Indian Institute of Technology Bombay

Climate Change Impacts & Adaptation
CM 615

Assignment 1
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1. ## Define climate change and provide two observational evidences that support its occurrence.

   Climate change can be defined as changes in the state of the climate system that occur when we perturb any of its components (atmosphere, hydrosphere, cryosphere, lithosphere, biosphere), ultimately affecting the planetary energy budget.
   Two observational evidences from the lecture materials include:

   (a) Increasing CO_2 concentrations as shown in the Keeling curve

   (b) Global mean surface temperature (GMST) increase since 1850, showing clear warming trends

2. ## What is global warming? Explain how it relates to climate change.

   Global warming refers to the observed increase in global mean surface temperature. From the lectures, we can see that it's one aspect of broader climate change. The current global mean surface temperature (T_S) is around 288K, which is 33K higher than Earth's emission temperature ($T_E = 255$K) due to the greenhouse effect. Global warming is a manifestation of climate change resulting from perturbations to Earth's energy balance.

3. ## Describe how greenhouse gases influence Earth's energy balance.

   Greenhouse gases influence Earth's energy balance by absorbing infrared radiation. While they are transparent to incoming solar radiation (shortwave), they absorb and re-emit longwave radiation from Earth's surface. This creates what the lectures call the "greenhouse effect", which maintains Earth's surface temperature about 33K warmer than it would be without an atmosphere.

4. ## Explain how aerosols impact Earth's energy balance.

   From the energy flow diagrams shown in the lectures, aerosols affect Earth's energy balance through:

   (a) Direct reflection and scattering of incoming solar radiation

   (b) Interaction with clouds, affecting their formation and properties

   These processes can influence both incoming and outgoing radiation.

5. Write the mathematical expression representing radiative equilibrium in Earth's energy budget.

The radiative equilibrium equation is:

$$\frac{S}{4(1-\alpha)} = \sigma T_e^4 \tag{1}$$

Where:

- S is the solar constant ($1365W\frac{W}{m^2}$)
- α is albedo
- σ is the Stefan-Boltzmann constant
- T_e is the emission temperature

6. Define climate forcing (or radiative forcing) and climate response. Give one example each of positive and negative feedback mechanisms.

Climate forcing (radiative forcing) refers to the initial perturbation to Earth's energy balance. Climate response is how the climate system reacts to this forcing.
Examples from the lectures:

(a) Positive feedback: Water vapor feedback (warming leads to more water vapor, which causes more warming)

(b) Negative feedback: Increased surface temperature leads to increased emission of long-wave radiation to space, which helps cool the system

2

Determine how much carbon (in gigatonnes, GtC) corresponds to an increase of 1 ppm in atmospheric CO_2. Then, convert the current atmospheric CO_2 concentration into its equivalent carbon stock.

1. **Step 1: Understanding Atmospheric CO_2 and Air Mass**
   - The Earth's atmosphere has a total mass of approximately 5.15×10^{18} kg.
   - 1 ppm of CO_2 means 1 molecule of CO_2 per 1 million air molecules.
   - The mass fraction of CO_2 is determined using the molecular weights of CO_2 and dry air.

2. **Mass of CO_2 for 1 ppm Increase**
   - Molar mass of air $\approx$ 29 g/mol
   - Molar mass of C in CO_2 = 12 g/mol
   - 1 ppm by volume means 1 CO_2 molecule per million air molecules, so in terms of mass:

     $\frac{12}{29} * 10^{-6} \approx 0.413 * 10^{-6}$

   - Since the total mass of the atmosphere is 5.15×10^{18} kg, the mass of CO_2 in the atmosphere per ppm is:

     $(5.15 \times 10^{18}$ kg) x $(0.413 \times 10^{-6}) = 2.126$ GtC

   Thus, 1 ppm increase in CO_2 corresponds to approximately 2.13 GtC.

3. **Estimating the Total Carbon Stock**
   - The current atmospheric CO_2 concentration is around **420 ppm**.
   - The total carbon stock is:

     $420 \times 2.13 =$ **894.6 GtC**

Conclusions:

- **1 ppm increase in CO_2 corresponds to $\sim$ 2.13 GtC.**
- **The total atmospheric carbon stock at 420 ppm is $\sim$ 894.6 GtC.**

3

Given Earth's emission temperature as 255K and planetary albedo as 30%, analyze two hypothetical scenarios:
i. If Earth's albedo decreases by 10%
ii. If albedo remains the same, but the infrared absorptivity of the atmosphere doubles
Compute the emission temperature and surface temperature for both cases, assuming a leaky atmosphere model or partially absorbing atmosphere. Discuss the real-world conditions under which these scenarios could occur and their implications for Earth's climate and energy budget.

