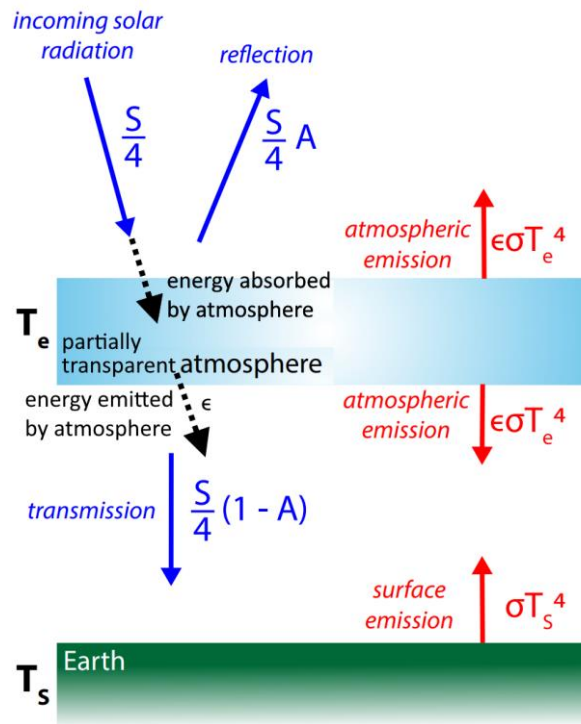


Q1. a) Added dotted lines to represent energy absorbed and radiated by a partially transparent atmosphere, with the emission represented by ϵ .



Q1. b) Based on the slide, we know that:

Incoming solar radiation: $S/4$

Reflected by Earth's atmosphere: $AS/4$, where A represents albedo

Absorbed by earth's surface: $(1-A)(S/4)$

Emitted by Earth's surface: σT_s^4 , where T_s is Earth's surface temperature

ϵ is the constant multiplied to atmospheric emission due to the atmosphere being a single later partially transparent atmosphere.

The atmosphere emits $\epsilon \sigma T_e^4$ upwards and downwards.

The earth's surface emits $\epsilon \sigma T_e^4$.

Earth and atmosphere are emitting equal radiation. Hence, energy balance equation for earth's surface is:

$$(1-A)(S/4) + \epsilon \sigma T_e^4 = \sigma T_s^4$$

Q1. c) Solving the above for T_s , we get: $T_s = \left[\frac{(\frac{S}{4})(1-A)}{\sigma(1-\frac{\epsilon}{2})} \right]^{\frac{1}{4}}$

Q1. d) Given $S = 1370 \text{ Wm}^{-2}$, $\epsilon = 0.78$ and $A = 0.3$

We know that the Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8} \text{ Wm}^{-2}\text{K}^{-4}$

Substituting this value in the above, we get

$$T_s = \left[\frac{(\frac{1370}{4})(1 - 0.3)}{(5.67)(1 - \frac{0.78}{2})} \right]^{\frac{1}{4}}$$

