Temperature Anomaly GIS Demonstration Project

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INTRODUCTION

This project is a demonstration of how to analyze climate projections from a Global Climate Model (GCM) in a Geographic Information System (GIS). This demonstration projects uses climate datasets generated by the Community Climate System Model (CCSM) for the IPCC 4th Assessment Report and distributed through the NCAR GIS Initiative Climate Change Scenarios portal in a GIS format. In this demonstration, we compare model output of a present day climate with future climate projections. Many atmospheric and land variables are available from the CCSM and the GIS Climate Change portal. Here, we demonstrate GIS-based analysis of the Northern hemisphere summer months' temperature anomaly in 2030 with respect to the average summer temperatures of present-day climate. The demonstration is performed using ESRI ArcGIS software with an ArcInfo license.

Variable: Air Temperature (tas)
Region: Global
Analysis: Summer months' temperature anomaly in 2030 with respect to the average summer temperatures of present-day climate.
CCSM model runs:

- 20th Century Experiment; Ensemble Average; months June, July, August; years 1980-1999
- Scenario A2; Ensemble Average; months June, July, August; years 2021-2040

This is a comparison of the most current climate available from the CCSM runs with an ensemble average, the 20th Century Experiment to the SRES A2 scenario ensemble average for 2030. An ensemble average is composed of many ensemble members or model runs that have been averaged and used for climate projections. This method tends to discriminate between the real climate "signal" and "noise" which is inherent in the internal variability of individual model runs. One of the final outputs in this demonstration is an anomaly map of future projected temperature compared to the present-day climate. In climate science, an anomaly is a deviation of a meteorological variable from the normal (mean) value. Determining this anomaly is best accomplished by taking an average over multiple ensemble members, and also by averaging over multiple years within each ensemble average. In climate models, internal variability in the climate system is expressed both as year-to-year variability and as differences between ensemble members. It is helpful to have a large number of data points included in the average for both the present-day and future climates when computing an anomaly. For this exercise, there are available 9 ensemble members for the present-day climate simulation and 5 ensemble members for the future climate scenario. In order to reduce the year-to-year variability within the ensemble runs, an average was calculated over 20 using the period from the present-day simulations (1980-1999), and the period from the future scenario (2021-2040). For each year, a mean temperature was calculated for the Northern Hemisphere summer, as a weighted average for June, July, and August.

For purposes of this demonstration, it was determined that the final 20 years of the 20th Century Experiment was the most appropriate choice for comparison to the A2 Scenario ensemble average. Initial consideration was given to the Present Day Control Run model run which is also available from the GIS Climate Change Portal. This model run was performed by the CCSM model community to show that the model could obtain a stable and appropriate representation of current climate conditions. However, because the Present Day Control run does not contain multiple initial starting conditions (e.g., ensemble members) it is difficult to compare its' climate signal to a model run that does have multiple starting conditions (e.g., ensemble average). It is evident from the similar range of standard deviations about the mean (Figure 9) that a statistical comparison of the 20th Century Model Run and SRES A2 climate simulations is appropriate. This homogeneity of variance is not the case when comparing the Present Day Control run to the A2 scenario again due to the ensemble averaging as stated above.

For further information on the CCSM, ensembles, and IPCC SRES scenarios, please refer to the GIS Climate Change Portal.

GIS DEMONSTRATION METHODS

From the NCAR GIS climate change portal download the following shapefiles:

Region: Global
CCSM Model Run: 20th Century Experiment, Ensemble Average
Dates of Interest: (note: this is 3 separate file downloads)
    June: Start Year: 1980, End Year: 1999
    July: Start Year: 1980, End Year: 1999
    August: Start Year: 1980, End Year: 1999
Dataset: Atmospheric Data
Atmospheric Variable: Air Temperature (tas, k)
Download: Download shapefile

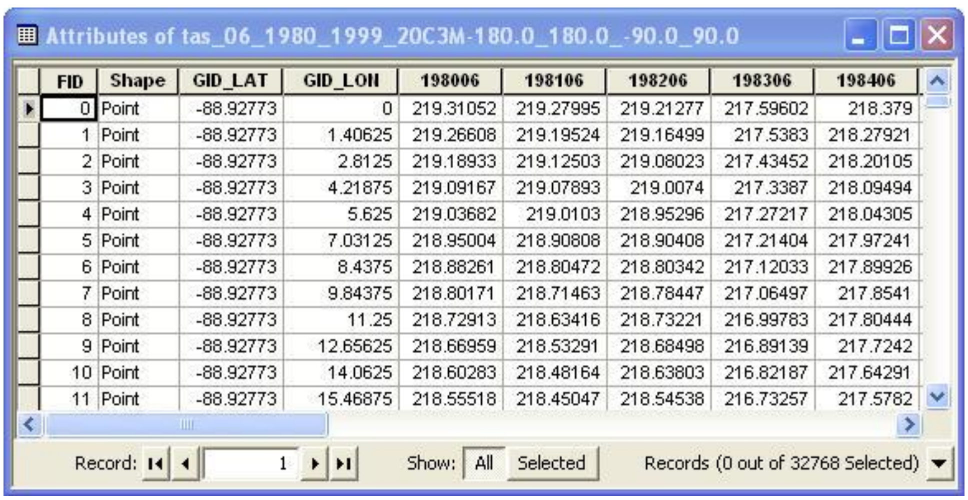
Region: Global
CCSM Model Run: Scenario A2, Ensemble Average
Dates of Interest: (note: this is 3 separate file downloads)
    June: Start Year: 2021, End Year: 2040
    July: Start Year: 2021, End Year: 2040
    August: Start Year: 2021, End Year: 2040
Dataset: Atmospheric Data
Atmospheric Variable: Air Temperature (tas, k)
Download: Download shapefile

There are 6 separate shapefiles downloaded from the NCAR GIS Climate Change Portal. They are:

<u>20th Century Experiment Ensemble Average Model Run:</u>
tas_06_1980_1999_20C3M-180.0_180.0_-90.0_90.0.shp
tas_07_1980_1999_20C3M-180.0_180.0_-90.0_90.0.shp
tas_08_1980_1999_20C3M-180.0_180.0_-90.0_90.0.shp

<u>Scenario A2 Ensemble Average Model Run:</u>
tas_06_2021_2040_SRESA2-180.0_180.0_-90.0_90.0.shp
tas_07_2021_2040_SRESA2-180.0_180.0_-90.0_90.0.shp
tas_08_2021_2040_SRESA2-180.0_180.0_-90.0_90.0.shp

As downloaded from the portal, the table of attributes associated with each shapefile represents each month (e.g., June) over the 20 year time frame as seen in Figure 1.