To start with the solution, we take $\alpha = 0.3$, $T_e = 255\ K$ and using the formulae calculated in the class :

$T_s^4 = \frac{s(1-\alpha)}{2\sigma(2-f)}$ and $T_a^4 = \frac{s(1-\alpha)}{4\sigma(2-f)}$, we get $f = 0.9963$ for $T_a = T_e = 255\ K$

1. $\alpha = 0.2$ and $f = 0.9963\ \approx 1$

   $T_s^4 = \frac{s(1-\alpha)}{2\sigma} = \frac{1365(1-0.2)}{2*5.67*10^{-8}} = 9,629,629,629.6296$, which gives $T_s = 313.25\ K$

   $T_a^4 = \frac{s(1-\alpha)}{4\sigma} = \frac{1365(1-0.2)}{4*5.67*10^{-8}} = 4,814,814,814.8148$, which gives $T_a = 263.417\ K$

   (a) Real world scenarios: A decrease in Earth's albedo means that the planet reflects less sunlight and absorbs more incoming solar radiation. This could occur due to:
      - Melting of Ice and Snow: Ice and snow have high albedo. With rising temperatures, ice sheets and glaciers shrink, reducing Earth's overall reflectivity.
      - Aerosol Reduction: Some aerosols (such as sulfate particles from volcanic eruptions or industrial pollution) increase albedo by reflecting sunlight. A decline in such aerosols would decrease albedo.

   (b) Implications:
      - Increased absorption of solar radiation would raise Earth's energy input, leading to higher surface temperatures.
      - This could accelerate global warming, intensifying heatwaves, glacial melting, and sea-level rise.

2. $\alpha = 0.3$ and $f = 0.9963 * 2 = 1.9926$ (practically impossible but for the sake of calculation)

   $T_s^4 = \frac{s(1-\alpha)}{2\sigma(2-f)} = \frac{1365(1-0.2)}{2*5.67*10^{-8}*(2-1.9926)} = 1,301,301,301,301$, which gives $T_s = 1068.057\ K$

   $T_a^4 = \frac{s(1-\alpha)}{4\sigma(2-f)} = \frac{1365(1-0.2)}{4*5.67*10^{-8}*(2-1.9926)} = 650,650,650,650.64$, which gives $T_a = 898.1253\ K$

(a) Real world scenarios: An increase in the atmosphere's infrared absorptivity means more outgoing thermal radiation is trapped, leading to a stronger greenhouse effect. This could occur due to:

- Increased Greenhouse Gas Concentrations: Higher levels of CO_2, CH_4, H_2O vapor, and other greenhouse gases enhance infrared absorption.
- Aerosol Effects: Some aerosols can enhance infrared absorption, depending on their chemical composition and distribution.

(b) Implications:

- Surface temperatures would rise significantly due to enhanced greenhouse warming.
- This could lead to more extreme weather patterns, including stronger storms, prolonged droughts, and changes in precipitation cycles.
- Long-term climate shifts, such as desertification and shifts in agricultural zones, would impact global food security.

Overall Impact on Earth's Energy Budget : Both scenarios disrupt Earth's energy balance by increasing the amount of absorbed or retained heat. The first scenario alters the shortwave (incoming solar) radiation budget, while the second affects the longwave (outgoing infrared) radiation. Together or individually, these changes could push Earth's climate toward a much warmer state, leading to significant ecological, economic, and societal consequences.

4

Calculate the emission temperatures of Venus and Mars, given:
i. Their mean orbital distances: **0.72 AU (Venus), 1.52 AU (Mars)**
ii. Solar flux at Earth's orbit: **1367** $\frac{W}{m^2}$, which decreases with the square of distance
iii. Planetary albedo: **0.77 (Venus), 0.24 (Mars)**

Assuming that the solar flux decreases with the square of distance in the form of $S = \frac{1367}{x^2}$ where x is the distance of the planet from the Sun (in AU).