$$T_s = \left[\frac{(342.5)(0.7)}{(5.67)(0.61)} \right]^{\frac{1}{4}}$$

Solving on a calculator, we get **T_s = 288.15 K or about 15°C.**

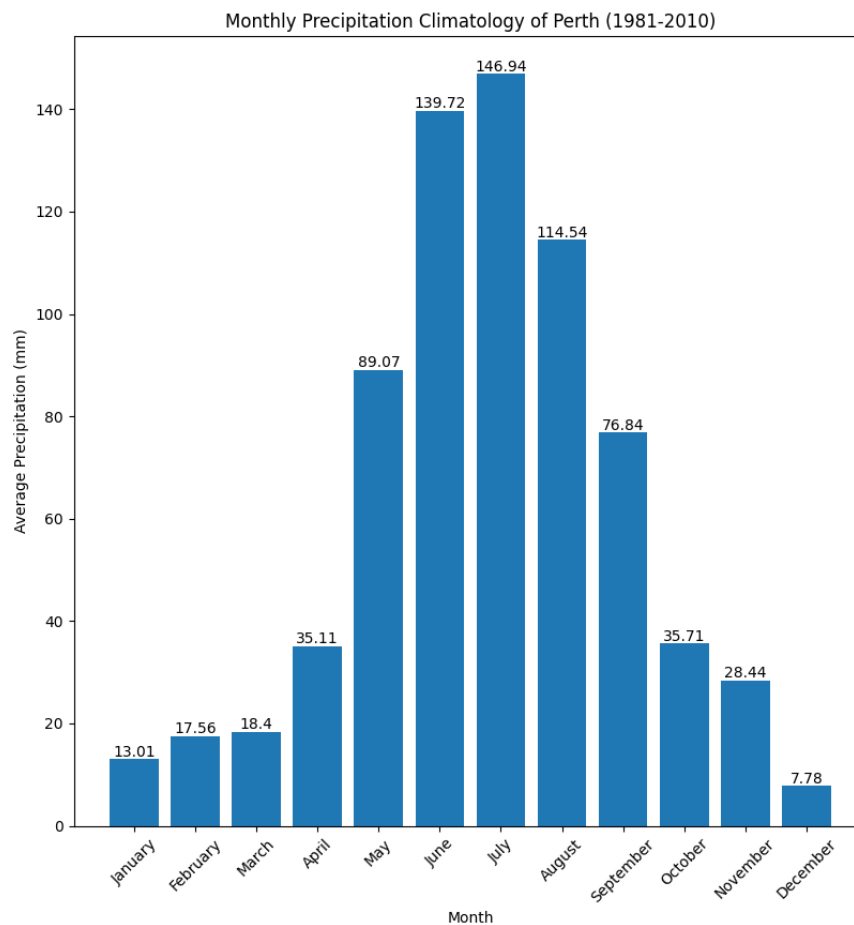
Q1. e) Substituting values, we can write the equation as:

$$-46 = \left[\frac{(\frac{589}{4})(1 - 0.24)}{5.67(1 - \frac{\epsilon}{2})} \right]^{\frac{1}{4}}$$

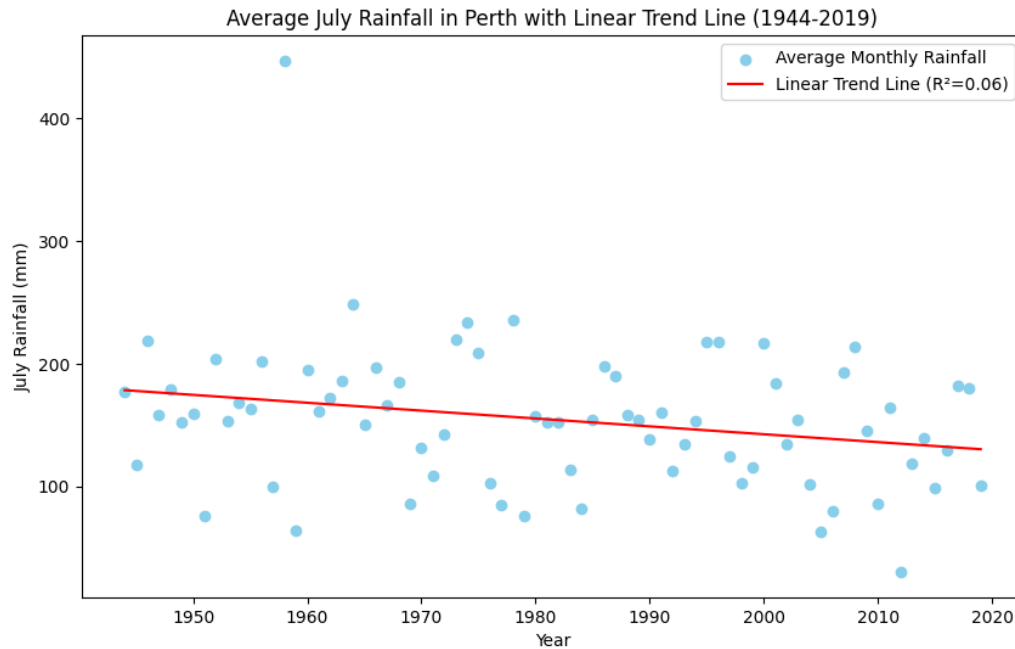
$$(-46)^4 \times 5.67(1 - \epsilon/2) = (589/4)(1 - 0.24)$$

or **ε = 0.5174**. Hence, Mars' atmospheric emissivity would need to be about **51.74%** to achieve its surface temperature of -46°C.

Q2. a) The rainiest month on average across 1981 to 2010 is July, as evident from the below bar plot of the monthly climatology of precipitation.

