Answer Sheet

LABORATORY 6: CLIMATE CHANGE – PART 1

Student Name ________________________________

Student Number ______________________________

QUESTION 1

Parker et al. (1981) collected tree-ring samples from living white spruce (*Picea glauca*) in 1979 at Cri Lake, Quebec for dendroclimatological analysis. In total, they collected samples from 16 trees, with each tree being cored twice for verification of ring changes. The density of each annual ring was derived using X-ray densitometry. **Table 6.1** shows the results:

Table 6.1. *Cri Lake tree-ring density indices. (Reprinted with permission from Parker, M.L., Jozsa, L.A., Johnson, S.G. & Bramhall, P.A. (1981)* Dendrochronological studies on the coasts of James Bay and Hudson Bay (Parts 1 and 2). *Syllogeus (33): 129-188.)*

Year	0	1	2	3	4	5	6	7	8	9
1700	0.88	1.12	0.96	1.06	0.97	0.98	1.04	1.14	0.89	0.80
1710	1.13	1.01	1.07	1.00	0.92	1.20	0.80	1.09	0.92	0.99
1720	0.91	0.98	1.10	1.05	1.00	1.00	0.91	0.98	1.04	1.17
1730	0.86	0.92	1.00	1.11	0.94	1.05	1.04	0.95	1.08	1.03
1740	0.82	1.01	0.98	1.05	1.05	1.00	0.88	1.03	1.08	1.06
1750	0.84	1.17	1.00	0.90	1.15	0.86	1.16	0.80	0.97	0.98
1760	0.97	1.01	0.94	1.21	1.09	0.77	1.11	0.88	1.06	1.10
1770	1.09	0.88	0.94	0.91	1.07	0.93	1.09	0.94	1.06	0.98
1780	0.90	1.11	1.13	1.03	0.81	1.05	0.97	0.86	1.10	1.14
1790	0.89	1.04	0.88	1.08	0.96	1.10	0.89	1.08	1.08	1.07
1800	0.76	1.04	0.96	0.96	1.15	1.12	0.92	0.85	0.99	0.96
1810	1.20	0.99	0.98	1.10	0.87	1.09	0.83	0.76	1.26	0.84
1820	1.15	1.10	0.92	0.99	0.88	1.03	1.17	0.79	1.13	1.01
1830	0.95	1.11	0.90	0.96	1.12	0.89	0.95	1.10	0.84	1.06
1840	1.16	1.08	0.84	0.87	1.12	0.82	1.19	0.94	0.99	1.05
1850	1.05	1.03	1.07	0.77	0.99	0.92	1.19	0.95	1.16	0.85
1860	1.10	1.00	0.87	0.94	1.07	0.89	1.11	1.08	0.96	0.88
1870	1.16	0.76	1.10	1.03	0.90	1.07	1.04	1.02	1.05	1.02
1880	0.87	1.15	1.04	0.95	0.81	0.90	1.19	1.08	0.80	1.15
1890	0.94	0.83	1.10	1.11	0.85	1.09	1.02	1.01	0.93	1.06
1900	0.97	1.11	0.93	1.03	0.95	0.90	1.03	1.03	1.03	0.93
1910	1.01	1.27	0.73	1.02	0.92	1.03	1.16	0.94	0.75	1.22
1920	1.04									

A portion of the raw data time series was then statistically **regressed** in a **step-wise multiple regression analysis** against 41 mean summer temperatures (May to October) recorded at a nearby weather station. The analysis suggested that there was a strong positive **correlation between** tree-ring density and the mean summer temperatures at the meteorological station (r = +0.77). Also, from the analysis, a simple mathematical model was constructed for the calculation of mean summer temperature using tree-ring density. The model is expressed as:

$$T_y = \left[\left(\frac{81.880}{3.162 - 0.257(D_{y-1}) - D_y}\right) - 32\right] \bullet 0.555$$

where **Ty** is the temperature (in °C), ***Dy*** is the tree-ring density measurement for year *y*, and ***Dy* – *1*** is the density in year *y* – *1* (the year before *y*).

1.1) Using the data in **Table 6.1** and the equation given above, calculate the mean summer temperatures at Cri Lake for the period 1916 to 1920 and fill in the blanks in the first row of the table below.

Year	**1911**	**1912**	**1913**	**1914**	**1915**	**1916**	**1917**	**1918**	**1919**	**1920**
Temp (°C)	10.1	3.8	5.5	5.2	6.3	?	?	?	?	?

1.1a) The calculate the mean summer temperatures (°C) at Cri Lake for 1916 is __________°C.

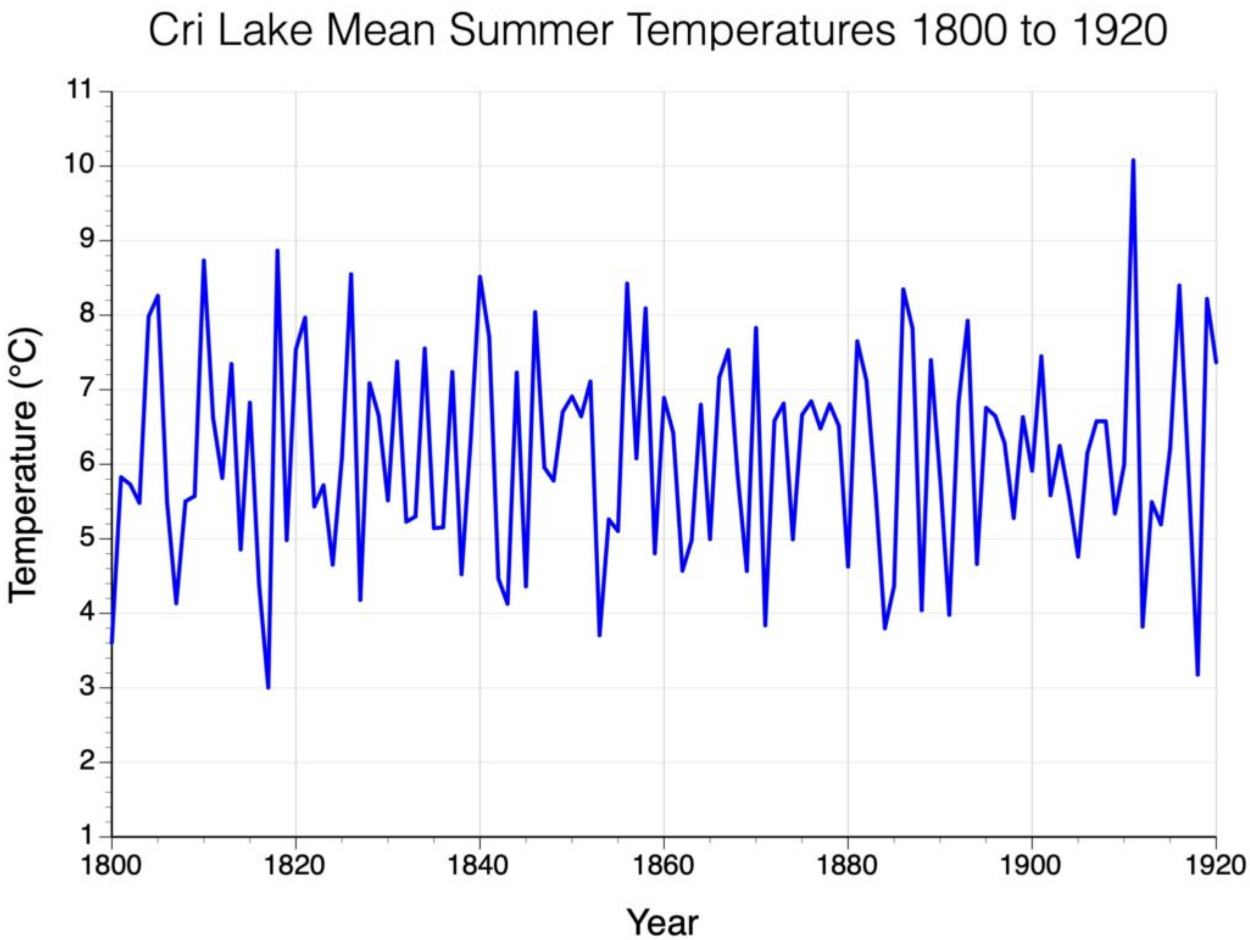
1.1b) The calculate the mean summer temperatures (°C) at Cri Lake for 1917 is __________°C.

1.1c) The calculate the mean summer temperatures (°C) at Cri Lake for 1918 is __________°C.

1.1d) The calculate the mean summer temperatures (°C) at Cri Lake for 1919 is __________°C.

1.1e) The calculate the mean summer temperatures (°C) at Cri Lake for 1920 is __________°C.

The following graph plots the mean summer temperatures at Cri Lake for the period 1800 to 1920. Answer the questions that follow the graph.



1.2) What does the graph show you about the interannual variability of summer temperature in the first part of the 20th century (i.e., compared to pre-1900)?

1.3) In the regression equation a lag variable was used – this means that one year's temperature is influenced by last year's tree ring density. How might the previous year's growth affect the present year's growth?

1.4) Research suggests that major explosive volcanic eruptions may cause a cooling of the Earth's atmosphere for about two to three years after the event. The Cri Lake data series includes two major volcanic events, **Tambora** in 1815 and **Krakatoa** in 1883. What type of temperature change occurred at Cri Lake as a result of these events? Examine this question by calculating the average mean summer temperature for the two-year period before and after these eruptions.

Tambora:

1.4a) The average for 1813-14 in °C was?

_________°C.

1.4b) The average for 1816-17 in °C was?

_________°C.

Krakatoa:

1.4c) The average for 1881-82 in °C was?

_________°C.

1.4d) The average for 1884-85 in °C was?

_________°C.

1.4e) For both comparisons, what pattern is suggested from your calculations?

QUESTION 2

Average annual temperatures in Winnipeg, Manitoba, Canada (Latitude 49.89°, Longitude -97.15°) for the years 1901-2019 are presented in **Table 6.2** and can be found in the Microsoft Excel file *Lab 6 Winnipeg_Temps.xlsx*.