Attributes of tas_06_1980_1999_20C3M-180.0_180.0_-90.0_90.0

FID	Shape	GID_LAT	GID_LON	198006	198106	198206	198306	198406
0	Point	-88.92773	0	219.31052	219.27995	219.21277	217.59602	218.379
1	Point	-88.92773	1.40625	219.26608	219.19524	219.16499	217.5383	218.27921
2	Point	-88.92773	2.8125	219.18933	219.12503	219.08023	217.43452	218.20105
3	Point	-88.92773	4.21875	219.09167	219.07893	219.0074	217.3387	218.09494
4	Point	-88.92773	5.625	219.03682	219.0103	218.95296	217.27217	218.04305
5	Point	-88.92773	7.03125	218.95004	218.90808	218.90408	217.21404	217.97241
6	Point	-88.92773	8.4375	218.88261	218.80472	218.80342	217.12033	217.89926
7	Point	-88.92773	9.84375	218.80171	218.71463	218.78447	217.06497	217.8541
8	Point	-88.92773	11.25	218.72913	218.63416	218.73221	216.99783	217.80444
9	Point	-88.92773	12.65625	218.66959	218.53291	218.68498	216.89139	217.7242
10	Point	-88.92773	14.0625	218.60283	218.48164	218.63803	216.82187	217.64291
11	Point	-88.92773	15.46875	218.55518	218.45047	218.54538	216.73257	217.5782

Record: 1 Show: All Selected Records (0 out of 32768 Selected)

Figure 1. Attribute table of a shapefile downloaded from the NCAR GIS Climate Change portal showing air temperature (tas) in kelvin for multiple years for the month of June (06).

The description that follows is used to analyze and compare the 20th Century Experiment ensemble averages for the northern hemisphere summer growing season months to the projected A2 Scenario ensemble averages for the same months. Any model run and/or set of years available from the NCAR GIS Climate Change Portal can be similarly analyzed.

The first step is to combine the months that were downloaded as separate files into one file in order to calculate a June, July, and August average for each of the 20 years. This is done separately for each model run. For example, from the 6 separate shapefiles, derive the June, July, August (JJA) average for each year and for each model.

<u>20th Century Experiment Model Run 1980 - 1999</u>
1980 JJA average
1981 JJA average
1982 JJA average
.
.
.
1999 JJA average

Similarly, for Scenario A2

<u>A2 Scenario Model Run 2021 – 2040</u>
2021 JJA average
2022 JJA average
2023 JJA average
.
.
.
2040 JJA average

From this, for each unique cell from the CCSM model output, a JJA weighted average for each year is calculated for each model run. The weighted average is simply considering the unequal number of days within each calendar month, and weighting appropriately by multiplying each monthly average by the number of days within each month and dividing by the total number of days. For example, the equation below demonstrates the calculation for the 2021 JJA average:

$$JJA2021Avg = \frac{(30*202106)+(31*202107)+(31*202108)}{30+31+31}$$

Consider the invented GIS attribute tables below as the resulting fields and data necessary to compute the JJA 20 year average and standard deviation for each modeled cell output.

20th Century Ensemble Average, JJA, 1980 – 1999								
ID	JJA1980Avg*	JJA1981Avg*	JJA1982Avg*	…	…	JJA1999Avg*	JJA20YearAvg	Std

Scenario A2 Ensemble Average, JJA, 2021 – 2040								
ID	JJA2021Avg*	JJA2022Avg*	JJA2023Avg*	…	…	JJA2040Avg*	JJA20YearAvg	Std

***** Values are weighted averages

To calculate the JJA 20 year average, in ArcMap, join the attribute tables of the three separate months of each 20 year time period (see files below). This allows the JJA yearly weighted average to be calculated.

tas_06_2021_2040_SRESA2-180.0_180.0_-90.0_90.0.shp
tas_07_2021_2040_SRESA2-180.0_180.0_-90.0_90.0.shp
tas_08_2021_2040_SRESA2-180.0_180.0_-90.0_90.0.shp

Tables can be joined in ArcMap by right-clicking on the file name > Joins and Relates > Joins. Joins can be made using the Object ID, or FID, attribute. Using the three files above as an example, it is first convenient to copy and rename one of the files (e.g. tas_06_2021_2040_SRESA2-180.0_180.0_-90.0_90.0.shp) to tas_JJA_2021_2040_SRESA2.shp. Join each of the 07 and 08 attribute tables to this table. This creates one attribute table that has all months, June, July, and August, for all 20 years. It may be convenient at this point to label field names with an alias and resize columns for readability.

Add new fields to this table to accommodate the calculations of the yearly JJA weighted averages. For example, the fields can be named as JJA2021avg, JJA2022avg, …, JJA2040avg.

Calculate JJA weighted average for each year using Field Calculator in attribute table.

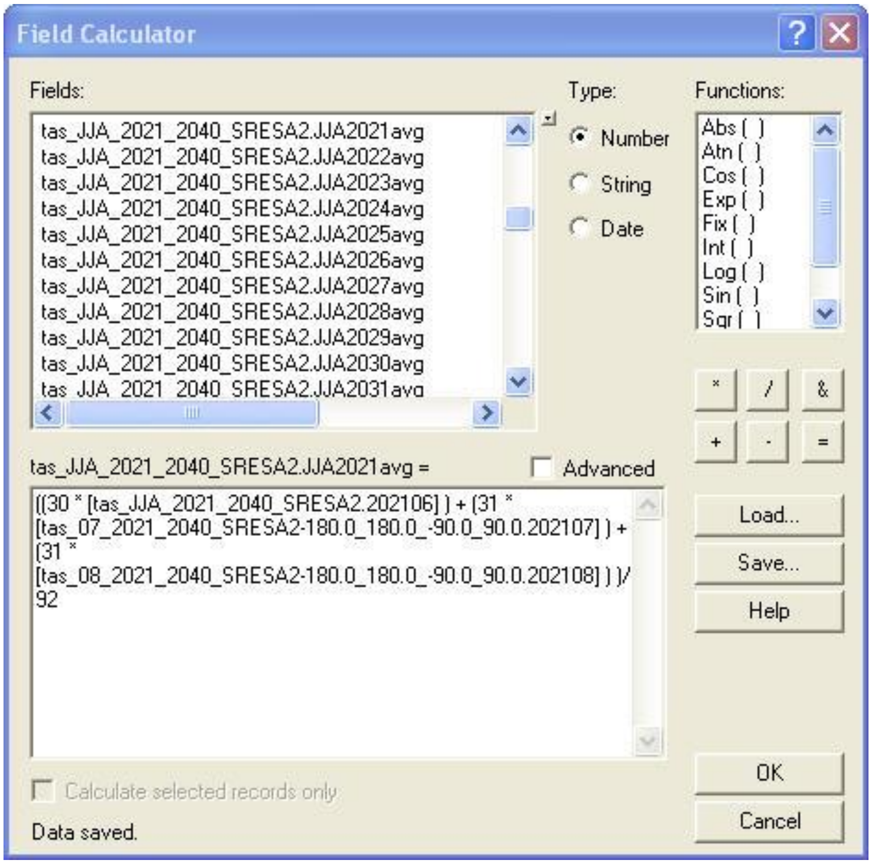


Figure 2. Attribute table field calculator showing the calculation of the JJA weighted average for year 2021 of the A2 Scenario model output data.

Add fields to accommodate the 20 year JJA average and standard deviation calculation (e.g., JJAA2avg, JJAA2std). From the individual year weighted averages, a 20 year mean and standard deviation over the growing season (JJA) is calculated again using Field Calculator in attribute table (Figure 3). For complete syntax please refer to Appendix A.