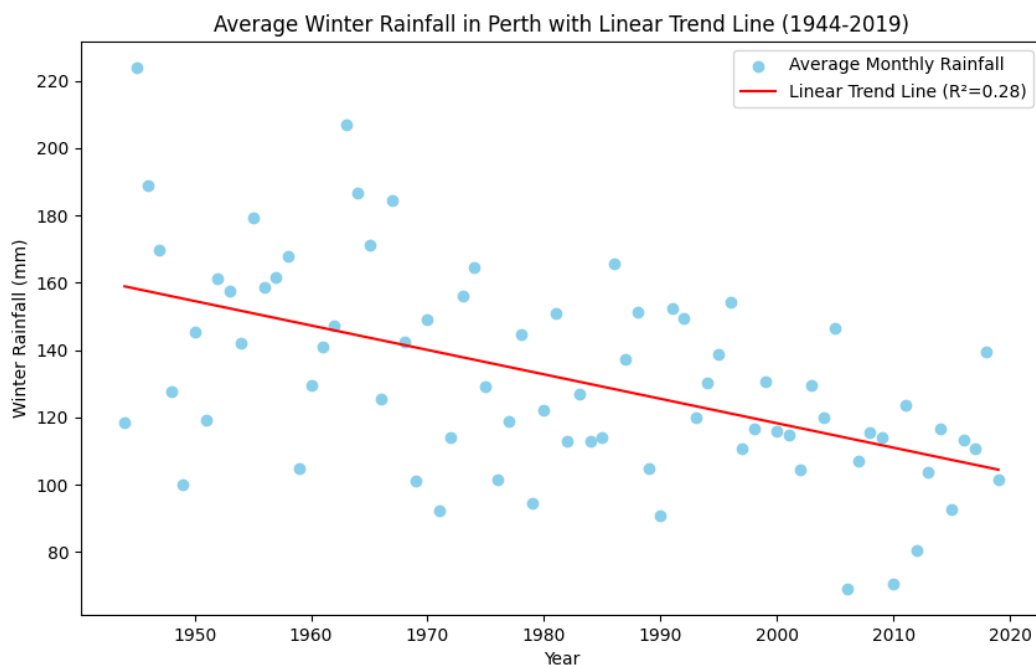


Q2. b) The trend line for the rainfall in July over the years 1944-2019 in Perth shows a slight downward trajectory, indicating a decrease in rainfall in the month of July over the years.



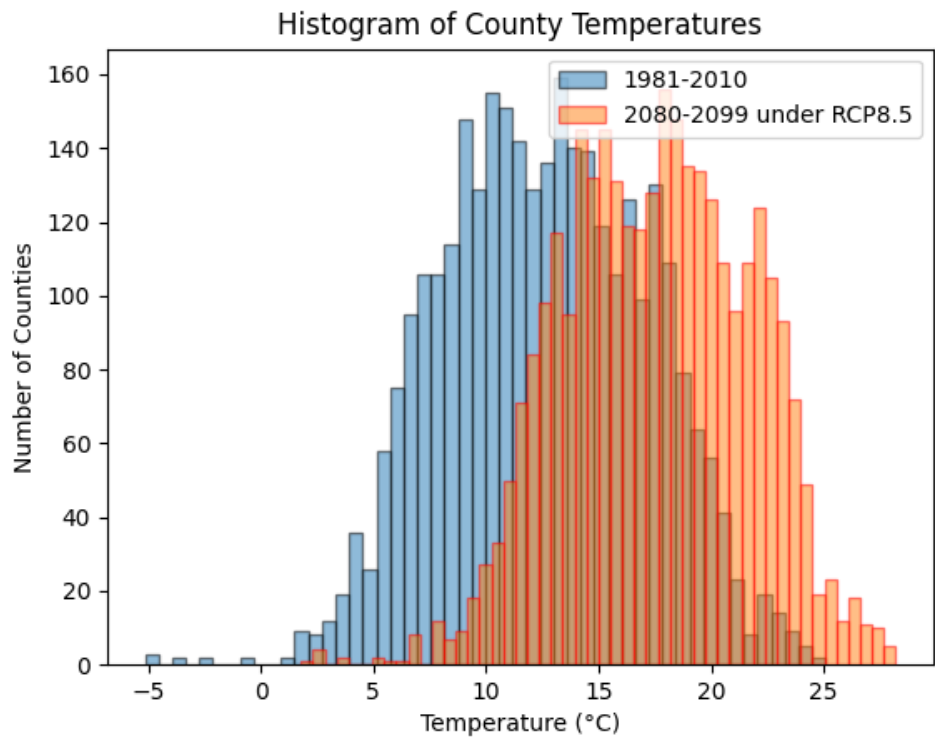
Based on the two-sample t-test performed using the scipy library in Python (see attached file), we see that the difference between the two periods is not statistically significant (fail to reject H_0). This means that there is insufficient evidence to conclude that there is a significant difference in July rainfall between the earlier period (1951-1980) and the later period (1981-2010). Based on the available data and the statistical test performed, the variation in July rainfall observed between the two periods could be due to random chance rather than a systematic, significant change.