Table 6.2. *Annual mean temperatures (in °C), Winnipeg from 1901-2019.*

Year	Annual Mean	Running-Mean 7-yr	Year	Annual Mean	Running-Mean 7-yr	Year	Annual Mean	Running-Mean 7-yr
1901	2.2	X	1941	3.1	2.7	1981	4.1	2.2
1902	2.4	X	1942	2.5	2.5	1982	1.4	2.2
1903	1.3	X	1943	1.8	2.4	1983	3.2	2.5
1904	0.7	1.5	1944	3.1	2.3	1984	2.9	2.9
1905	1.7	1.5	1945	1.6	2.2	1985	1.0	2.8
1906	2.2	1.4	1946	2.2	2.1	1986	2.7	2.8
1907	0.1	1.6	1947	1.9	1.8	1987	5.0	2.7
1908	2.4	1.7	1948	2.1	1.5	1988	3.2	2.8
1909	1.2	1.6	1949	2.0	1.7	1989	1.4	2.9
1910	2.6	1.6	1950	-0.4	1.9	1990	2.9	2.8
1911	1.5	1.9	1951	0.9	2.0	1991	3.1	2.5
1912	1.4	1.9	1952	3.4	1.9	1992	2.3	2.3
1913	1.8	1.8	1953	3.3	1.8	1993	1.8	2.2
1914	2.2	1.4	1954	2.5	2.2	1994	2.7	2.1
1915	2.7	1.5	1955	1.7	2.5	1995	2.0	2.3
1916	0.4	1.5	1956	1.4	2.3	1996	0.4	2.6
1917	0.0	1.6	1957	2.5	2.1	1997	2.5	2.8
1918	1.8	1.7	1958	2.7	2.2	1998	4.7	3.0
1919	1.7	1.7	1959	1.8	2.2	1999	4.4	3.1
1920	2.2	2.0	1960	2.2	2.4	2000	2.9	3.5
1921	2.8	2.1	1961	2.8	2.3	2001	4.0	3.5
1922	2.9	2.1	1962	1.8	2.0	2002	2.8	3.3
1923	2.4	2.1	1963	3.0	1.9	2003	3.2	3.3
1924	1.1	2.0	1964	1.9	1.7	2004	2.2	3.3
1925	1.7	2.0	1965	0.8	1.6	2005	3.5	3.0
1926	1.6	1.7	1966	0.6	1.6	2006	4.4	2.9
1927	1.3	1.7	1967	1.3	1.4	2007	2.9	3.0
1928	2.9	2.2	1968	1.9	1.4	2008	1.7	3.3
1929	0.8	2.2	1969	1.8	1.4	2009	2.3	3.4
1930	2.6	2.2	1970	1.3	1.7	2010	4.3	3.0
1931	4.6	2.4	1971	1.9	1.7	2011	3.7	2.8
1932	1.8	2.2	1972	0.7	1.8	2012	4.6	3.2
1933	1.4	2.1	1973	3.1	1.9	2013	1.7	3.5
1934	2.4	2.0	1974	1.5	2.1	2014	1.4	3.4
1935	1.5	1.8	1975	2.3	2.0	2015	4.3	3.3
1936	0.7	1.9	1976	2.2	2.0	2016	4.4	2.9
1937	1.5	2.1	1977	3.1	1.9	2017	3.5	X
1938	3.0	2.2	1978	1.3	2.3	2018	3.0	X
1939	2.5	2.3	1979	0.5	2.1	2019	1.9	X
1940	2.8	2.5	1980	2.3	2.3			

Using this data, answer the following questions:

2.1) Calculate the missing **climate normals** using the Microsoft Excel spreadsheet for the time periods 1961-1990, 1971-2000, and 1981-2010 (“normal” in climatology refers to the mean for a standard 30-year period):

1911-1940: 1.8°C

1921-1950: 1.9°C

1931-1960: 2.1°C

1941-1970: 2.4°C

1951-1980: 2.0°C

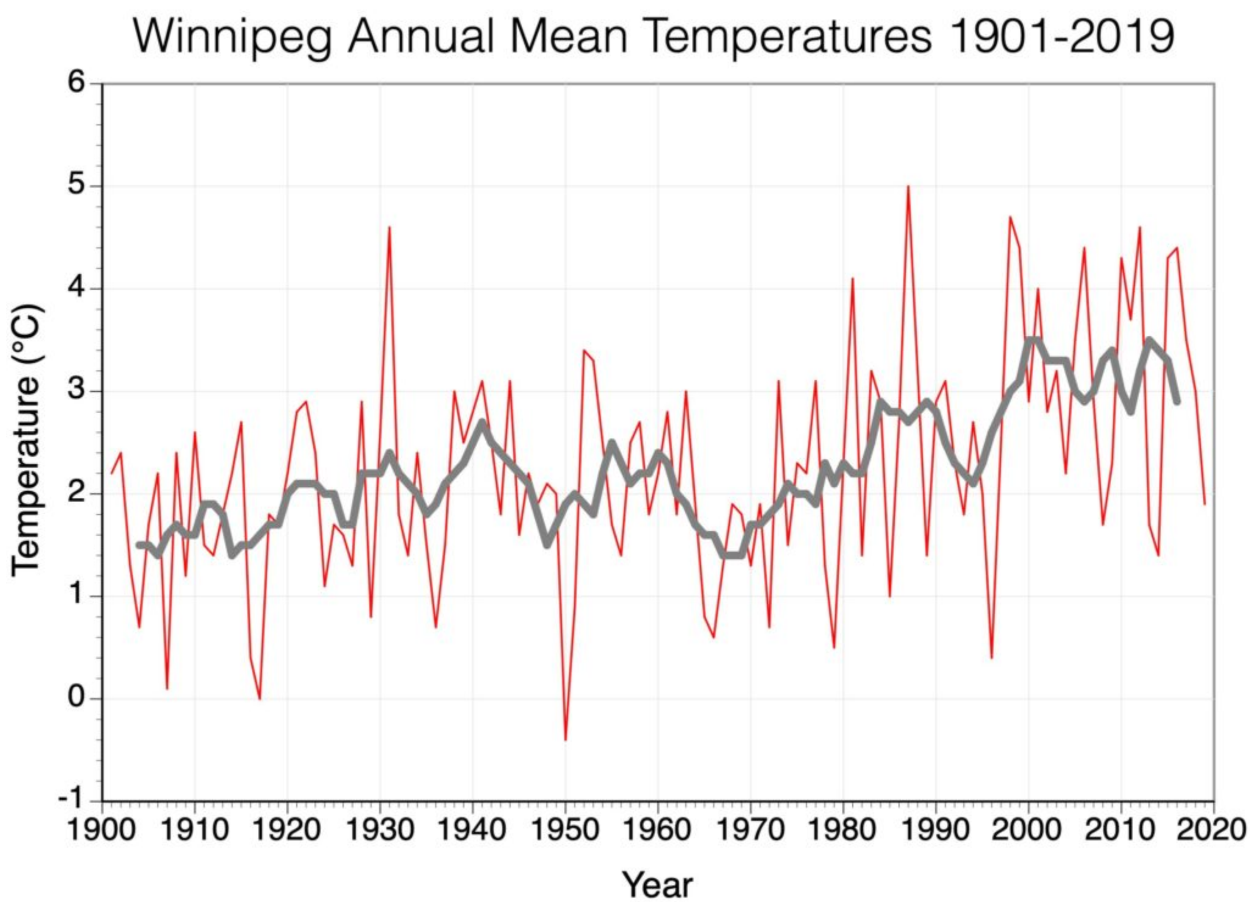
2.1a) 1961-1990: ______°C

2.1b) 1971-2000: ______°C

2.1c) 1981-2010: ______°C

2.1d) What is happening to the climatological normal over the eight consecutive 30-year periods?

2.2) Climate data is typically "noisy" – that is, there is a lot of interannual variability. A commonly used technique used to depict smoother trends is the **running mean** or **moving average**. This involves the calculation of a mean of a specified number of consecutive years. For example, in **Table 6.2** a *7-year running mean* has been calculated for this time series. For example, for the year **1904**, the average annual temperatures for 1901, 1902, 1903, **1904**, 1905, 1906, and 1907 were summed and then divided by 7 (note that 1904 is the middle year). The graph below shows the year-to-year change in Winnipeg's annual mean temperature (red line) and a 7-year running mean (dark grey heavy line). Notice how the running mean is less variable than the raw data, providing a clearer picture of the trends in this time series.



2.2a) According to the 7-year mean, which of the periods listed show trends of increasing temperatures?

A 1901-1940
B 1940-1950
C 1950-1960
D 1960-1970
E 1970-1990
F 1995-2000
G 2000-2015

2.2b) According to the 7-year mean, which of the periods listed show trends of decreasing temperatures?

A 1901-1940
B 1940-1950
C 1950-1960
D 1960-1970
E 1970-1990
F 1995-2000
G 2000-2015

2.2c) According to the 7-year mean, annual temperatures (°C) in Winnipeg have increased by how much since 1970?

A 0.5
B 1.0
C 1.5
D 3.0

QUESTION 3

Researchers have constructed a number of historical climate datasets for the purpose of examining recent climate change on our planet. The following **table** describes SIX datasets that are most commonly used to research how recent global surface temperatures have changed over our planet's terrestrial and ocean surfaces.

Name of the Dataset	Organization Responsible	Time Coverage	Spatial Resolution	Ocean Surface Coverage
Global Surface Temperature Analysis (GISTEMP)	NASA Goddard Institute for Space Studies (GISS)	1880 – Today	2 x 2 degrees	Yes
HadCRUT4 and CRUTEM4	University of East Anglia / UK Met Office Hadley Centre	1850 – Today	5 x 5 degrees	Yes
Berkeley Earth Surface Temperatures (BEST)	University of California, Berkeley	1701 – Today	1 x 1 degrees	No

Merged Land-Ocean Surface Temperature Analysis (MLOST)	National Oceanic and Atmospheric Admin.(NOAA)	1871 – Today	5 x 5 degrees	Yes
Global (land) Precipitation and Temperature: Willmott & Matsuura, University of Delaware	University of Delaware	1900 – 2014	0.5 x 0.5 degrees	No
TerraClimate	John Abatzoglou, University of Idaho	1958 – Today	~4 km (1/24th degree)	No

We are going to use NASA's Global Surface Temperature Analysis (GISTEMP)climate database to examine variations in mean temperature over time as calculated for various parts of Earth's surface/atmosphere system. This climate database can be accessed at the following website:

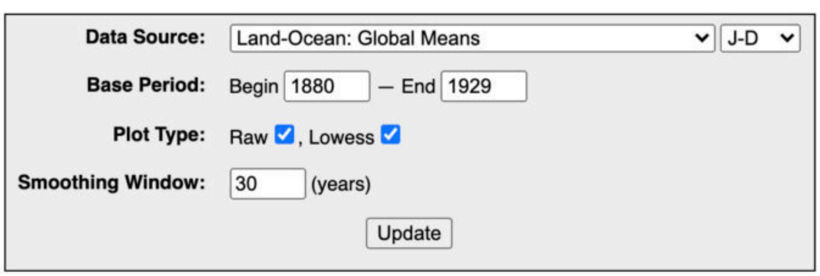
https://data.giss.nasa.gov/gistemp/graphs_v4/customize.html

For all of the questions that follow, we are going to use 1880 to 1929 (50 years) as the baseline for our comparisons. During this period, little additional warming of the Earth's climate system should have taken place because of the increasing concentration of greenhouse gases in the atmosphere. From 1880 to 1929, carbon dioxide concentrations in the atmosphere increased by about 16 parts per million (ppm) (from 290 to 306 ppm). In comparison, carbon dioxide concentrations in the atmosphere by 88 ppm in the last 50 years (from 326 to 414 ppm, see NOAA's Trends in CO_2 website). The concentration of atmospheric carbon dioxide before the onset of industrialization (around the year 1700) is estimated to be about 280 ppm.