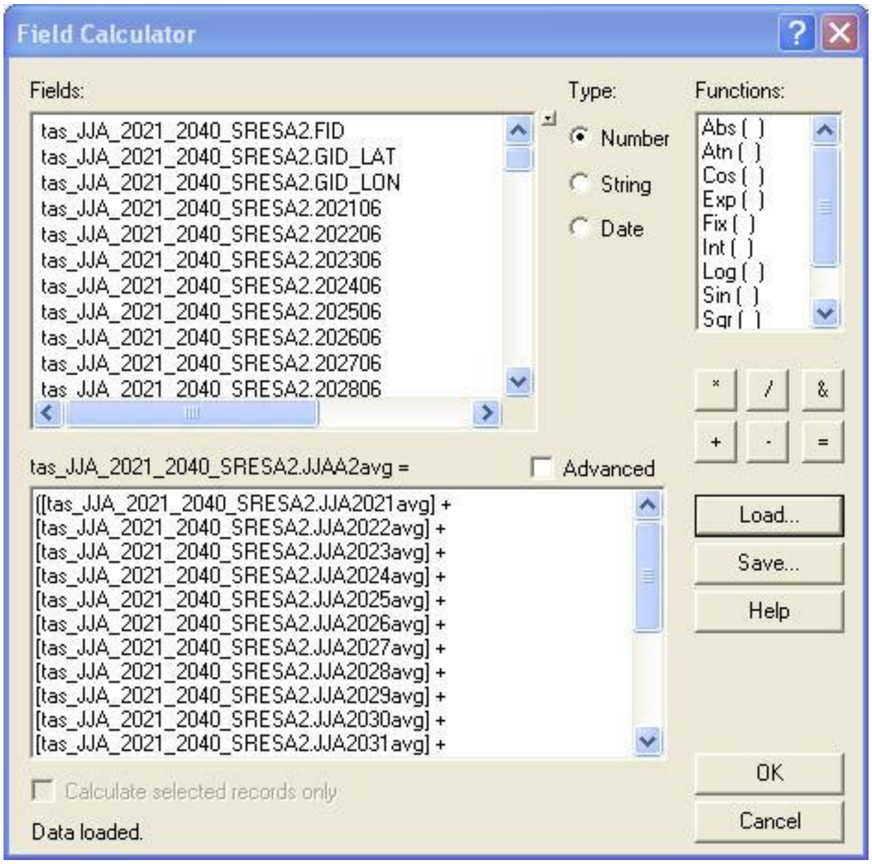


Figure 3. Attribute table field calculator showing the calculation of the JJA 20 year average for the A2 Scenario model run years 2021-2040.

The calculation for the standard deviation follows the formula below and is shown in Figure 4 and Appendix A.

$$\sigma_{N-1} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(x_i - \bar{x}\right)^2}$$

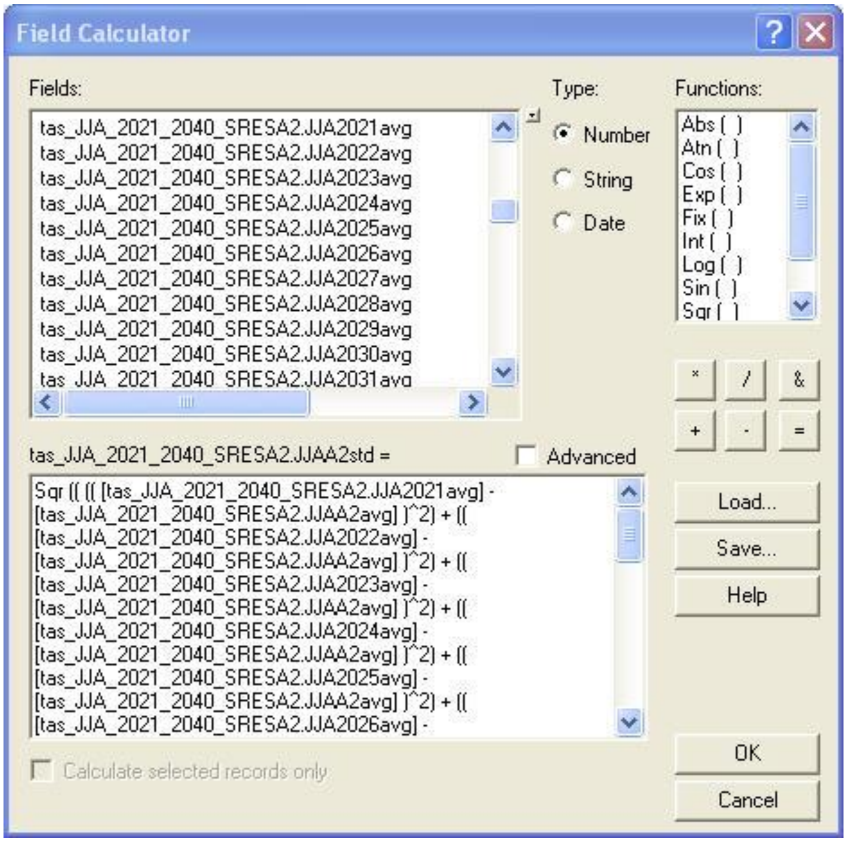


Figure 4. Attribute tables field calculator showing the calculation of the standard deviation of the 20 year time period 2021-2040 for the A2 scenario output.

Following the same procedures as outlined above, calculate a JJA 20 year average and standard deviation for the CCSM 20^{th} Century Experiment model run for the years 1980-1999. The results of average JJA temperatures for both model runs are shown in Figure 5. Please note that these maps render point shapefiles that were downloaded from the NCAR GIS Climate Change Portal and display point features, centroids of CCSM grid cells.