Q2. c) The trend line for rainfall during winter months in Perth over 1944 to 2019 shows a clear downward trajectory over time, indicating a steady decline in rainfall over the years. While there are outliers, the R-squared value of 0.28 shows a weak but present correlation between years and decrease in rainfall.



The result of the two-sample t-test shows that the difference in average winter rainfall trend is statistically significant since the p-value of 0.005178 is smaller than significance level of 0.05, contrary to the same test performed for just a single month. Since the p-value is less than the significance level, we reject the null hypothesis (H0) which states that there is no effect or no difference. Hence, it is safe to say that there is indeed a statistically significant difference in the average winter rainfall trend between the two periods being compared. The positive t-statistic of 2.906 indicates that the average winter rainfall in the later period is higher than in the earlier period.

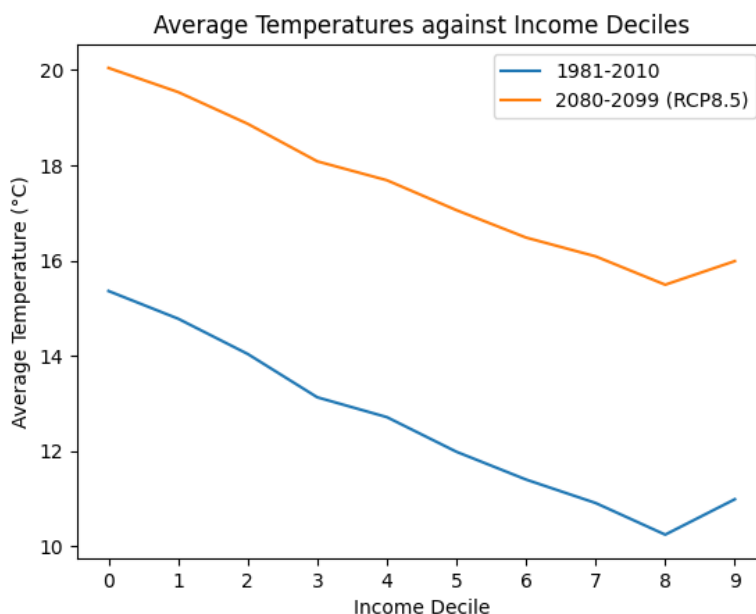
Q3. a) Based on the graph as shown below, we see that most counties' temperatures will increase by around 5°C compared to historical climate as per the RCP8.5 emissions.



Q3. b) The below table contains all calculations as required:

Income Decile	1981-2010 (Normal)	2020-2039 (RCP8.5)	2040-2059 (RCP8.5)	2080-2099 (RCP8.5)
0	15.358	16.634	17.692	20.046
1	14.776	16.072	17.147	19.539
2	14.035	15.345	16.438	18.872
3	13.124	14.474	15.595	18.083
4	12.707	14.067	15.18	17.686
5	11.979	13.351	14.497	17.057
6	11.395	12.767	13.908	16.481
7	10.902	12.292	13.458	16.086
8	10.237	11.644	12.826	15.49
9	10.981	12.333	13.455	15.986
All figures (except Income Decile) are in °C				

Q3. c) Graph plotted using Python as specified below:



Q3. d) Based on the above plots, it is evident that the higher income deciles' average temperature is much lower than those from lower income deciles. This implies that the population present in the lower income deciles will feel the highest impact of climate change, since the climate was already warmer for them compared to higher deciles, and it only worsens as per the RCP8.5 estimates.