3.1) Use the following web link to go to NASA's Global Surface Temperature Analysis (GISTEMP) climate database.

https://data.giss.nasa.gov/gistemp/graphs_v4/customize.html

Create a graph showing yearly change in **global annual mean temperature** for **combined land and ocean surfaces** for the period 1880-2019. See the settings in the graphic below.



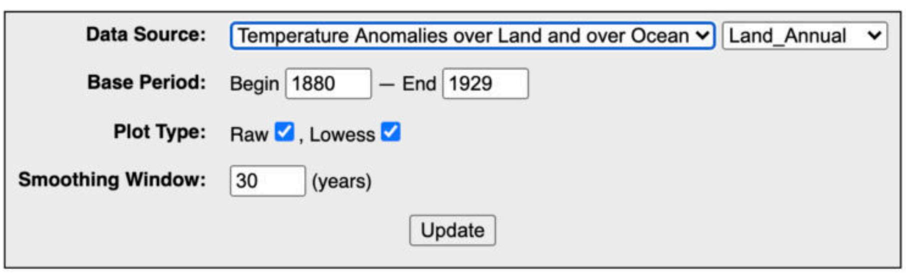
3.1a) According to the Lowess Curve how much global warming has occurred relative to the 50-year baseline 1880-1929?

A 0.3°C.
B 0.8°C.
C 1.2°C.
D 1.6°C.

3.1b) When did global warming start increasing at a rapid rate?

A 1930.
B 1950.
C 1970.

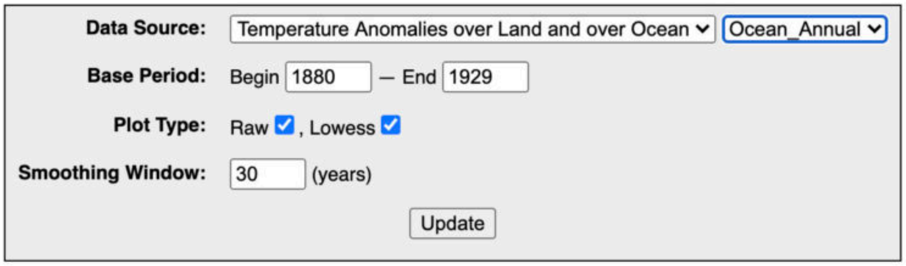
3.2) Create a graph showing yearly change in **global annual mean temperature** for just **land surfaces** for the period 1880-2019. See the settings in the graphic below.



3.2a) According to the Lowess Curve how much global warming has occurred over land surfaces globally relative to the 50-year baseline 1880-1929?

A 0.3°C.
B 0.8°C.
C 1.2°C.
D 1.6°C.

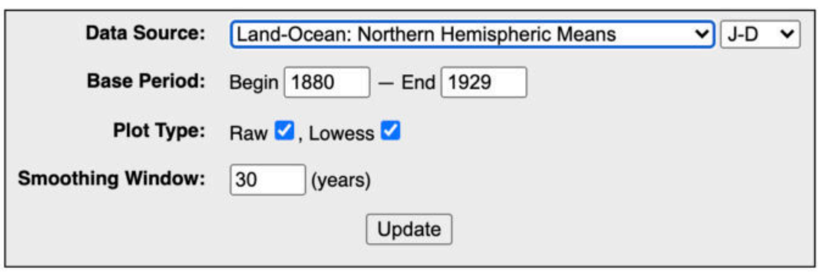
3.3) Create a graph showing yearly change in **global annual mean temperature** for just **ocean surfaces** for the period 1880-2019. See the settings in the graphic below.



3.3a) According to the Lowess Curve how much global warming has occurred over ocean surfaces globally relative to the 50-year baseline 1880-1929?

A 0.3°C.
B 0.8°C.
C 1.2°C.
D 1.6°C.

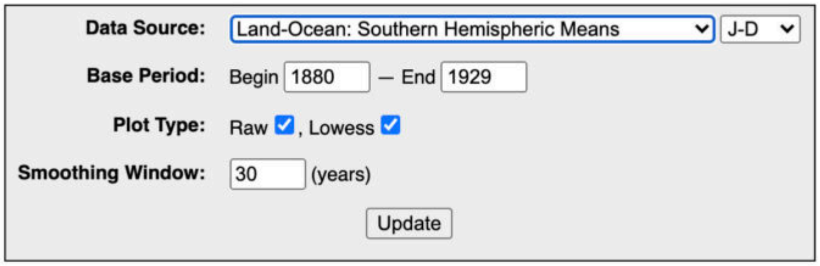
3.4) Create a graph showing yearly change in **annual mean temperature** for **combined land and ocean surfaces** in just the **Northern Hemisphere** for the period 1880-2019. See the settings in the graphic below.



3.4a) According to the Lowess Curve how much global warming has occurred over land and ocean surfaces in the Northern Hemisphere relative to the 50-year baseline 1880-1929?

A 0.3°C.
B 0.8°C.
C 1.2°C.
D 1.4°C.

3.5) Create a graph showing yearly change in **annual mean temperature** for **combined land and ocean surfaces** in just the **Southern Hemisphere** for the period 1880-2019. See the settings in the graphic below.



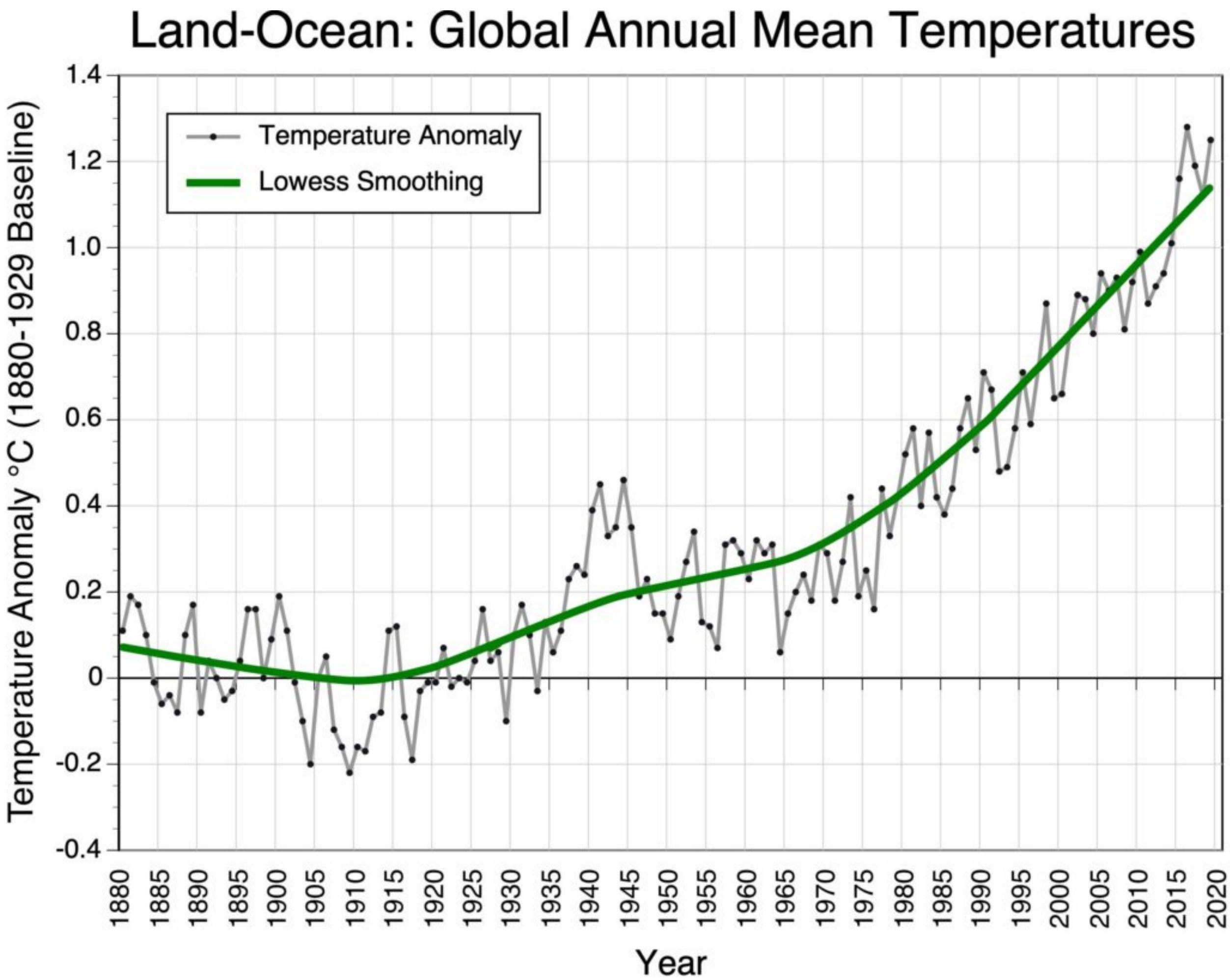
3.5a) According to the Lowess Curve how much global warming has occurred over land and ocean surfaces in the Southern Hemisphere relative to the 50-year baseline 1880-1929?

A 0.3°C.
B 0.8°C.
C 1.2°C.
D 1.4°C.

3.5b) Why has the Southern Hemisphere less global warming than the Northern Hemisphere?