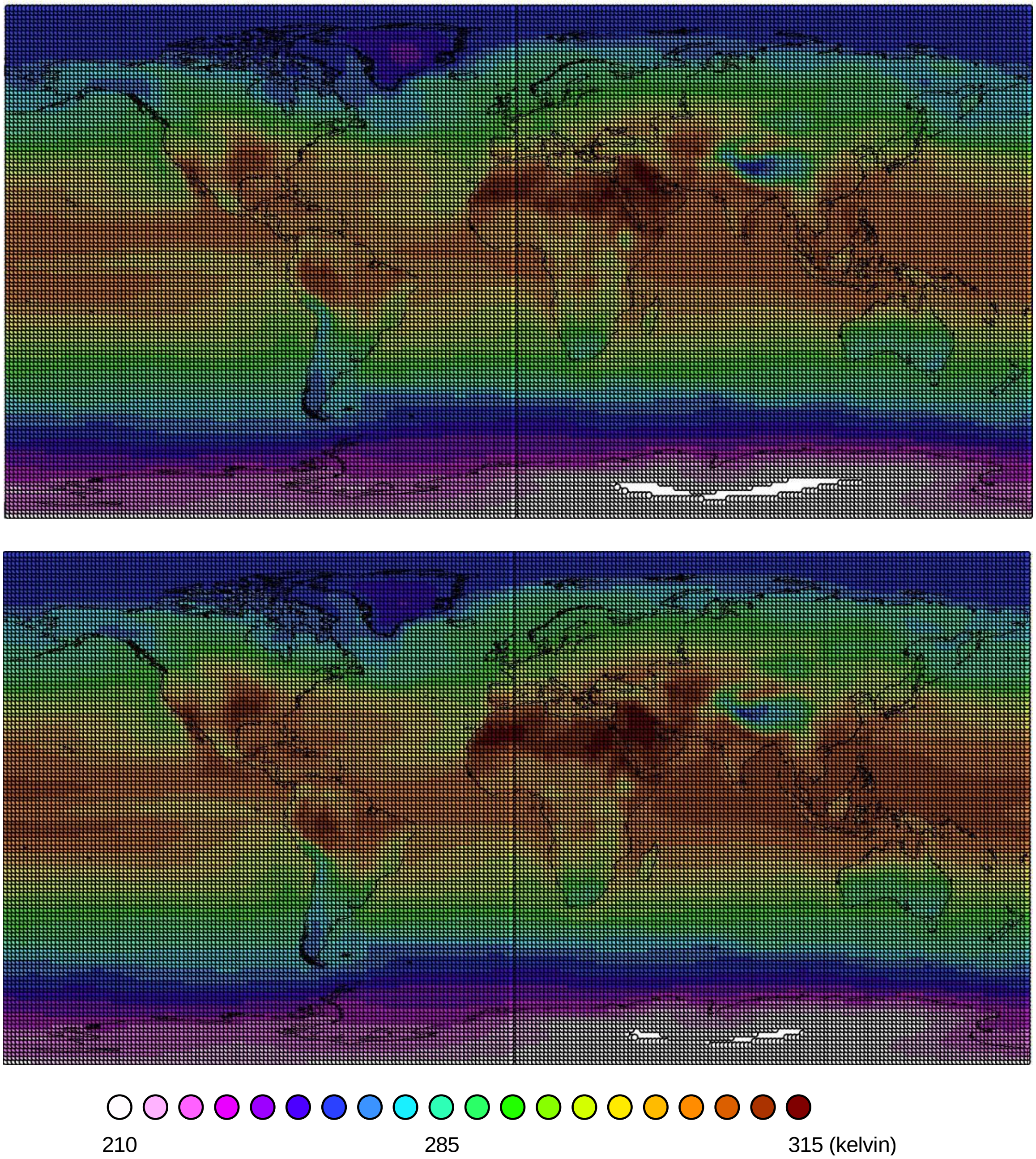


Figure 5. CCSM Model Output – Mean JJA air temperature (tas) in kelvin. Top figure: 20th century model run ensemble average, average JJA for years 1980 - 1999. Bottom figure: A2 Scenario ensemble average, average JJA for years 2021 - 2040.

At this point, it is convenient to perform a Spatial Join of the point shapefiles with the CCSM global polygon shapefile (Figure 6). The CCSM polygon shapefile and additional documentation are available from the NCAR GIS Initiative Climate Change Portal. The polygon layer was derived using the 4 corner coordinates, based on latitude and longitude, for each grid cell of the CCSM output data. This creates a rectangular grid (referred to as a Gaussian grid) often used in scientific modeling on a sphere. The polygon file is in the same CCSM-defined projection as the CCSM climate change data - a Geographic Coordinate System on a perfect sphere with a radius of 6371.22 km. With this polygon layer, the attributes of the climate change data (which are downloaded as a point shapefile from the Climate Change Portal) can be appended to the corresponding polygon to get an accurate spatial distribution of the modeled climate data. Each point is the centroid of the corresponding polygon cell.

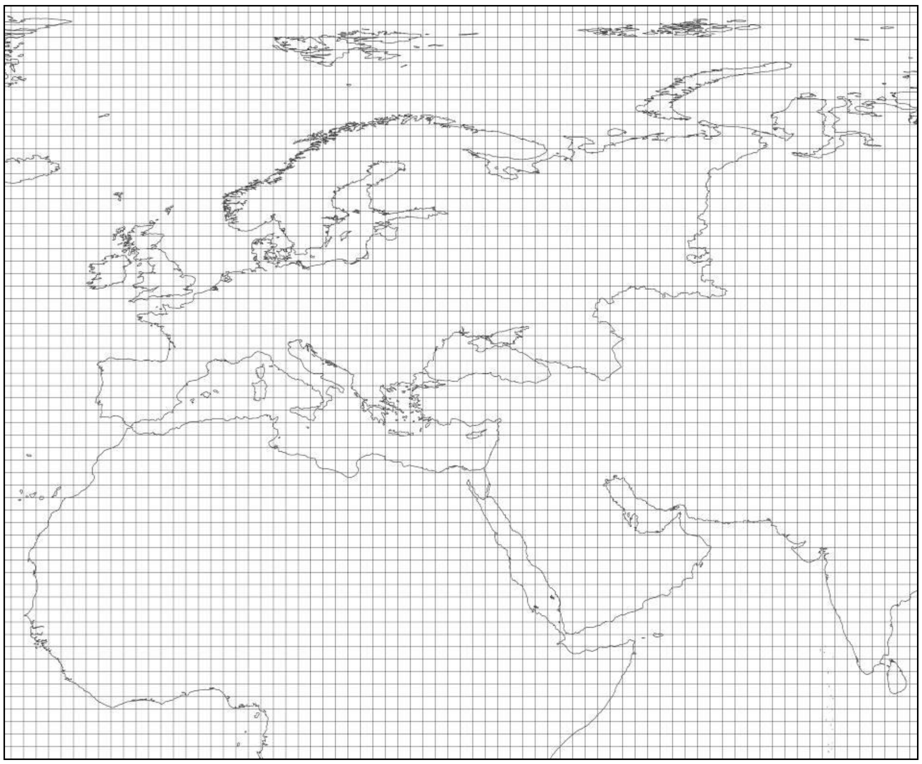


Figure 6. CCSM polygon shapefile. The CCSM model output points can be joined with the polygon file to accurately fill the spatial extent of each model run cell.

In ArcGIS, the Spatial Join tool creates a table join in which fields from one layer's attribute table are appended to another layer's attribute table based on the relative locations of the features of the two layers. The Spatial Join tool is found in ArcToolbox > Analysis Tools > Overlay > Spatial Join (Figure 7).