Q3. e) The variable created was “temp_change” for the required purpose. Income decile 8 will experience the most change. Below is a table representing the various statistics (including latitude) associated with this income decile:

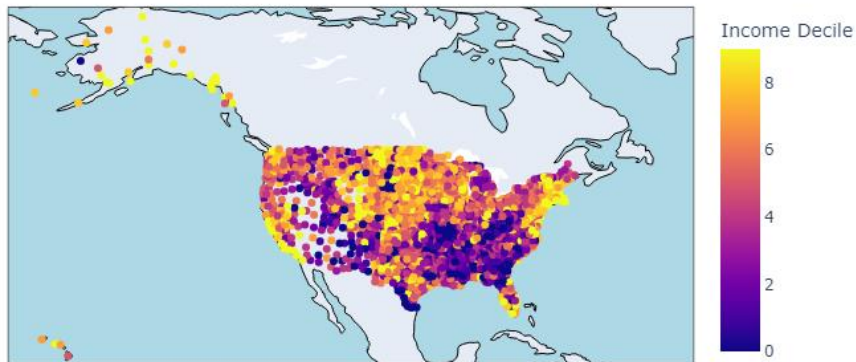
Statistic	lat	lon	temp_change
count	311	311	311
mean	41.423	-94.289	5.252
std	5.196	15.203	0.624
min	26.576	-170.28	3.256
25%	38.767	-99.708	4.919
50%	41.772	-95.310	5.322
75%	44.309	-84.687	5.667
max	65.018	-68.345	7.722

For comparison, here is a similar table comprising all deciles:

Statistic	lat	lon	temp_change	Income Decile
count	3112	3112	3112	3112
mean	38.471	-92.390	4.983	4.500
std	5.329	12.877	0.595	2.874
min	19.598	-170.28	2.878	0.000
25%	34.659	-98.348	4.678	2.000
50%	38.418	-90.495	5.072	4.500
75%	41.852	-83.602	5.361	7.000
max	69.306	-67.638	7.722	9.000

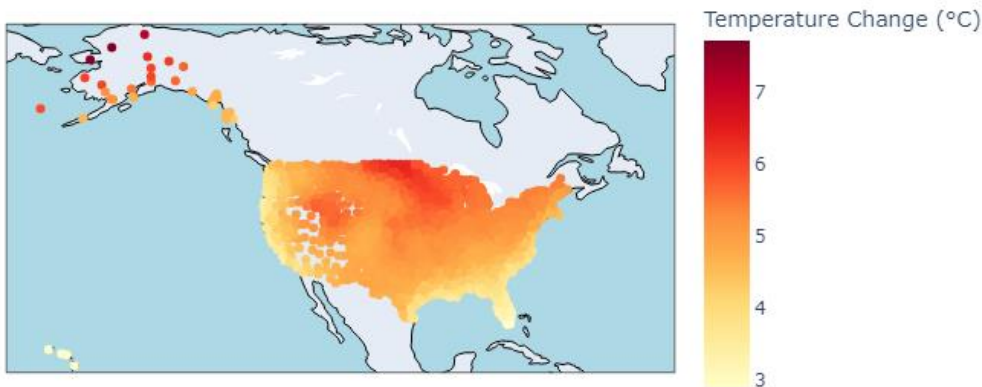
Below are cartographical representations of these spatial patterns:

Spatial pattern of income deciles



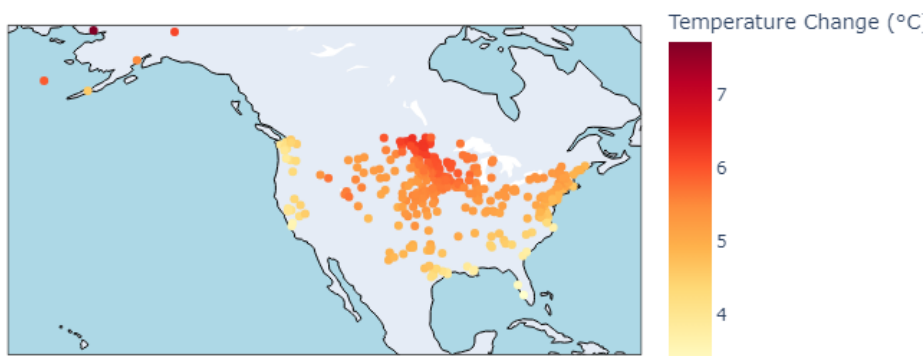
Map 1

Spatial pattern of temperature changes (RCP8.5)