QUESTION 4

The graph below plots yearly change in **global annual mean temperature** for **combined land and ocean surfaces** for the period 1880-2019 based on the dataset available from NASA's Global Surface Temperature Analysis (GISTEMP) (same data plotted in Question 3.1). The graph indicates that the yearly rise (black dots connected by grey line) in global temperatures between 1880 and 2019 has not been incrementally steady but variable. Scientists have found that this short-term variability is internal to Earth's climate system. Two factors seem to account for most of these short-term temperature fluctuations: volcanic emissions that block incoming solar radiation for 1 to 2 years and atmosphere-ocean oscillations that vary the transfer of heat energy from the ocean surface to the lower atmosphere.



The most important atmosphere-ocean oscillation responsible for short-term temperature fluctuations in Earth's global mean temperature is the **El Niño–Southern Oscillation** (ENSO). El Niño–Southern Oscillation is produces cyclical changes in the **Trade Winds** and sea surface temperatures in the Pacific Ocean. It involves three phases: Neutral, **La Niña** or **El Niño**.

In an **El Niño** year, air pressure drops over a large region of the central Pacific and along the coast of South America (**Figure 6.7**). The normal low-pressure system is replaced by a weak high in the western Pacific (the Southern Oscillation). This change in pressure pattern causes the Trade Winds to be significantly reduced in wind speed. This reduction allows the equatorial counter current (which flows from west to east) to strengthen and to send a pulse of warm ocean water to the coastlines of Peru and Ecuador (**Figure 6.8**). Since 1935, particularly strong El Niños have developed in 1941, 1958, 1966, 1973, 1978, 1983, 1987, 1992, 1998, 2003, 2010, and 2016.

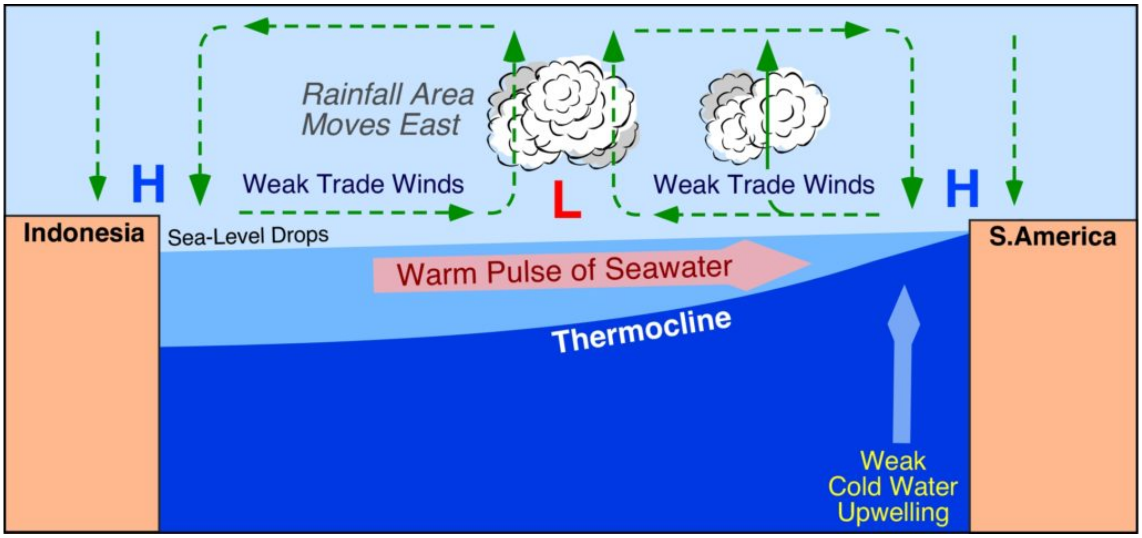


Figure 6.7. *This cross-section of the Pacific Ocean, along the equator, illustrates the pattern of atmospheric circulation that causes the formation of the El Niño. Note how the cold water upwelling is reduced, the position of the thermocline moves eastward, and how the warm equatorial ocean current switches direction. Image Copyright: Michael Pidwirny.*

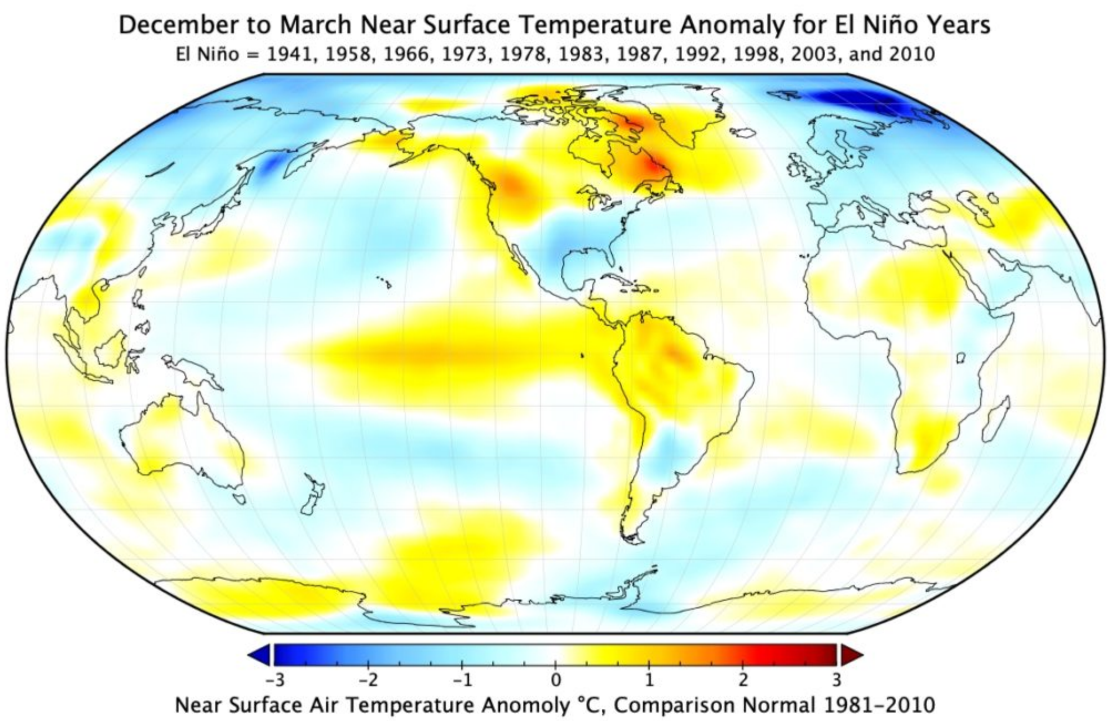


Figure 6.8. *Global surface temperature effects of El Niño during December to March. This map describes the average temperature anomaly of eleven significant El Niño events (1941, 1958, 1966, 1973, 1978, 1983, 1987, 1992, 1998, 2003, and 2010) from the 30-year average 1981-2010. Image Copyright: Michael Pidwirny.*

After an El Niño event weather conditions usually return back to normal (neutral state) or they can change into a condition known as **La Niña**. La Niña form when the Trade Winds become very strong and cause an unusual accumulation of cold water along the equator in the central and eastern Pacific Ocean (**Figure 6.9**). Strong La Niña's have occurred in 1939, 1951, 1955, 1971, 1974, 1976, 1989, 1999, 2000, 2008, and 2011 (**Figure 6.10**).

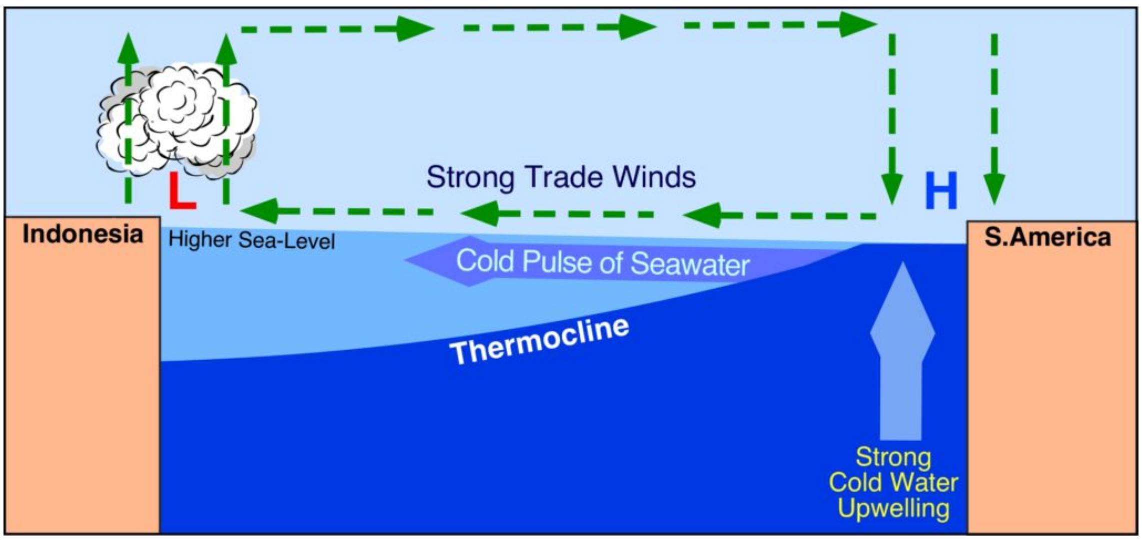


Figure 6.9. *This cross-section of the Pacific Ocean, along the equator, illustrates the pattern of atmospheric circulation that causes the formation of the La Niña. Note how the cold water upwelling has intensified, the position of the thermocline has moved westward, and how the equatorial ocean current is now cold (compare with Figure 6.7). Image Copyright: Michael Pidwirny.*

