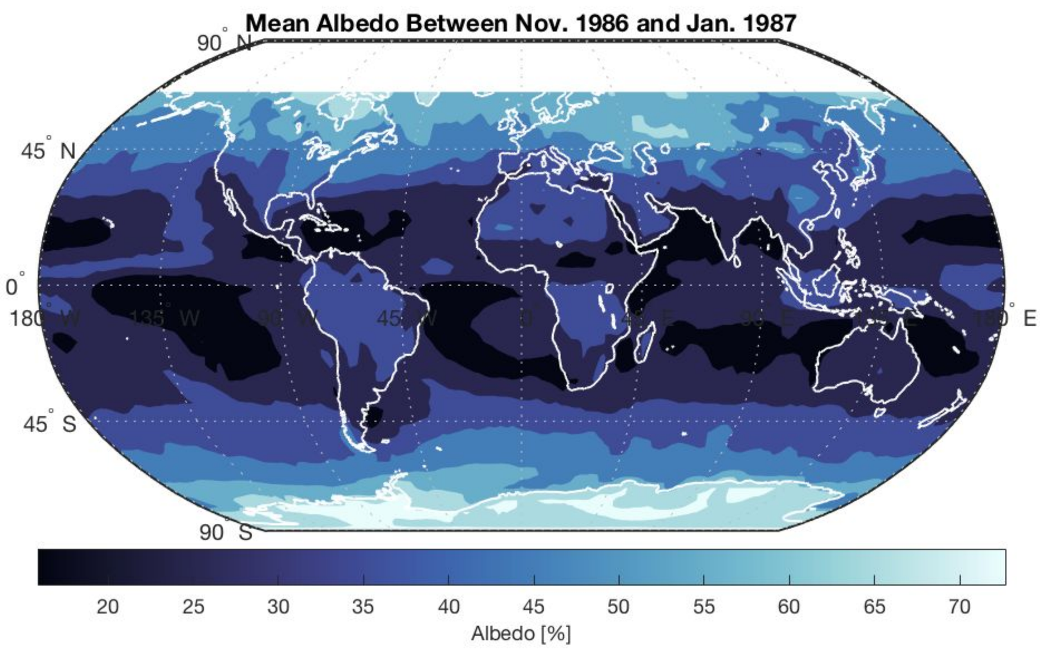

Figure 1. The percent mean albedo of the Earth from the ERBE instrument. The region above +70° latitude has no data.

Temperature

Before calculating the observed temperatures T_{obs}, we calculated the mean temperatures of the whole period between 1961-1990 by taking the mean of the mean monthly temperatures between 1961-1990 (Figure 2). After calculating the mean of the whole period, we calculated the observed temperatures by adding the temperature anomaly to the mean temperatures. The present-day observed temperatures are plotted in Figure 3. It is clear that the observed temperature record has large regions of missing values, and this result adds further constraints to the global coverage of our model. However, despite these missing values, these results are extremely promising and can certainly be used in our future calculations for the Version 2 for this project.

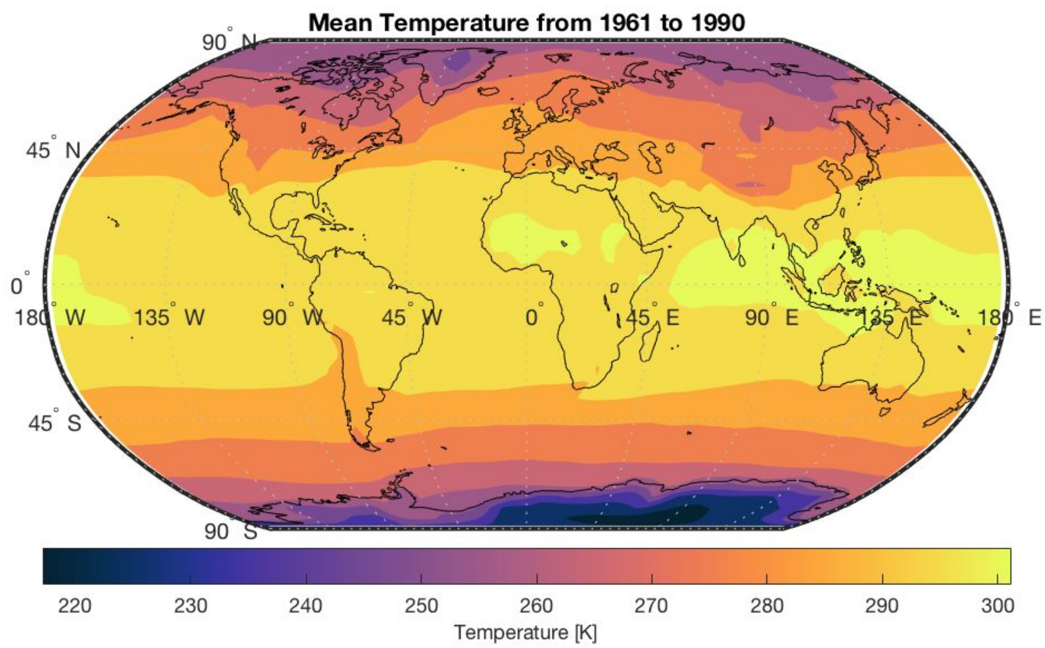

Figure 2. Mean temperature of the whole period from 1961 to 1990.