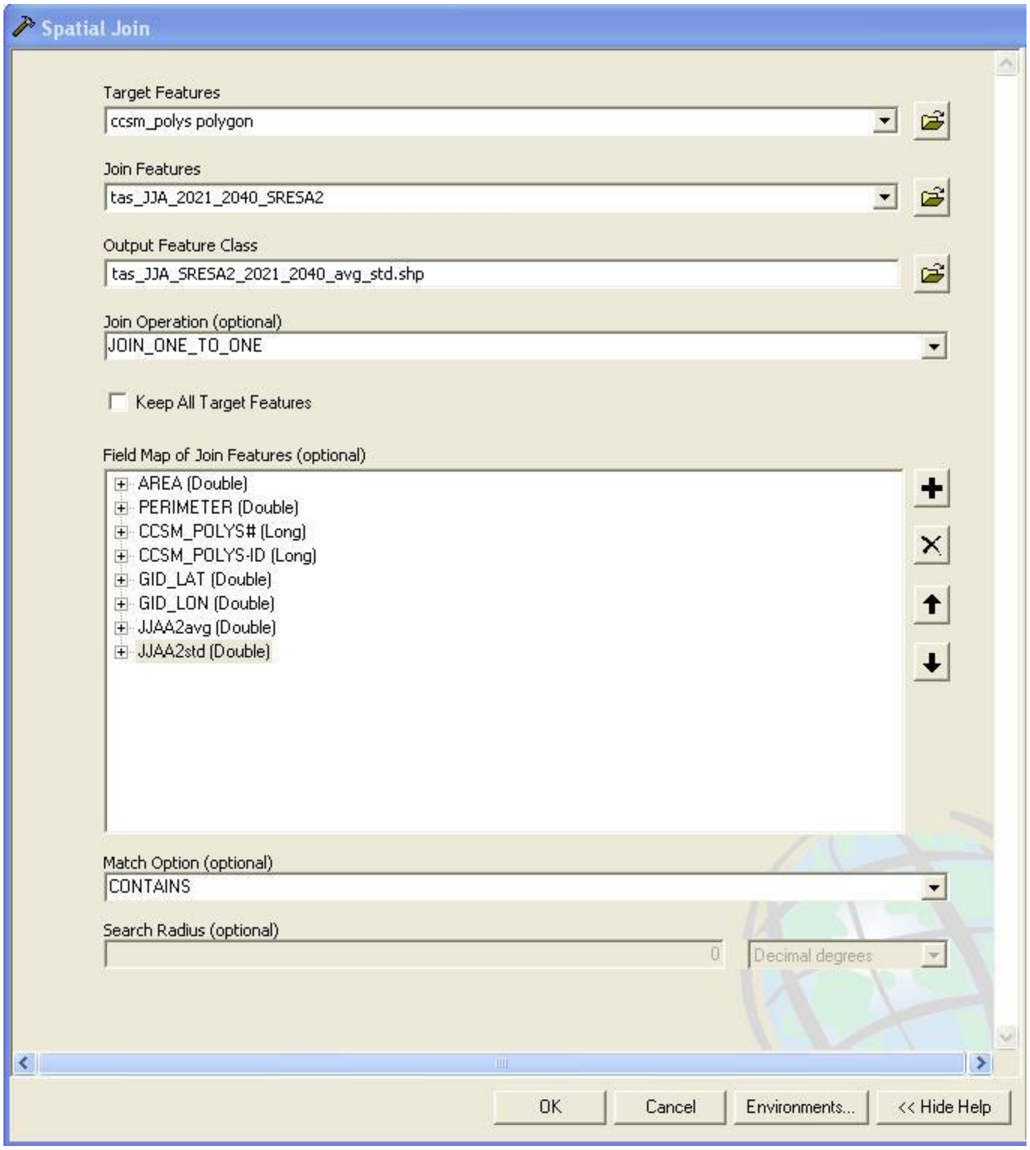


Figure 7. The Spatial Join Tool showing the join of the CCSM polygon layer with the attributes of the data from the A2 scenario.

Results are shown in Figure 8 where average air temperatures for each model run are spatially joined with the CCSM polygon layer. In Figure 9, the standard deviations for each model run are shown also spatially joined with the CCSM polygons. Notice also in Figure 9 that the standard deviations maps show a similar range in values which allows for a robust comparison of the model means. The low range of variation suggests that the values represent an appropriate climate signal for each time period.

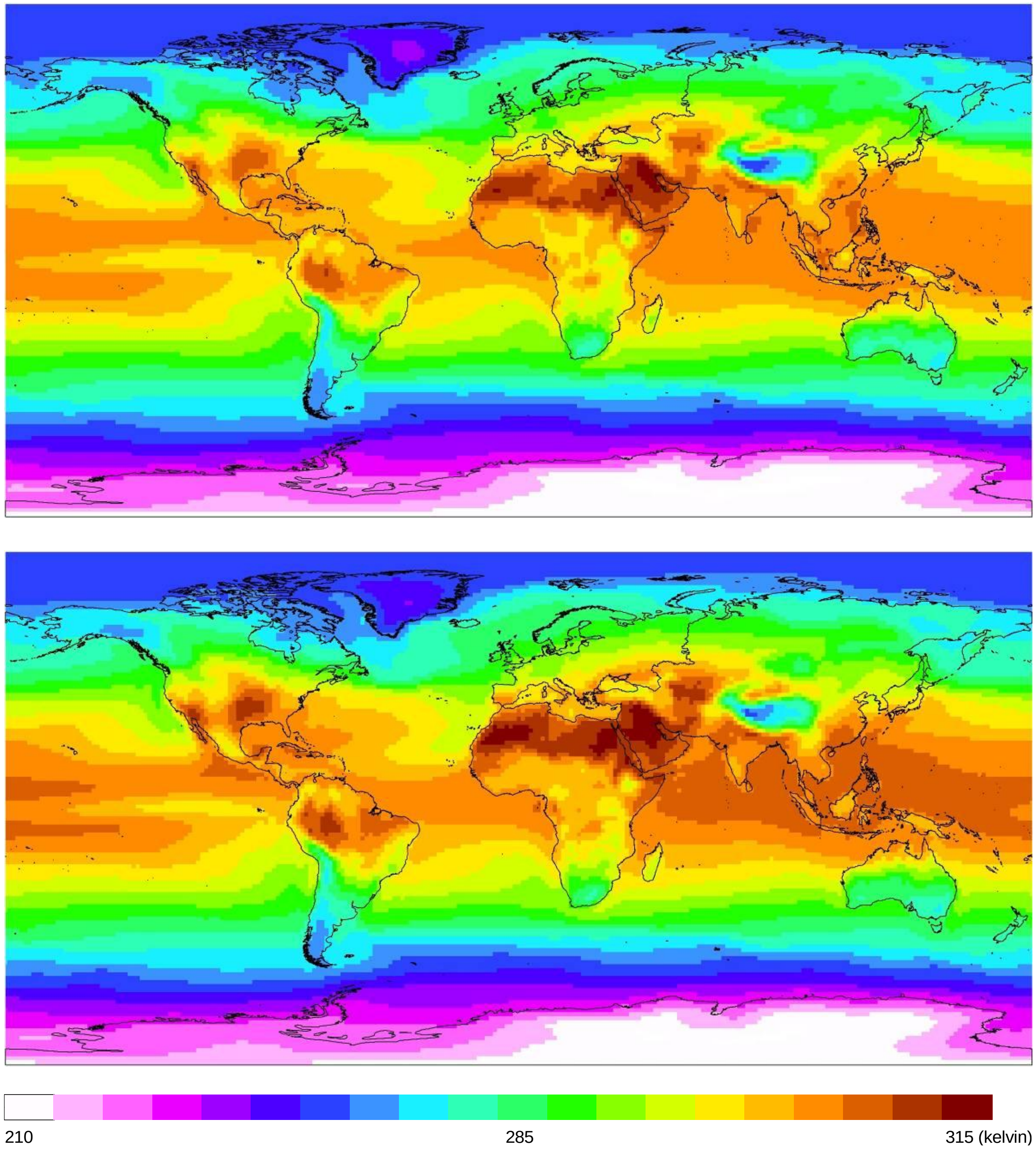


Figure 8. CCSM model output spatially joined with the CCSM polygon shapefile. Mean JJA air temperature (tas) in kelvin. Top figure: 20th Century Experiment model run ensemble average, average JJA for years 1980 – 1999. Bottom figure: Scenario A2 ensemble average, average JJA for years 2021 - 2040.