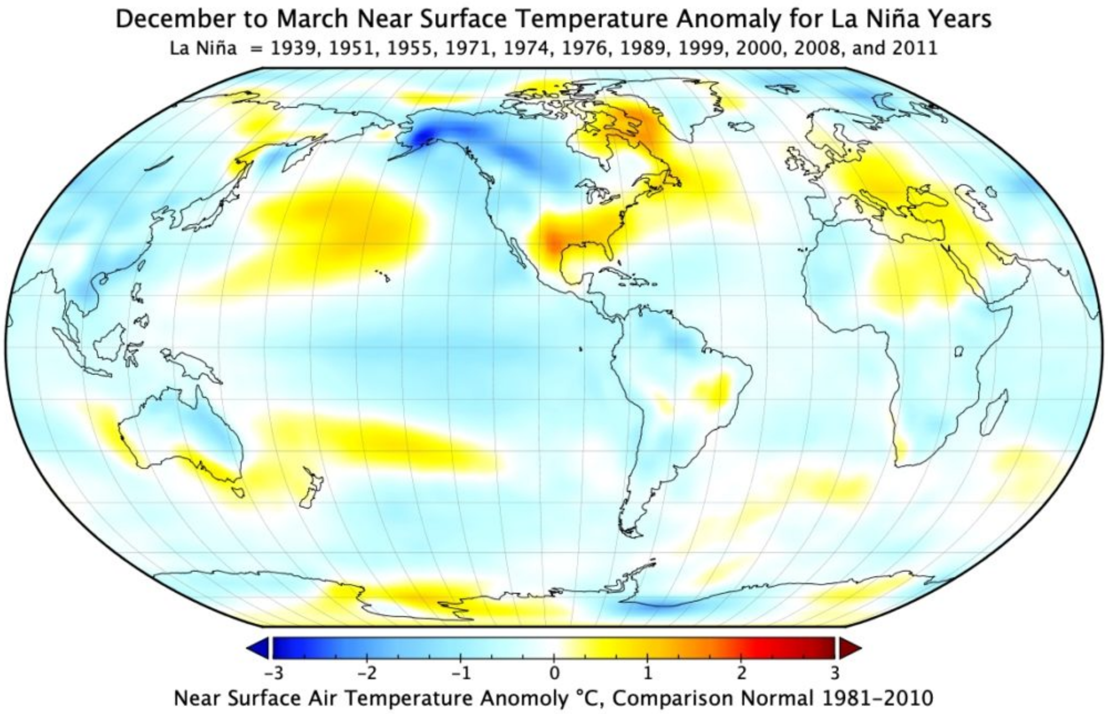
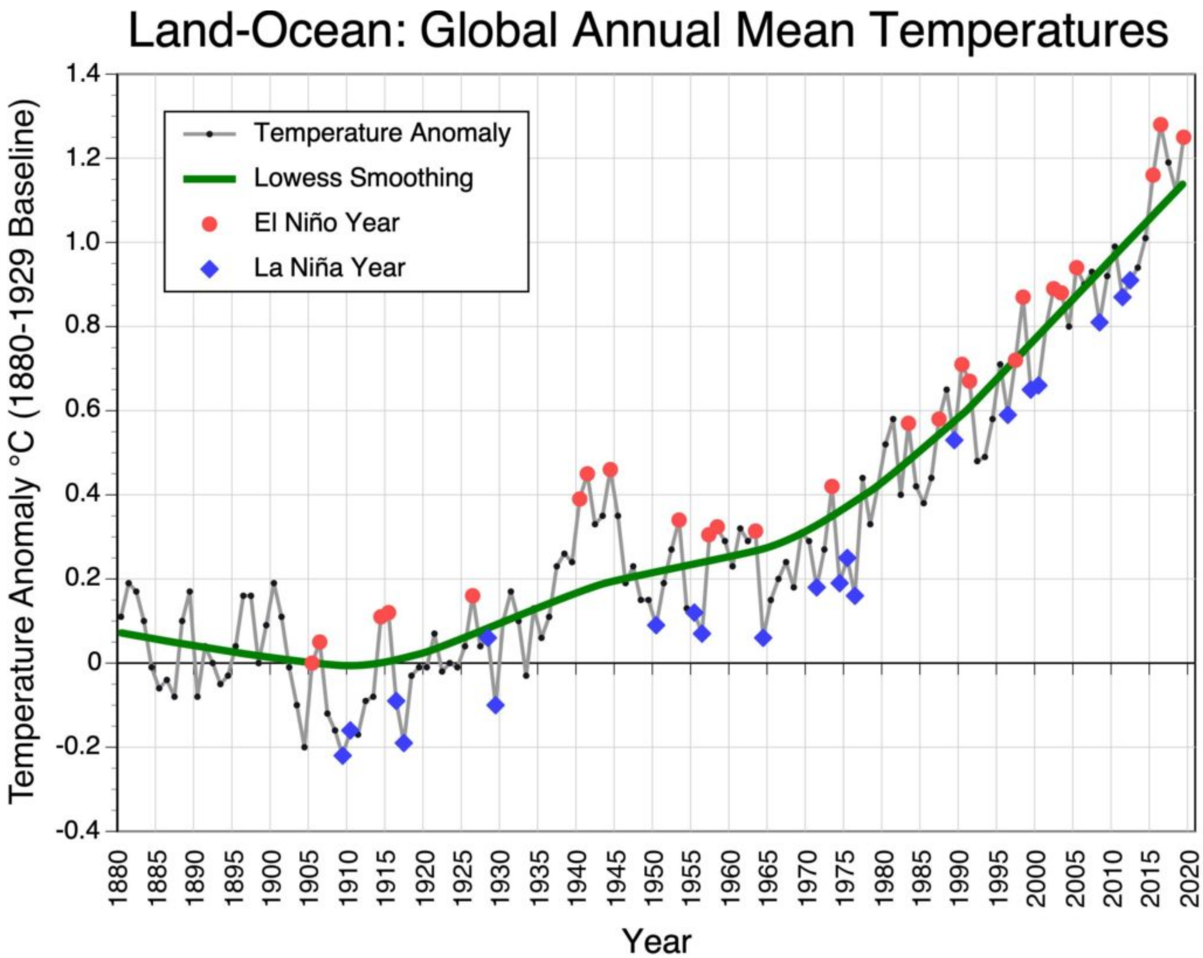


Figure 6.10. *Global surface temperature effects of La Niña during December to March. This map describes the average temperature anomaly of eleven significant La Niña events (1939, 1951, 1955, 1971, 1974, 1976, 1989, 1999, 2000, 2008, and 2011) from the 30-year average 1981-2010. Image Copyright: Michael Pidwirny.*

The graph below once again plots **global annual mean temperature** for **combined land and ocean surfaces** and identifies significant El Niño (red dots) and La Niña (blue diamonds) event years.

4.1) Based on the graph, would you suggest that El Niño and La Niña events might be responsible for some of the fluctuations seen in Earth's global temperature record? Explain.



QUESTION 5

Three climate simulations were run using the publicly available **EdGCM** global circulation model. The EdGCM model is available to run on a Windows or Mac computers.

http://edgcm.columbia.edu

The source code for this desktop computer simulation model is identical to NASA's GISS Model II which was used for climate change research in the 1980s and early 1990s.

The three climate simulations produced output for the following climate change scenarios:

- The climate the Earth experience in 1958 – **Modern SST Climate**
- The climate that would be produced by increasing carbon dioxide concentrations in the atmosphere to 630 ppm – **Doubled CO_2 Climate**
- The climate that would be produced by lowering current solar output by 2% – **Decreased Solar Climate**

The output produced for each of these simulations consists of global maps of the following climate variables: average annual surface air temperature and annual precipitation (**Figures 6.11** to **6.16**). **Figures 6.17** to **6.20** depict the difference between modeled future conditions and the Modern SST Climate. Examine this output and answer the following questions.

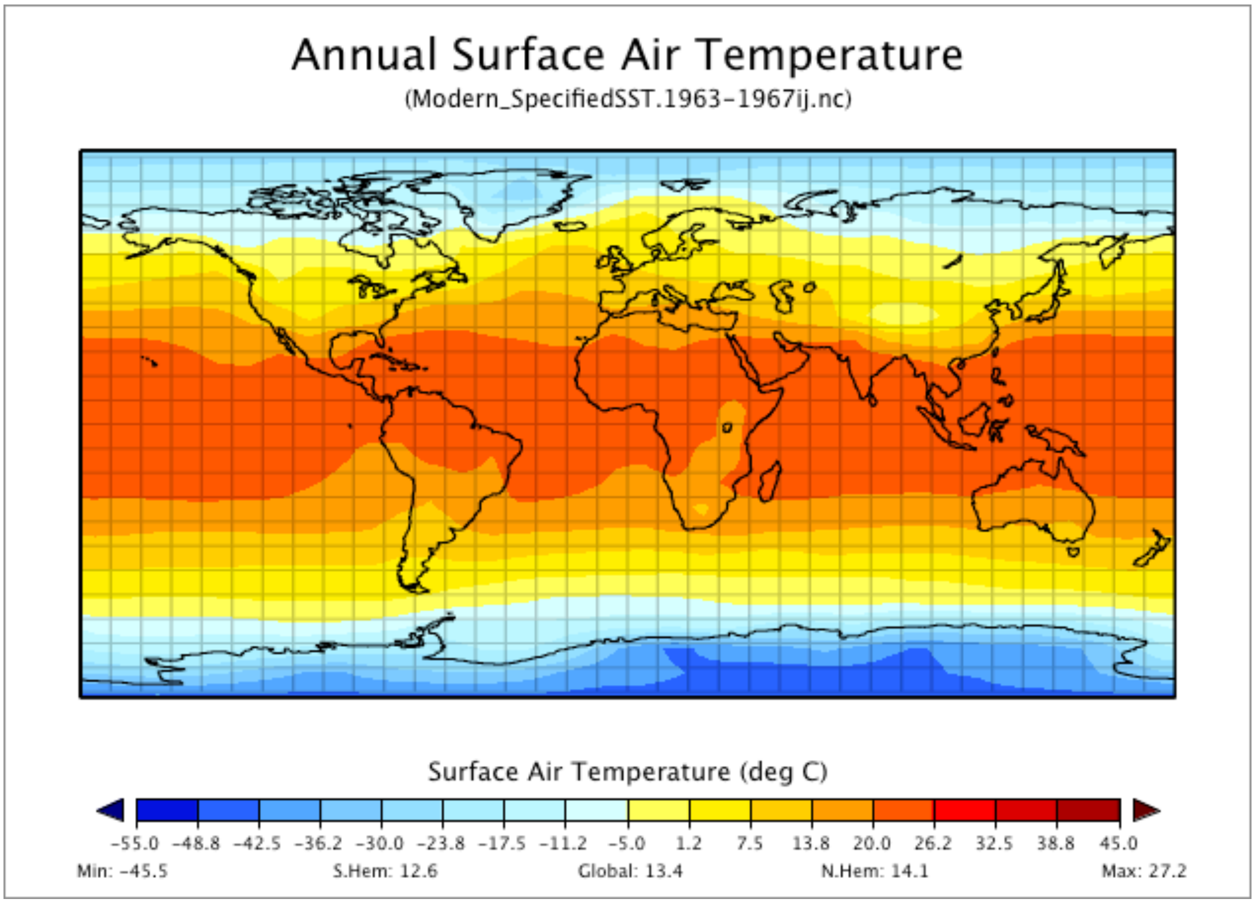


Figure 6.11. *Global average annual surface air temperature – Modern SST simulation scenario. Image Copyright: Michael Pidwirny. Data Source: EdGCM model output.*