Map 2

Spatial pattern of temperature changes for decile 8 counties (RCP8.5)



Map 3

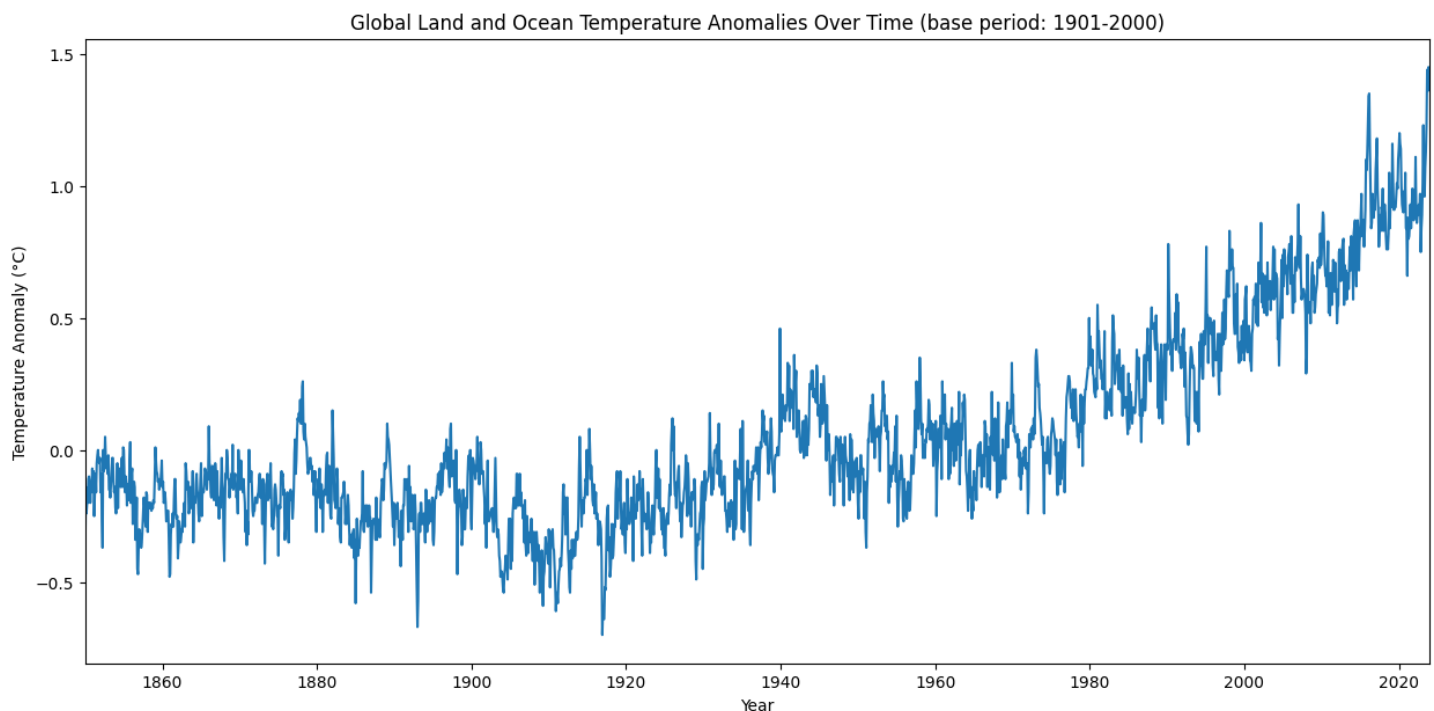
In *Map 2*, we see that the temperature change is disproportionate. Counties farther north from the equator are heating much more than those closer to it. In other words, a higher latitude correlates to a higher temperature change. At the same time, the *Map 2* shows us that counties with higher income deciles are concentrated more around central USA, similar to the map showing decile 8 counties.

It seems that there may be some correlation between the counties having a higher income decile and temperature changes, as temperature changes seem to be the highest in those areas (*Map 3* and *Map 2* in combination with *Map 1*), as seen from the above maps. The latitudes that they occupy are higher up on the globe, ie, farther away from the equator as noted previously, and it may be the case that the higher temperature changes in these latitudes are due to a higher concentration of wealthier deciles (*Map 1*).