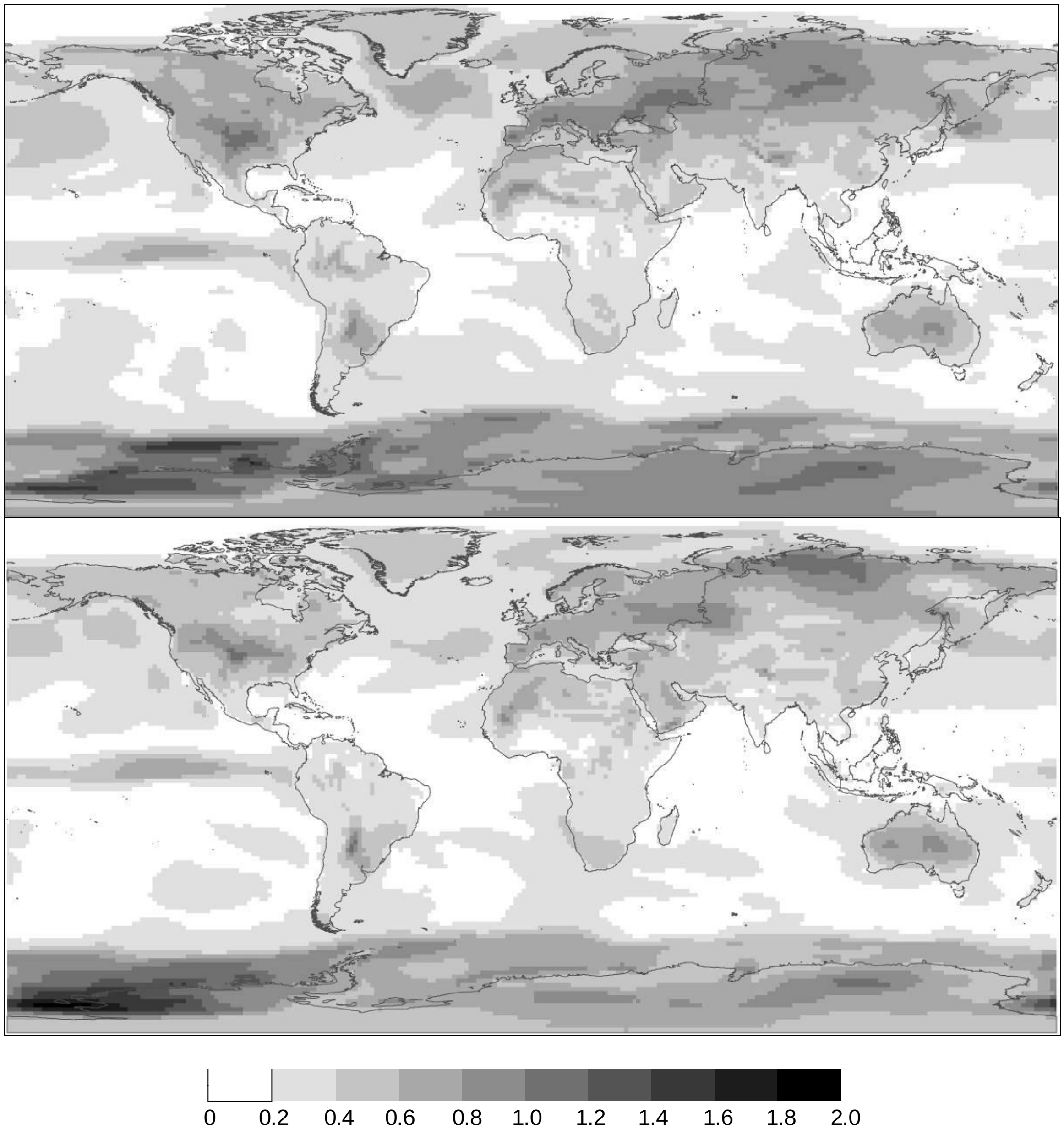


Figure 9. Standard deviation spatially joined with the CCSM polygon shapefile. Standard deviation spatially represented within each CCSM model cell showing deviation from the mean over the 20 year evaluation period. Top figure: 20th Century Experiment model run ensemble average JJA for years 1980 – 1999. Bottom figure: Scenario A2 model run ensemble average JJA for years 2021 - 2040.

The resulting files can now be used to determine a difference (or anomaly) map which will compare the JJA temperature of the present-day climate simulations to the temperatures projected for 2030 using A2 emission scenario. From these anomaly calculations, statistical characterizations such as significant variance from the mean, shown below as a student's t-test, can be derived.

In ArcMap Tables, Join Tables, tas_JJA_SRESA2_2021_2040_avg_std with tas_JJA_20C3M_1980_1999_avg_std. Then, right click, > Data > Export Data

Save as
tas_JJA_anomalies2021_2040-1980_1999

Add two new fields to this attribute table for the anomaly and t-test calculations. To calculate Anomaly, in Field Calculator, subtract the JJAA2avg from the JJA20Cavg (Figure 10).

Attributes of tas_JJA_anomalies2021_2040-1980_1999

FID	Shape	Join_Count	AREA	PERIMETER	GID_LAT	GID_LON	JJA20CAVG	JJA20CSTD	JJAA2avg	JJAA2std	Anomaly	t_test
0	Polygon	1	2.484534	6.34606	88.92773	-178.59375	271.82301	0.14192	272.1578	0.09286	0.33479	8.82797
1	Polygon	1	2.484534	6.34606	88.92773	-177.1875	271.82149	0.14187	272.15688	0.09299	0.33539	8.84226
2	Polygon	1	2.484534	6.34606	88.92773	-175.78125	271.81975	0.14182	272.15574	0.09313	0.33599	8.85625
3	Polygon	1	2.484534	6.34606	88.92773	-174.375	271.81787	0.1418	272.15442	0.09328	0.33655	8.86758
4	Polygon	1	2.484534	6.34606	88.92773	-172.96875	271.8159	0.14181	272.15298	0.09344	0.33708	8.8765
5	Polygon	1	2.484534	6.34606	88.92773	-171.5625	271.81374	0.14182	272.15138	0.09362	0.33764	8.88563
6	Polygon	1	2.484534	6.34606	88.92773	-170.15625	271.81141	0.14182	272.1497	0.09378	0.33829	8.89812
7	Polygon	1	2.484534	6.34606	88.92773	-168.75	271.81016	0.14187	272.14886	0.09381	0.33870	8.90585
8	Polygon	1	2.484534	6.34606	88.92773	-167.34375	271.80958	0.14192	272.14857	0.09376	0.33899	8.91273
9	Polygon	1	2.484534	6.34606	88.92773	-165.9375	271.80879	0.14196	272.14807	0.09373	0.33928	8.91948
10	Polygon	1	2.484534	6.34606	88.92773	-164.53125	271.80793	0.14201	272.1475	0.09372	0.33957	8.9252
11	Polygon	1	2.484534	6.34606	88.92773	-163.125	271.80699	0.14205	272.14686	0.09374	0.33987	8.93075
12	Polygon	1	2.484534	6.34606	88.92773	-161.71875	271.80599	0.14208	272.14617	0.09373	0.34018	8.93787

Record: 0 Show: All Selected Records (0 out of 32768 Selected) Options

Figure 10. Attribute table of the anomalies polygon shapefile.

Summer months' temperature anomaly in 2030 with respect to the average summer temperatures of present-day climate is shown in Figure 11.