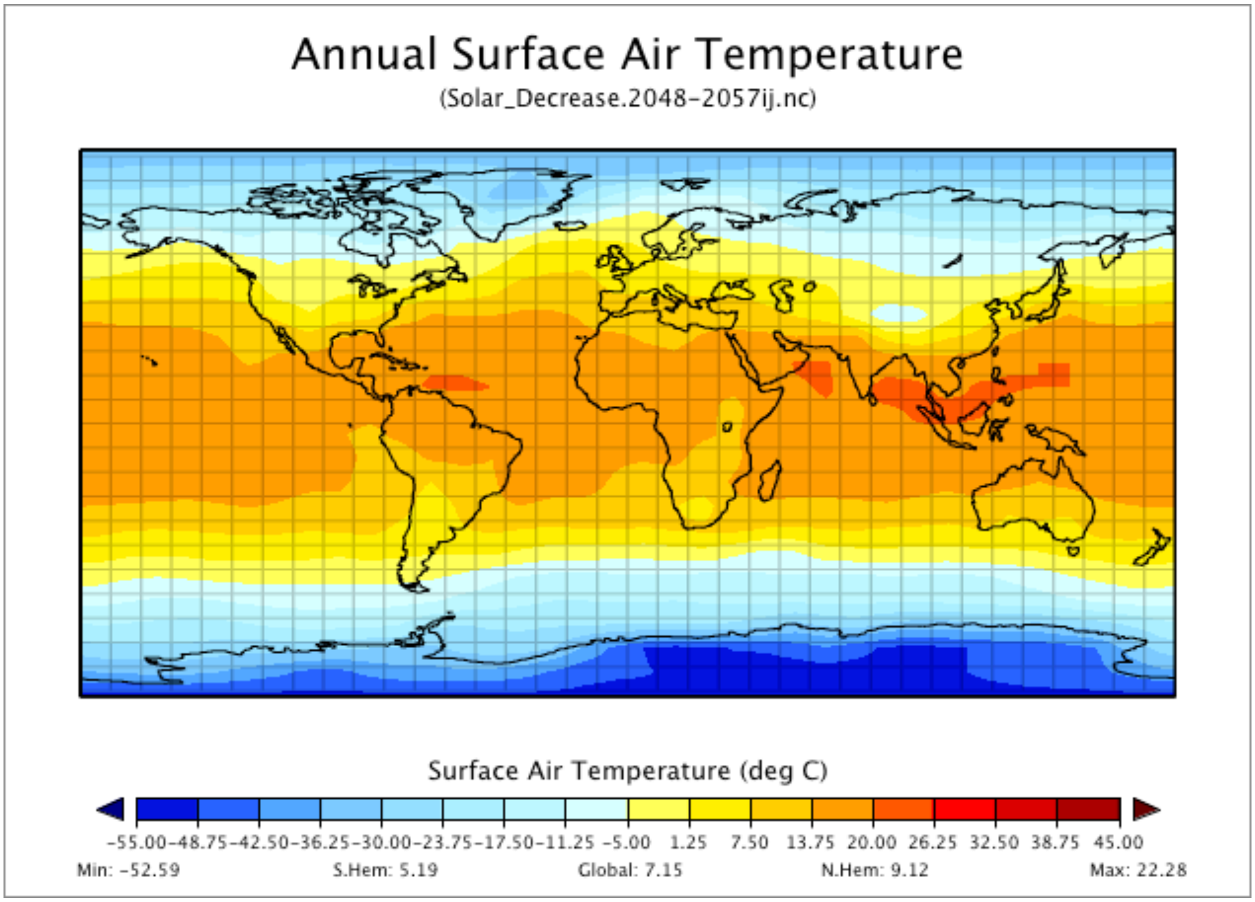


Figure 6.13. *Global average annual surface air temperature – Solar Decrease simulation scenario. Image Copyright: Michael Pidwirny. Data Source: [EdGCM] model output.*

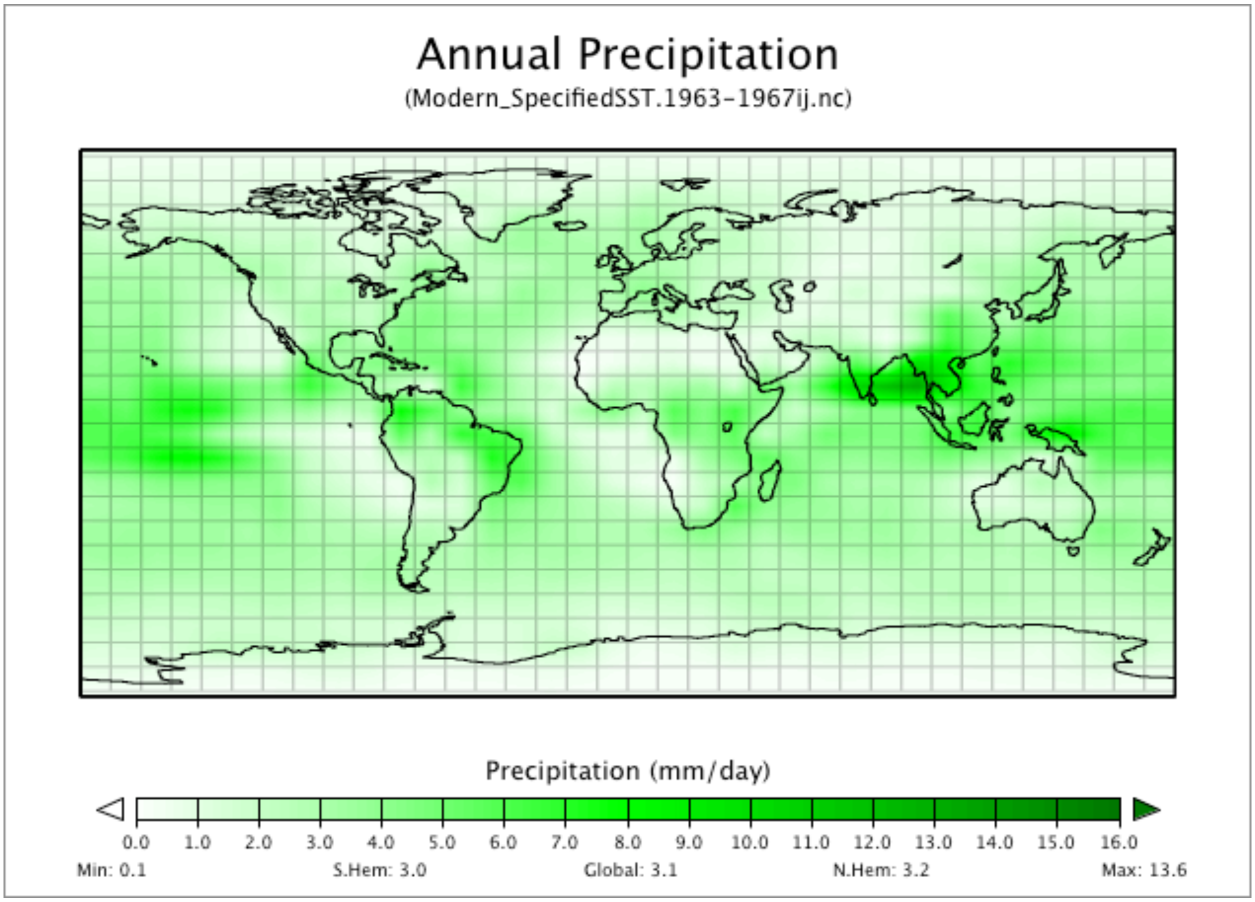


Figure 6.14. *Global annual precipitation – Modern SST simulation scenario. Image Copyright: Michael Pidwirny. Data Source: EdGCM model output.*

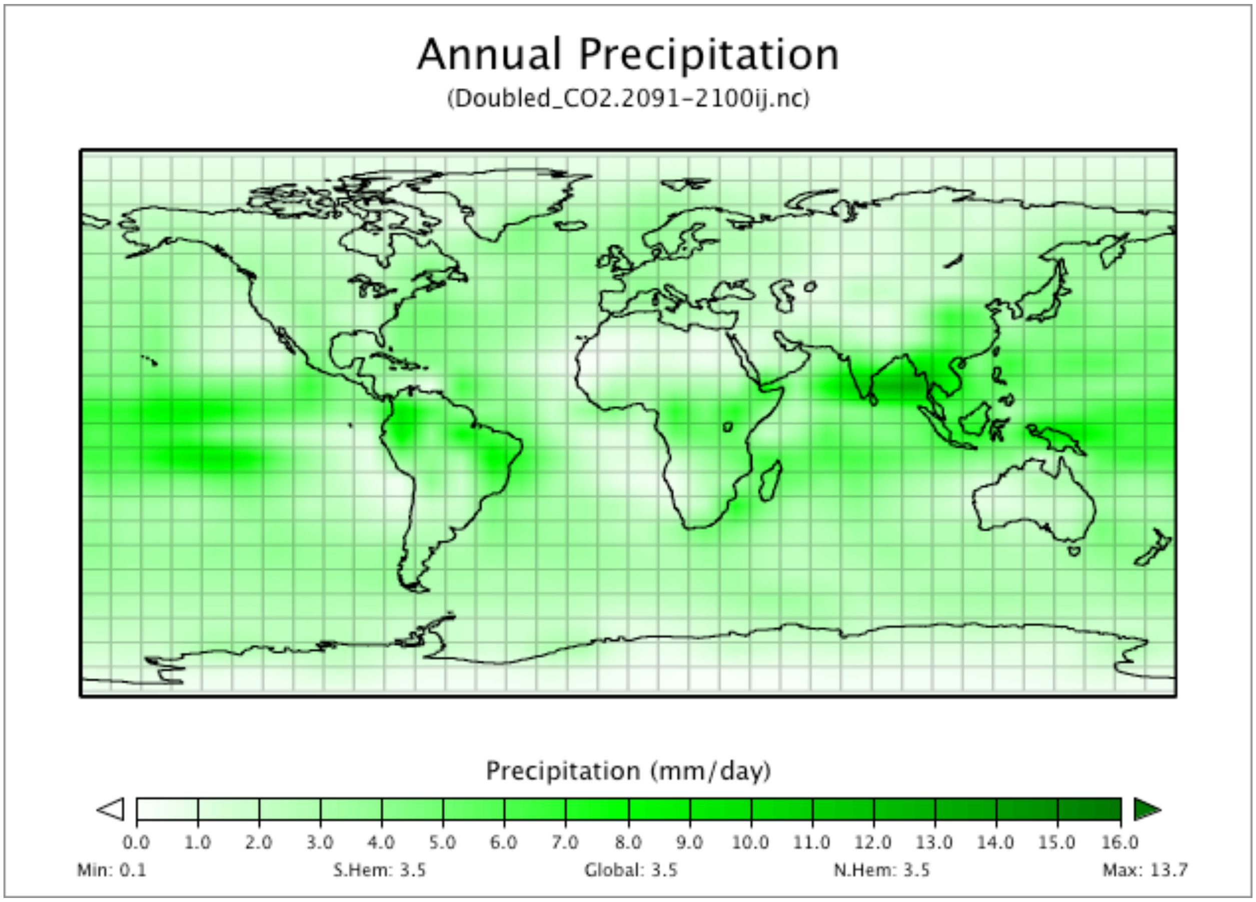


Figure 6.15. *Global annual precipitation – Doubled CO_2 simulation scenario. Image Copyright: Michael Pidwirny. Data Source: EdGCM model output.*