Now for Venus, $S_V = \frac{1367}{(0.72)^2} = 2636.9598$ and subsequently for Mars, $S_M = \frac{1367}{(1.52)^2} = 591.6724$

Using the formula for emission temperature $T = (\frac{s(1-\alpha)}{4\sigma})^{0.25}$, we get :

$T_V = (\frac{S_V(1-\alpha)}{4\sigma})^{0.25} = (\frac{(2636.9598)(1-0.77)}{4*5.67*10^{-8}})^{0.25} = 227.403\ K$, and

$T_M = (\frac{S_M(1-\alpha)}{4\sigma})^{0.25} = (\frac{(591.6724)(1-0.24)}{4*5.67*10^{-8}})^{0.25} = 211.014\ K$

Thus, $T_V =$ **227.403 K** and $T_M =$ **211.014 K**

5

Use Modtran (tropospheric atmosphere, looking down mode) to analyze the impact of greenhouse gases on Earth's outgoing infrared flux. Comment on the Upward IR Heat Flux and emission spectra for the following cases:
i. Set all atmospheric gases to zero.
ii. Use default settings for all gases except CO_2, which is set to 4 ppm and 440 ppm.
iii. Keep all gases at default except water vapor, which is set to 1x and 4x water vapour scale.

The tropospheric atmosphere is assumed to be at 13 km of height which is the average troposphere height, to be used in the model.

1. **Set all atmospheric gases to zero :**

   We get **Upward IR Heat Flux = 443.996** $\frac{W}{m^2}$ and the following emission spectra :

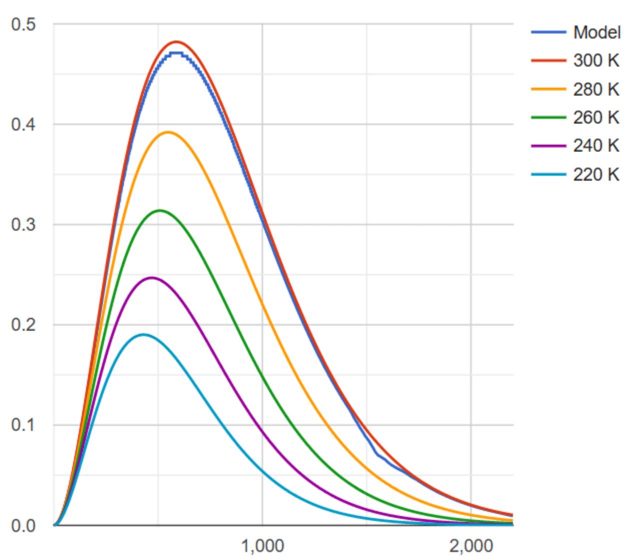


Figure 1: Emission spectra with all atmospheric gases set to zero

This emission spectrum is the smoothest and the most ideal case which can happen where there are no GHGs in the atmosphere at all. The Upward IR Heat Flux is also a bit higher compared to the standard value of 306.307 at the standard gas levels. This is because of the fact that reducing the GHGs in the atmosphere, more LWR is able to escape into the space insted of being reflected back towards the Earth.

2. **Use default settings for all gases except CO_2, which is set to 4 ppm and 440 ppm :**

   We get **Upward IR Heat Flux = 329.072** $\frac{W}{m^2}$ and the following emission spectra when CO_2 is at 4 ppm :

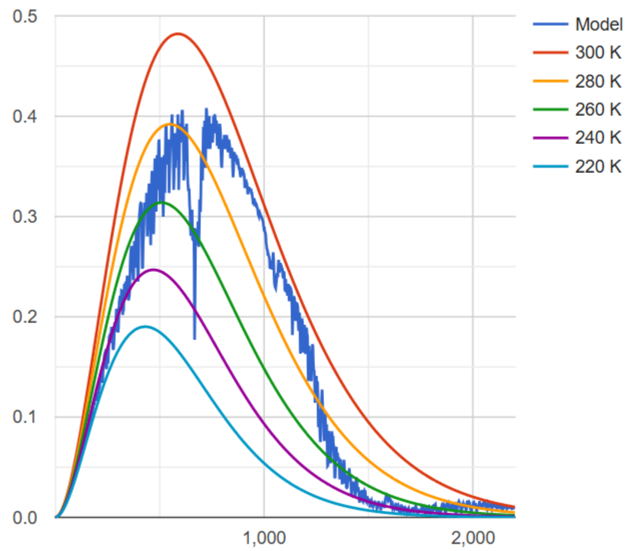


Figure 2: Emission spectra with 4 ppm CO_2

   We get **Upward IR Heat Flux = 305.742** $\frac{W}{m^2}$ and the following emission spectra when CO_2 is at 440 ppm :