It is also interesting to note that the wealthier counties usually start off with a temperature significantly lower than the poorer ones, which means that the poorer counties will continue to feel the heat (pun intended).

Q3. f) Seeing as to how climate change disproportionately affects poorer counties compared to wealthier ones, along with the fact that the temperature changes are the most pronounced in the wealthier counties (which will eventually influence neighboring and global climate; rich and poor alike – the latter for no fault of their own, without any of the benefits reaped by the wealthier counties from likely higher emissions) it would be appropriate that equitable climate adaptation includes a component of wealth transfer. This can be achieved in several ways, one of which could be taxing richer people and corporations higher and using that as a kickback for better resources, infrastructure and development of more sustainable consumption, majorly benefitting the poorer counties. Regulations are another way to achieve higher equity, where there may be limits or caps on how much carbon emissions are allowed per unit (per capita, per county, or others).

Q4. a) Created timeseries as instructed using matplotlib in Python:



Q4. b) i) The most notable aspect of this plot for me is that the base period is 1901-2000. While I understand the reasoning that there needs to be a fairly long period of time with actual data to be used as a baseline period, it is interesting to note that the 20th century was also the era where we had several wars and industrialization was at perhaps the fastest pace yet. That this century is chosen as a baseline, and yet we have still breached that baseline by nearly 1.5 °C already, is almost surreal to me.

ii) The peak and valley between around 1940 and 1960 are quite interesting since those were years comprising World War II and the Great Depression. The interesting part is how the temperature anomaly decreased more than it had increased post the WW2, and it was only around 1990 that the temperature anomalies matched those around 1940.

iii) Although 1850 onwards is somewhat widely regarded as the beginning of the era of industrialization, the rate of change of anomalies does not vary a great deal till around 1930. It is only after the global war years that the rate of change seems to increase much more compared to before. It is reasonable to say that the peace in the post-war years fostered increasing global cooperation (at least on a global scale compared to most of history), and this globalization seems to have affected the rate of change the most – which I believe is evidenced by the sharp increase in rate of change of anomalies from just after 1980 which continues till today (barring the dip during the pandemic years of 2020-2021).

iv) It seems that for every positive anomaly, there follows a negative one not much later. This is probably making people put more weight on anecdotal evidence rather than science (“last year was so much colder and this year is not much warmer” etc), since climate change does not take place linearly. Moreover, in the age of information overload with ever-decreasing attention spans and ever-faster news cycle, it is easier than ever to omit thinking over larger time scales. Additionally, “1.5 (°C)” as a number does not sound a lot to the layman, who may think that climate change is all hullabaloo over this small number when in fact it is more about the anomalies and extreme weather events than just the number defined as the climate anomaly.

Q4. c) i) I really liked the 3D visualization aspect of the Climate Spiral. It enables people to visualize what exactly anomalies of 2F look compared to baseline, and how much further we have strayed from it over time. An interesting thought that popped up while I was watching the video is that we could also do a similar visualization with concentration of CO₂ in the atmosphere over the same time period. The moment when the animation flips from the top-down view to a side view is simply wonderful. Another idea on the same lines that may be even more eye-catching since the numbers involved are significantly bigger compared to climate anomalies – a change of 2F sounds much less dire compared to a change from 280 PPM to about 420 PPM in the same time frame (1850 to present day).

ii) The most striking aspect of the Climate Stripes is that there is no text involved in the visualization – it is a visual treat, and helps one visualize just by purely seeing. Apart from the bare minimum social context cue that blue is better than red, and that red usually signals danger, no additional knowledge is needed by the layperson to comprehend this visual. That one may agree or disagree is a different matter, but it is eye-catching while also conveying a lot of information in a second or less. I also liked that the colors were vivid and saturated, compared to the pastel shades we see in most graph-based visualizations.

Q4. d) I would love to do my own suggestion of visualizing CO₂ in a manner similar to the Climate Spiral (see Q4; part c), due to my hypothesis that a bigger number and delta of change might be more striking and attention-grabbing.

Apart from the above specific idea, another interesting climate change visualization could be visualizing the loss in economic terms by showing how much income (or another metric, like GDP) per capita has been lost due to climate change since 1850, and if there is any relation to temperature anomalies. A visualization around climate refugees, showing their numbers over the years, may also make a compelling visualization; although I am not sure if anything more appealing than a simple graph could be made for these.