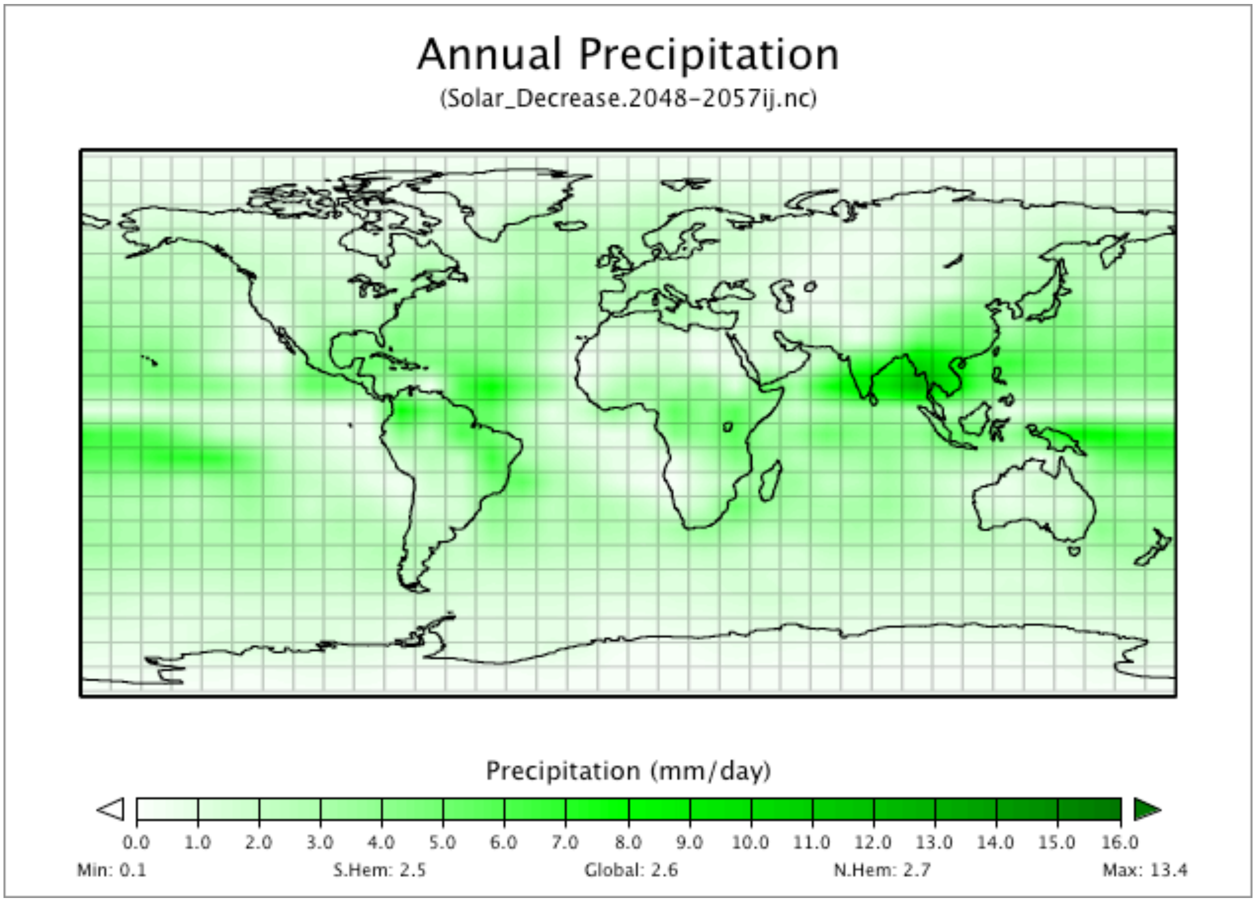


Figure 6.16. *Global annual precipitation – Solar Decrease simulation scenario. Image Copyright: Michael Pidwirny. Data Source: EdGCM model output.*

Examine **Figure 6.17** carefully and answer the following questions.

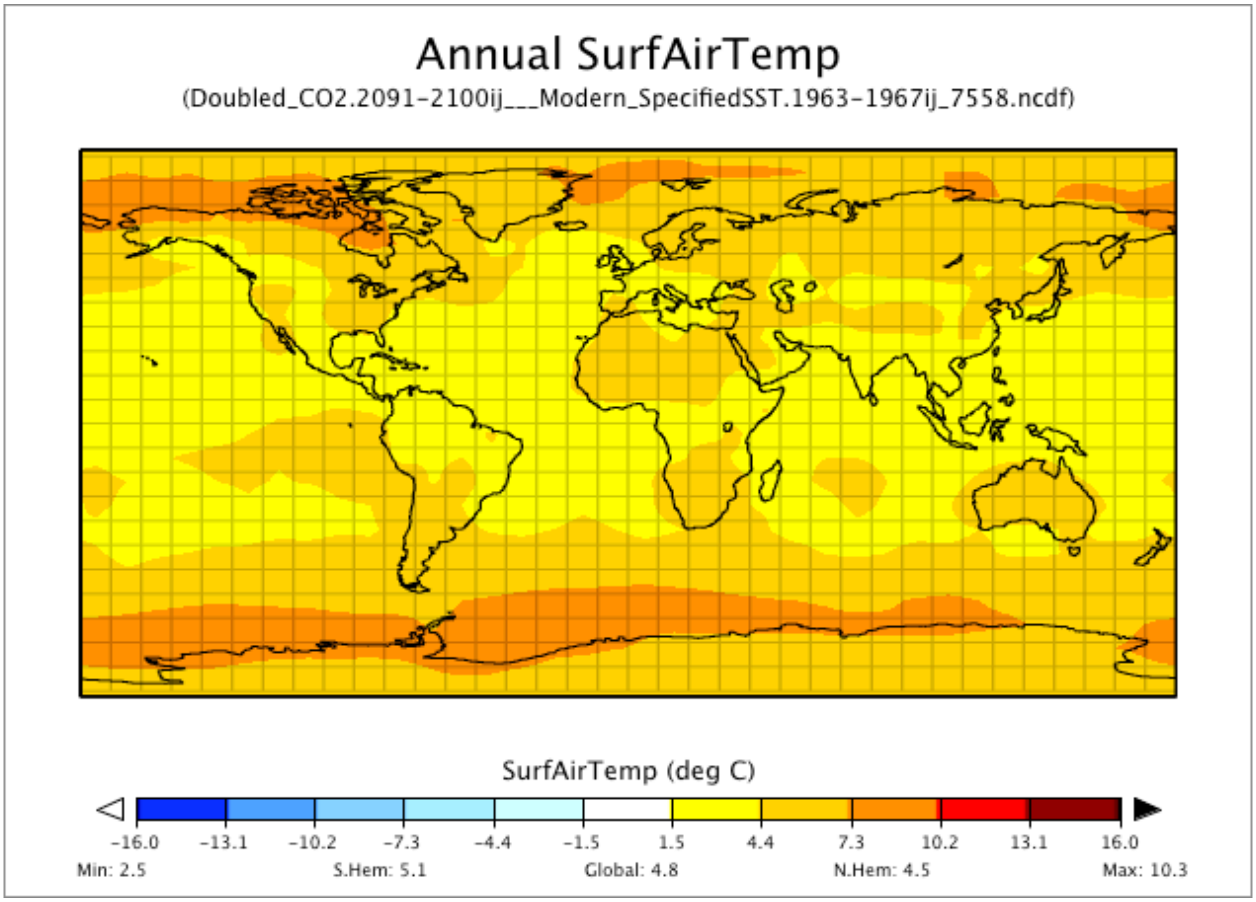


Figure 6.17. *Difference between Doubled CO_2 and Modern SST annual surface air temperatures. Image Copyright: Michael Pidwirny. Data Source: EdGCM model output.*

5.1) How would average annual surface air temperature change if the concentration of CO_2 doubled in the atmosphere?

5.2) List the locations of greatest temperature change.

5.3) List the locations of least temperature change.

Examine **Figure 6.18** carefully and answer the following questions.