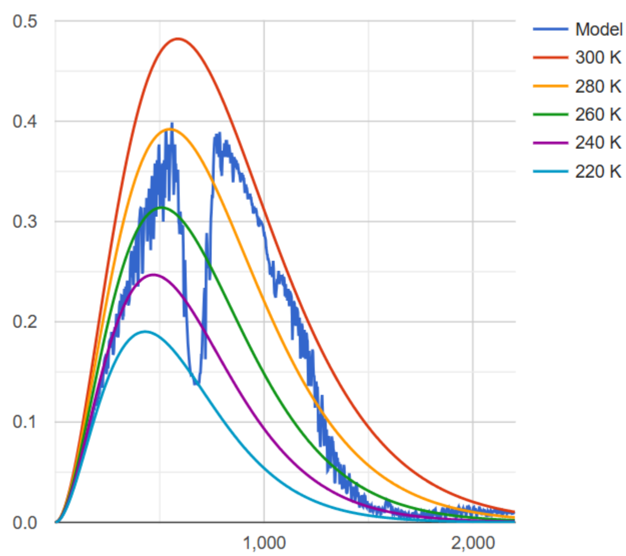


Figure 3: Emission spectra with 440 ppm CO_2

These emission spectra maps are the most accurate representation of the real life atmosphere. The Upward IR Heat Flux in the case of 4 ppm CO_2 is more as compared to that of 440 ppm CO_2 because as the concentration of CO_2 in the atmosphere increases, the less LWR radiation is able to escape the Earth's atmosphere and thereby increasing the Upward Heat Flux significantly.
The same story is told through the emission spectrum curves where the intensity of the light corresponding to the particular wavenumber of CO_2 decreases as the concentration of CO_2 increases, suggesting that CO_2 has absorbed quite a bit of radiation from the received total.

3. **Keep all gases at default except water vapor, which is set to 1x and 4x water vapour scale :**

We get **Upward IR Heat Flux = 306.307** $\frac{W}{m^2}$ and the following emission spectra when water vapour is at 1x :

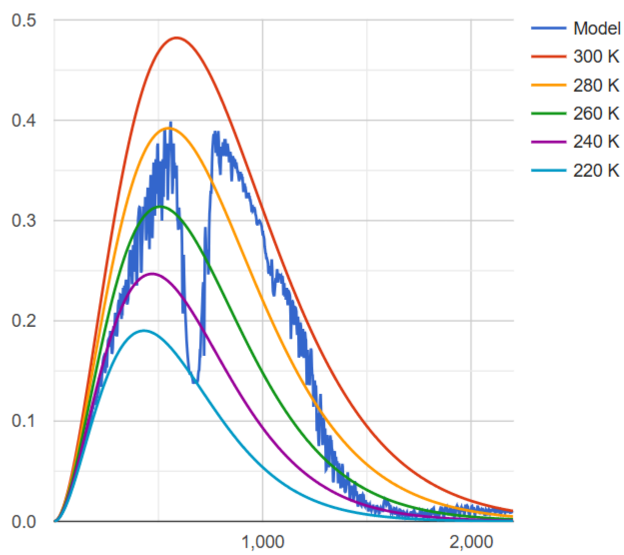


Figure 4: Emission spectra with water vapour scale 1x

We get **Upward IR Heat Flux = 264.796** $\frac{W}{m^2}$ and the following emission spectra when water vapour is at 4x :

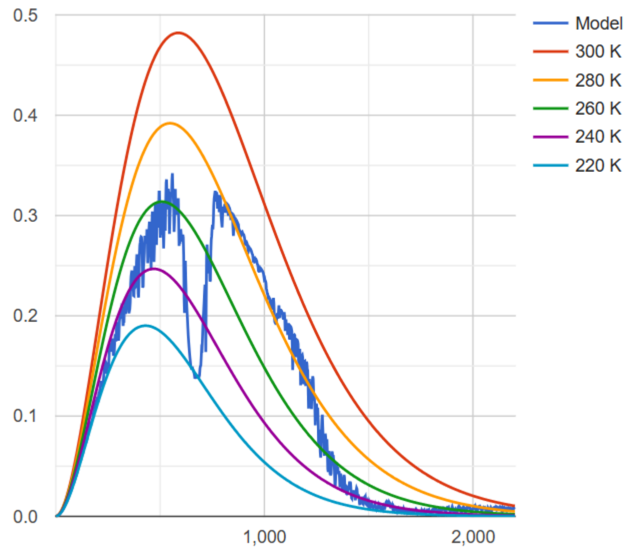


Figure 5: Emission spectra with water vapour scale 4x

The Upward IR Heat Flux in the case of 1x water vapour is more as compared to that of 4x water vapour because as the effect or scale of water vapour in the atmosphere increases, the air absorbs more LWR and thereby reducing the transmitted LWR.
The same can be inferred through the emission spectrum curves where the overall spectra shifts down when the scale of water vapour is made 4x because water vapour absorbs radiations at all wavelengths equally and thus decreases the transmitted radiation significantly.