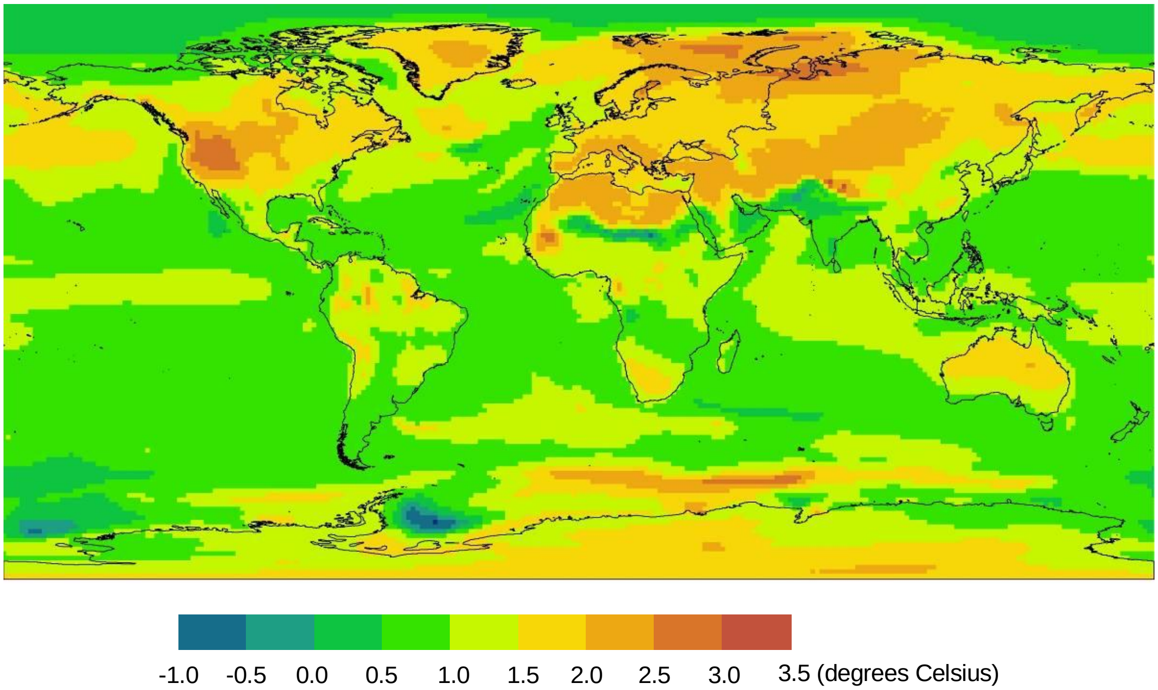


Figure 11. Temperature anomaly map showing the difference of the CCSM model runs; JJA 20 year average for Scenario A2 years 2021-2040 subtracted from the JJA 20 year average 20th Century Experiment Model Run years 1980-1999.

Statistical analysis, such as a t-test, can be used to assess whether the calculated means *for each point* of the two time periods are *significantly different*.

Student's t-test calculations were derived from the general formula:

$$t = \frac{\overline{X}_1 - \overline{X}_2}{\sqrt{\frac{\sigma_1{}^2 + \sigma_2{}^2}{N}}}$$

Where, X_1 and X_2 are the means of the two groups that are being compared (such as two climate simulations in a given point) and σ_1 and σ_2 are the standard deviations (Figure 12). The results of the t-test for this demonstration project (t(38), $p < 0.05$) show that greater than 98% of the mean summer temperatures for the two time periods are significantly different. A small sample of those results is seen in the last column (t-test) of the attribute table in Figure 10.

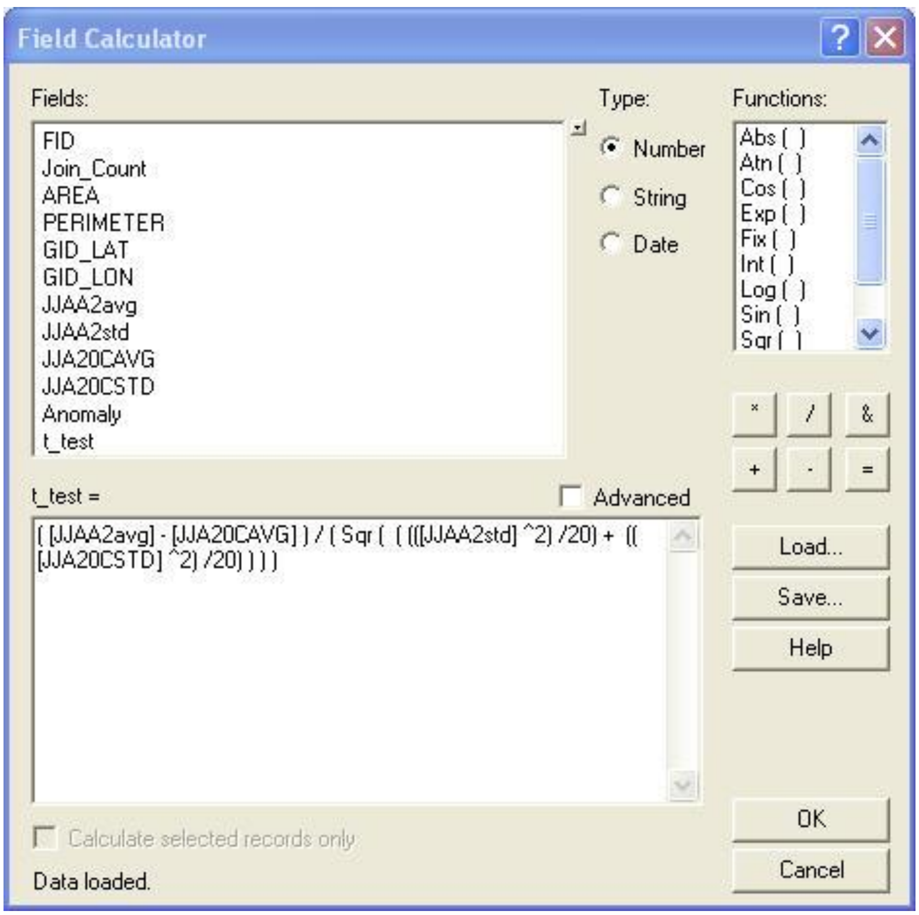


Figure 12. Field calculator showing the calculation of the t-test to determine significant differences of the average surface temperature of the 20th Century Experiment (JJA 1980-1999) and the A2 Scenario (JJA 2021-2040).

CONCLUSIONS

This example shows how to analyze and compare CCSM model runs, available through the GIS Climate Change Scenarios portal, in a GIS. This demonstration used one variable, air temperature, and compared simulations of a present-day climate to a projected climate of 2030. Same method can be applied to other, scenarios, variables and time periods that are available from the CCSM and the GIS portal. In addition, within a GIS framework, additional spatial information such as land use/land cover change, population projections, or any other environmental and social spatial data of interest can be used for climate change impacts studies. For example, Figure 13 shows the summer months' temperature anomalies (as derived in this demonstration project) with the US Census-projected patterns of elderly population for the United States in 2030. These preliminary results show that regions with increased summer temperatures will also see influx of elderly population (age 65 and older), with several western and northern plains states among top 10 in the percentage of elderly population.