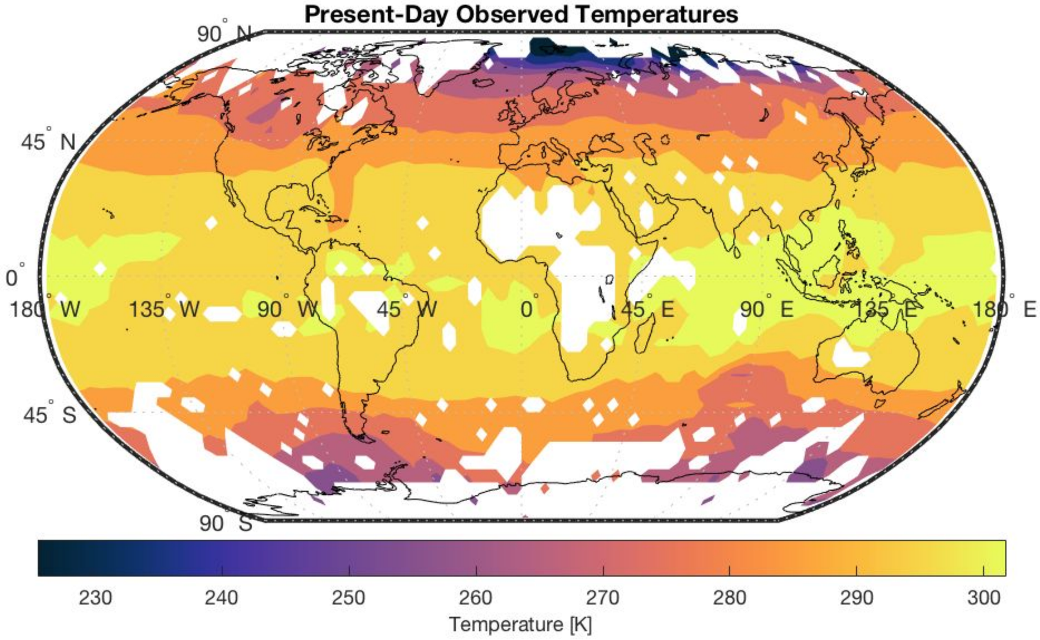

Figure 3. Observed temperatures at the present day. These temperatures were computed by adding the mean temperature between 1961-1990 to the temperature anomaly from the HadCRUT4 dataset.

Future Work

Moving on to the Version 2 of this project, we plan to use the datasets detailed in this Version 1 Report in the final calculations for our SLGCM. After computing our modeled surface temperatures T_g, we plan to take the difference between the observed temperatures from the HadCRUT4 dataset and the modeled surface temperatures. In creating this final graph, we will be able to constrain the magnitude of the difference between the observed and modeled temperatures ΔT. One major consideration for Version 2 of this project is whether or not to limit the number of lines read from each of the UK datasets in order to significantly cut down processing time. Another major step for Version 2 is finding a method of splitting the dataset into segments that can be run in parallel rather than in series as the most recent attempt to run the full dataset lasted over 23 hours before it had to be terminated manually. Further debugging of the global irradiance data is also necessary for plotting purposes.

Author Responsibilities

Leafia Sheraden Cox

Leafia is in charge of working with the MIDAS data and the ERBE data along with Jocelyn. She is primarily involved in data wrangling and data cleaning for the MIDAS dataset. She conducted the initial processing of the ERBE data and she is currently working to troubleshoot the code for the Station 712 MIDAS data to obtain a singular Irradiation map. She has made contributions to the writing and presenting of these findings, though her involvement is more programming-oriented.

Jocelyn Reahl

Jocelyn is predominantly in charge of working with the HadCRUT4 dataset. Previously, she was in charge of processing and plotting the GHCN-M v3 dataset. She is also heavily involved with writing and presenting these findings. Leafia and Jocelyn worked together to create the ERBE albedo plot, but she did not initially process the ERBE data. She is not in charge of processing the MIDAS data.

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