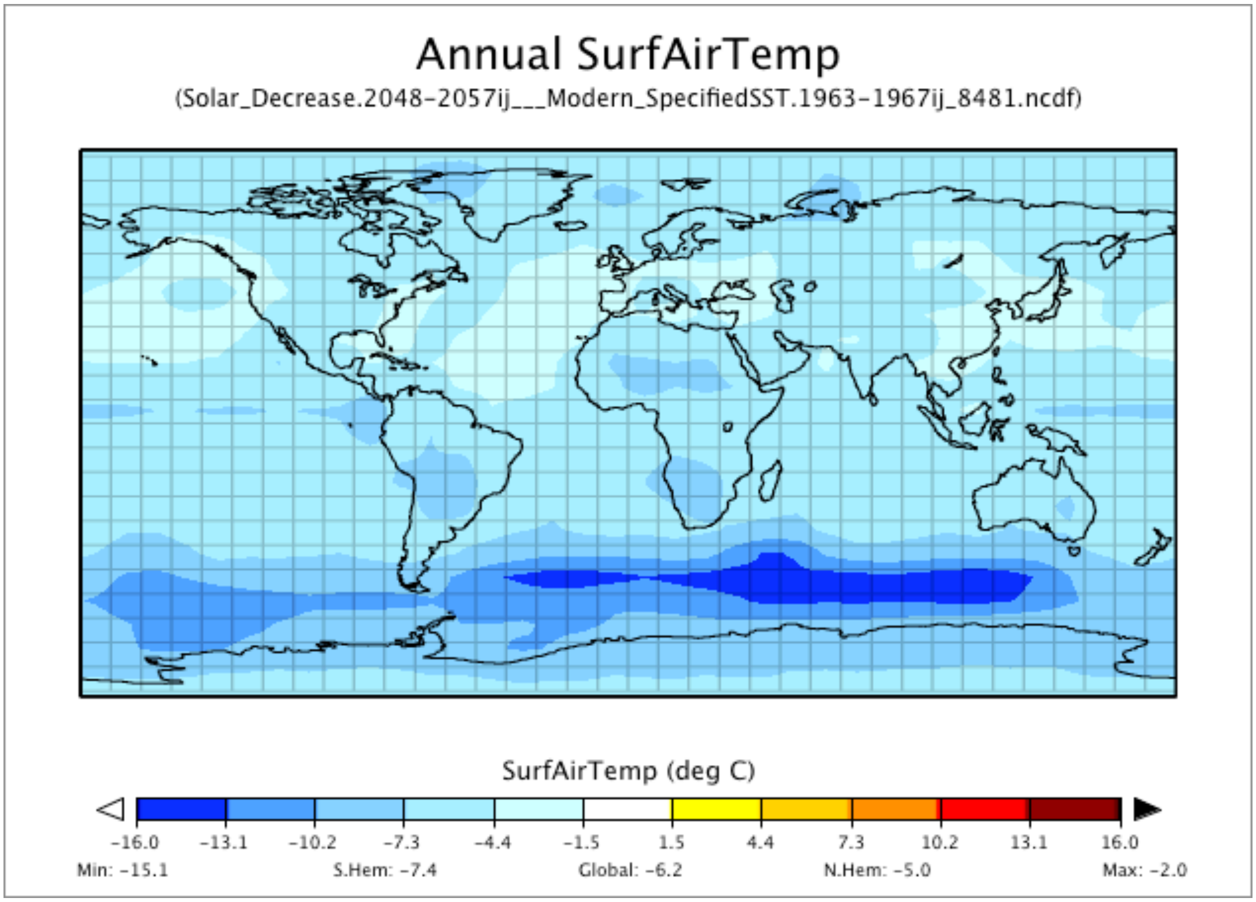


Figure 6.18. *Difference between Solar Decrease and Modern SST annual surface air temperatures. Image Copyright: Michael Pidwirny. Data Source: EdGCM model output.*

5.4) How would average annual surface air temperature change if solar output decreased by 2%?

5.5) List the locations of greatest temperature change.

5.6) List the locations of least temperature change.

Examine **Figure 6.19** carefully and answer the following questions.

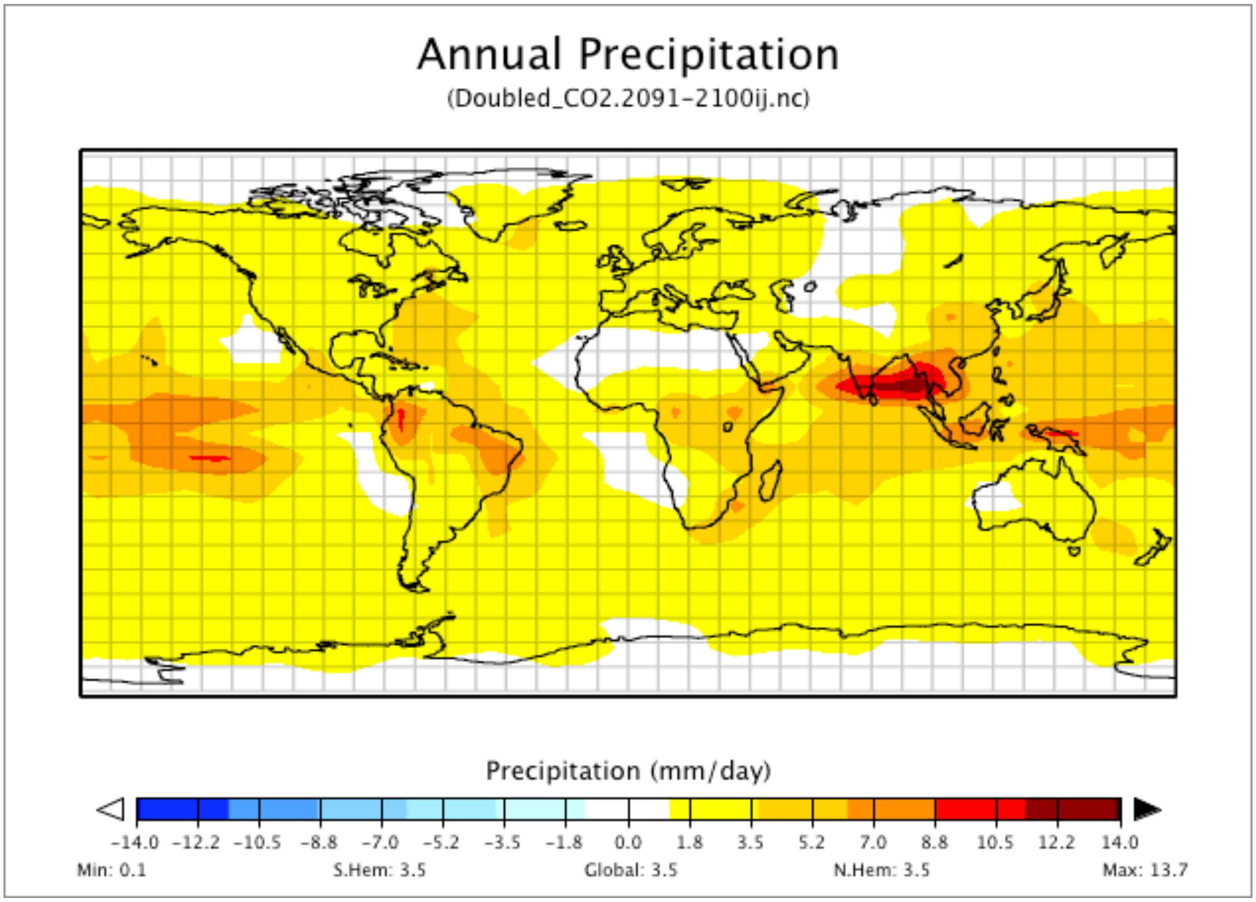


Figure 6.19. *Difference between Doubled CO_2 and Modern SST annual precipitation. Image Copyright: Michael Pidwirny. Data Source: [EdGCM] model output.*

5.7) How would annual precipitation change if the concentration of CO_2 in the atmosphere doubled?

5.8) List the locations that will have the greatest increase in precipitation.

5.9) List the locations that see no change or a decrease in precipitation.

Examine **Figure 6.20** carefully and answer the following questions.

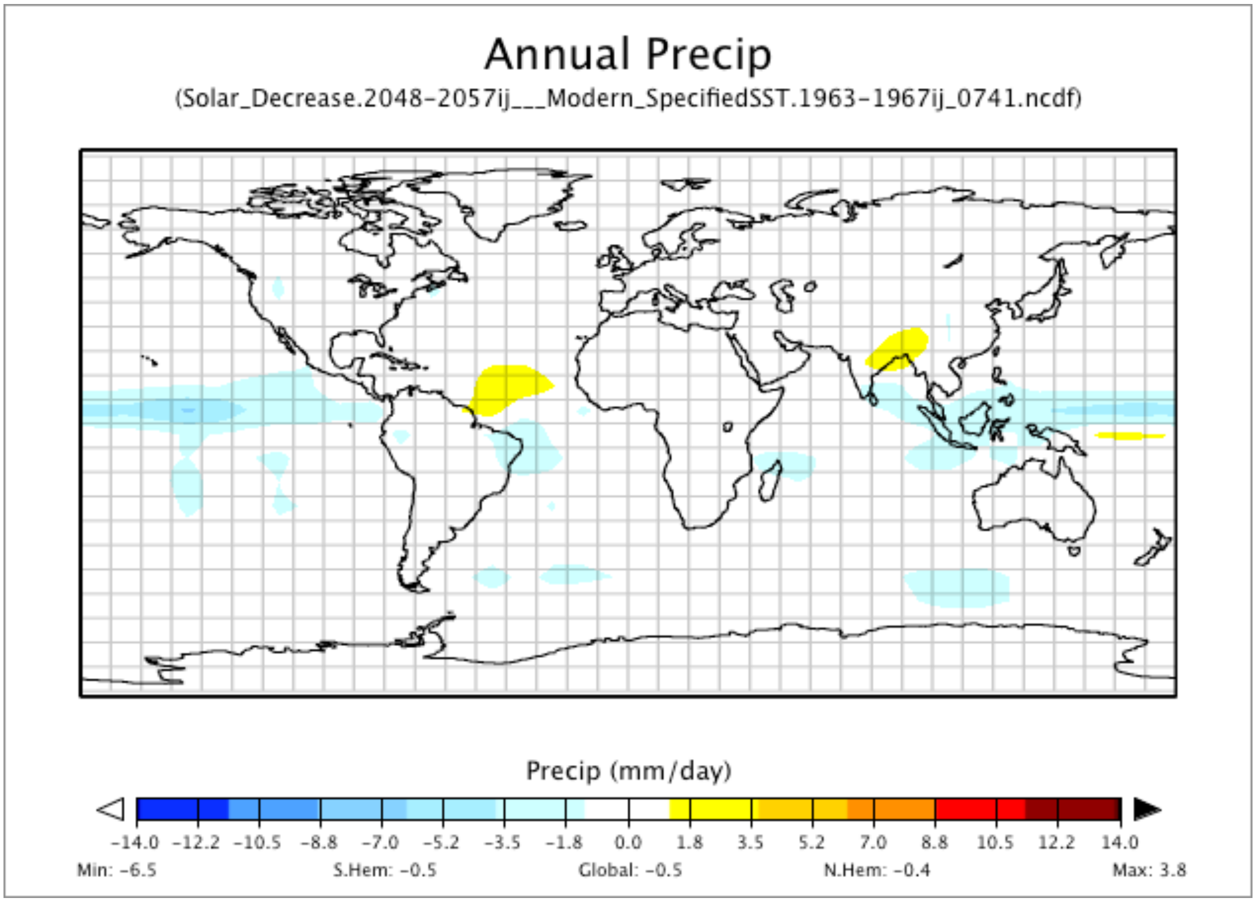


Figure 6.20. *Difference between Solar Decrease and Modern SST annual precipitation. Image Copyright: Michael Pidwirny. Data Source: EdGCM model output.*

5.10) How would annual precipitation change if solar output decreased by 2%?

5.11) List the regions on our planet that will have an increase or decrease in precipitation.