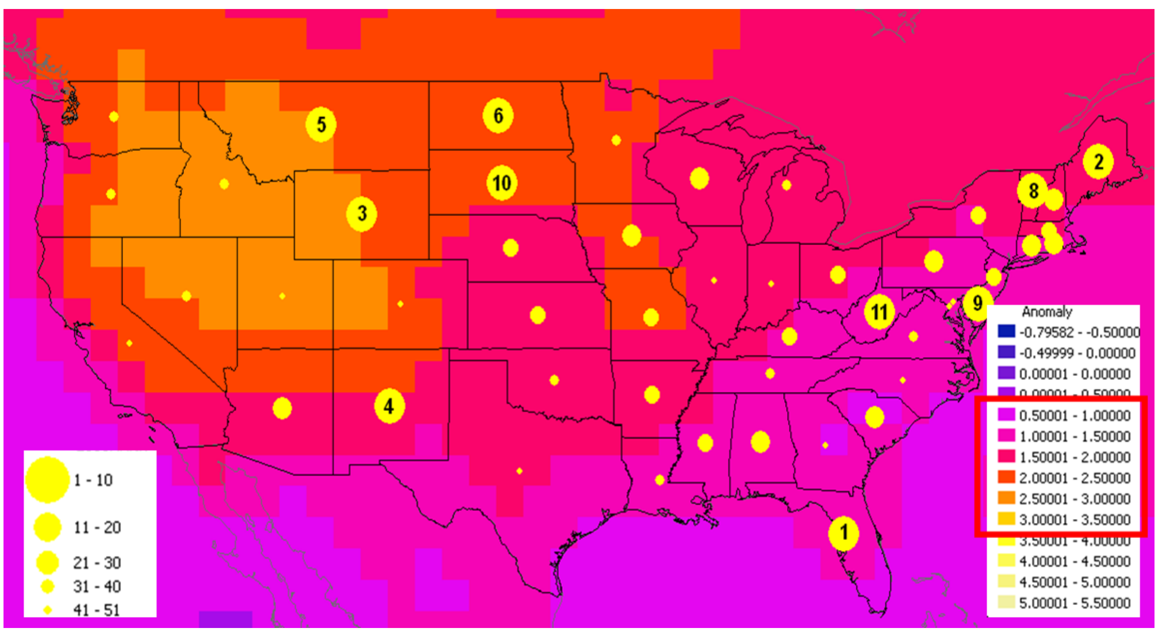


Figure 13. Climate change (temperature anomaly) and demographic projections for the United States.

It is up to the user to fully understand the meaning and uncertainties of climate model projections. The data available through the NCAR Climate Change Portal are from one of many GCMs, (i.e., the Community Climate System Model), that contributed to the current understanding of the Earth's Climate System and reported in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). IPCC climate change projections were based on multi-model results from a world-wide climate modeling effort. For further information on the CCSM and the IPCC Fourth Assessment Report, please refer to the GIS Climate Change Portal web site.

APPENDIX A

Calculation of the JJA 20 year average for the A2 Scenario model run (years 2021-2040).

([tas_JJA_2021_2040_SRESA2.JJA2021avg] +
[tas_JJA_2021_2040_SRESA2.JJA2022avg] +
[tas_JJA_2021_2040_SRESA2.JJA2023avg] +
[tas_JJA_2021_2040_SRESA2.JJA2024avg] +
[tas_JJA_2021_2040_SRESA2.JJA2025avg] +
[tas_JJA_2021_2040_SRESA2.JJA2026avg] +
[tas_JJA_2021_2040_SRESA2.JJA2027avg] +
[tas_JJA_2021_2040_SRESA2.JJA2028avg] +
[tas_JJA_2021_2040_SRESA2.JJA2029avg] +
[tas_JJA_2021_2040_SRESA2.JJA2030avg] +
[tas_JJA_2021_2040_SRESA2.JJA2031avg] +
[tas_JJA_2021_2040_SRESA2.JJA2032avg] +
[tas_JJA_2021_2040_SRESA2.JJA2033avg] +
[tas_JJA_2021_2040_SRESA2.JJA2034avg] +
[tas_JJA_2021_2040_SRESA2.JJA2035avg] +
[tas_JJA_2021_2040_SRESA2.JJA2036avg] +
[tas_JJA_2021_2040_SRESA2.JJA2037avg] +
[tas_JJA_2021_2040_SRESA2.JJA2038avg] +
[tas_JJA_2021_2040_SRESA2.JJA2039avg] +
[tas_JJA_2021_2040_SRESA2.JJA2040avg]) / 20

Calculation of the standard deviation of the 20 year time period 2021-2040 for the A2 scenario output.

Sqr (((([tas_JJA_2021_2040_SRESA2.JJA2021avg] - [tas_JJA_2021_2040_SRESA2.JJAA2avg])^2) +
(([tas_JJA_2021_2040_SRESA2.JJA2022avg] - [tas_JJA_2021_2040_SRESA2.JJAA2avg])^2) +
(([tas_JJA_2021_2040_SRESA2.JJA2023avg] - [tas_JJA_2021_2040_SRESA2.JJAA2avg])^2) +
(([tas_JJA_2021_2040_SRESA2.JJA2024avg] - [tas_JJA_2021_2040_SRESA2.JJAA2avg])^2) +
(([tas_JJA_2021_2040_SRESA2.JJA2025avg] - [tas_JJA_2021_2040_SRESA2.JJAA2avg])^2) +
(([tas_JJA_2021_2040_SRESA2.JJA2026avg] - [tas_JJA_2021_2040_SRESA2.JJAA2avg])^2) +
(([tas_JJA_2021_2040_SRESA2.JJA2027avg] - [tas_JJA_2021_2040_SRESA2.JJAA2avg])^2) +
(([tas_JJA_2021_2040_SRESA2.JJA2028avg] - [tas_JJA_2021_2040_SRESA2.JJAA2avg])^2) +
(([tas_JJA_2021_2040_SRESA2.JJA2029avg] - [tas_JJA_2021_2040_SRESA2.JJAA2avg])^2) +
(([tas_JJA_2021_2040_SRESA2.JJA2030avg] - [tas_JJA_2021_2040_SRESA2.JJAA2avg])^2) +
(([tas_JJA_2021_2040_SRESA2.JJA2031avg] - [tas_JJA_2021_2040_SRESA2.JJAA2avg])^2) +
(([tas_JJA_2021_2040_SRESA2.JJA2032avg] - [tas_JJA_2021_2040_SRESA2.JJAA2avg])^2) +
(([tas_JJA_2021_2040_SRESA2.JJA2033avg] - [tas_JJA_2021_2040_SRESA2.JJAA2avg])^2) +
(([tas_JJA_2021_2040_SRESA2.JJA2034avg] - [tas_JJA_2021_2040_SRESA2.JJAA2avg])^2) +
(([tas_JJA_2021_2040_SRESA2.JJA2035avg] - [tas_JJA_2021_2040_SRESA2.JJAA2avg])^2) +
(([tas_JJA_2021_2040_SRESA2.JJA2036avg] - [tas_JJA_2021_2040_SRESA2.JJAA2avg])^2) +
(([tas_JJA_2021_2040_SRESA2.JJA2037avg] - [tas_JJA_2021_2040_SRESA2.JJAA2avg])^2) +
(([tas_JJA_2021_2040_SRESA2.JJA2038avg] - [tas_JJA_2021_2040_SRESA2.JJAA2avg])^2) +
(([tas_JJA_2021_2040_SRESA2.JJA2039avg] - [tas_JJA_2021_2040_SRESA2.JJAA2avg])^2) +
(([tas_JJA_2021_2040_SRESA2.JJA2040avg] - [tas_JJA_2021_2040_SRESA2.JJAA2avg])^2)) / 19)