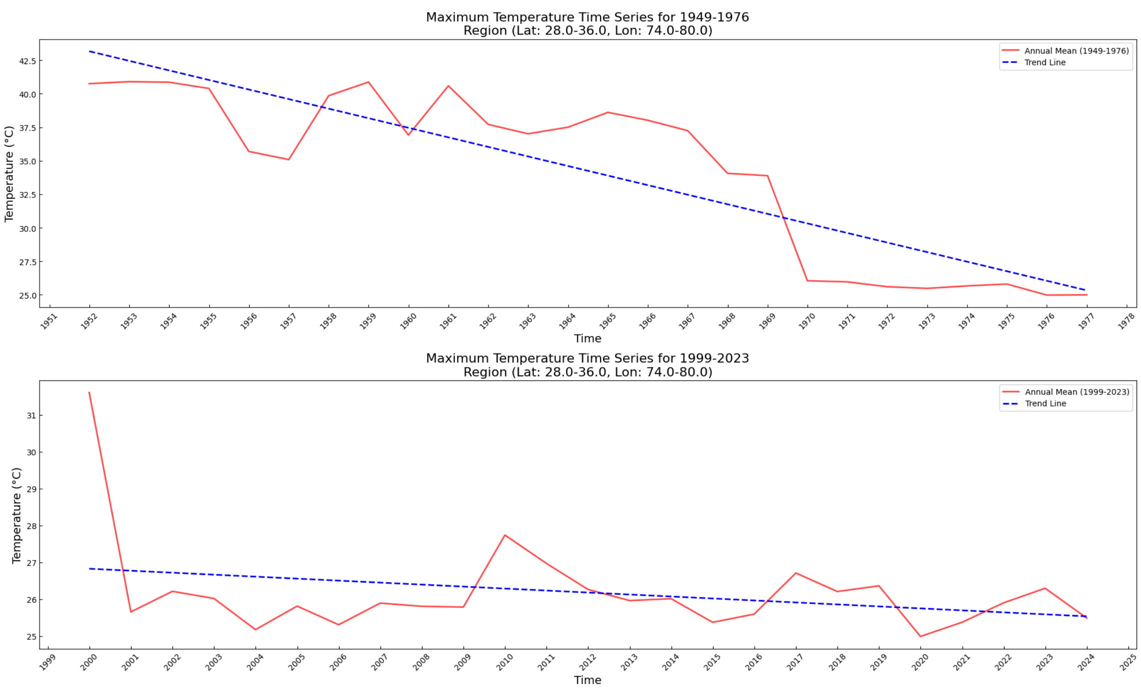
6

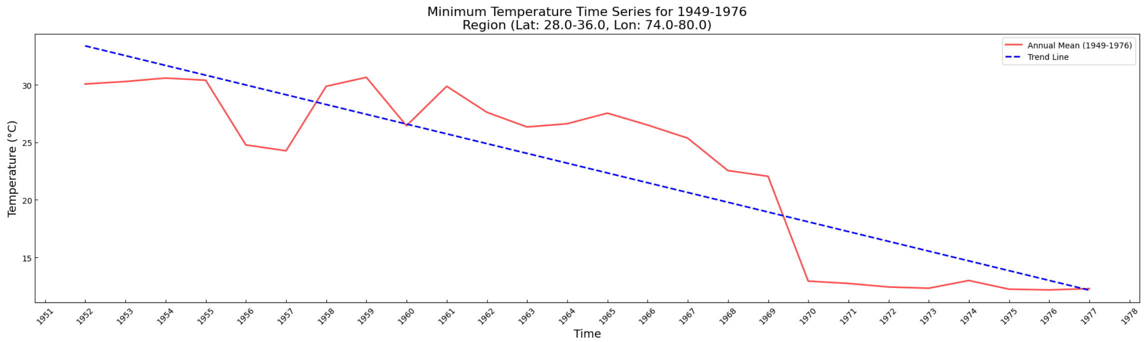
Plot the trends of annually averaged T_{min} and T_{max} over India for two periods: 1950-1975 and 2000-2023. Perform this analysis for the entire country and four specific regions:

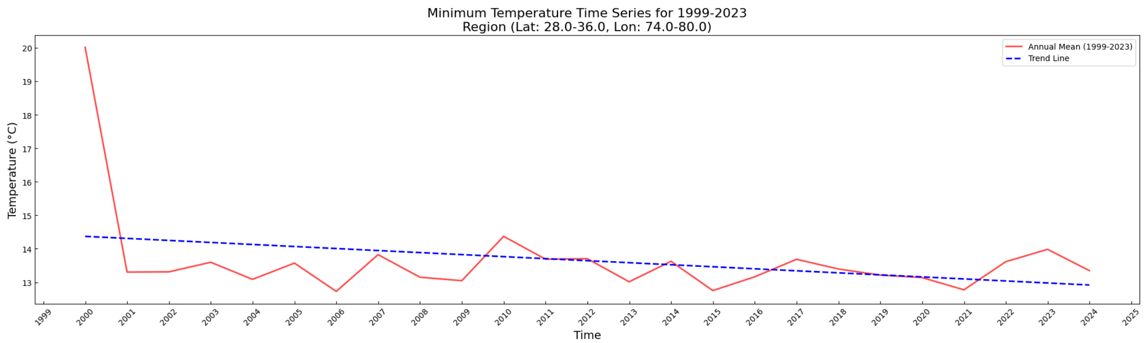
- North: (74–80°E, 28–36°N)
- South: (74–80°E, 14–22°N)
- East: (80–94°E, 22–28°N)
- West: (70–80°E, 21–28°N)

Compare the results and provide insights based on the plots.

1. **North (74–80°E, 28–36°N)**

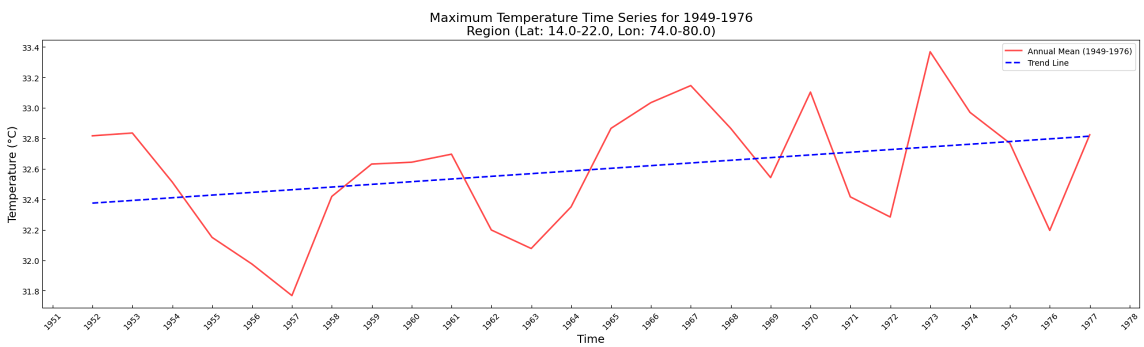


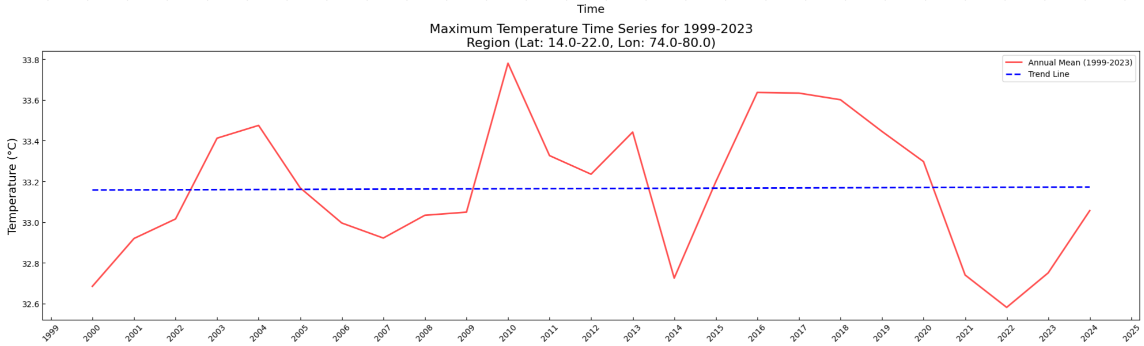


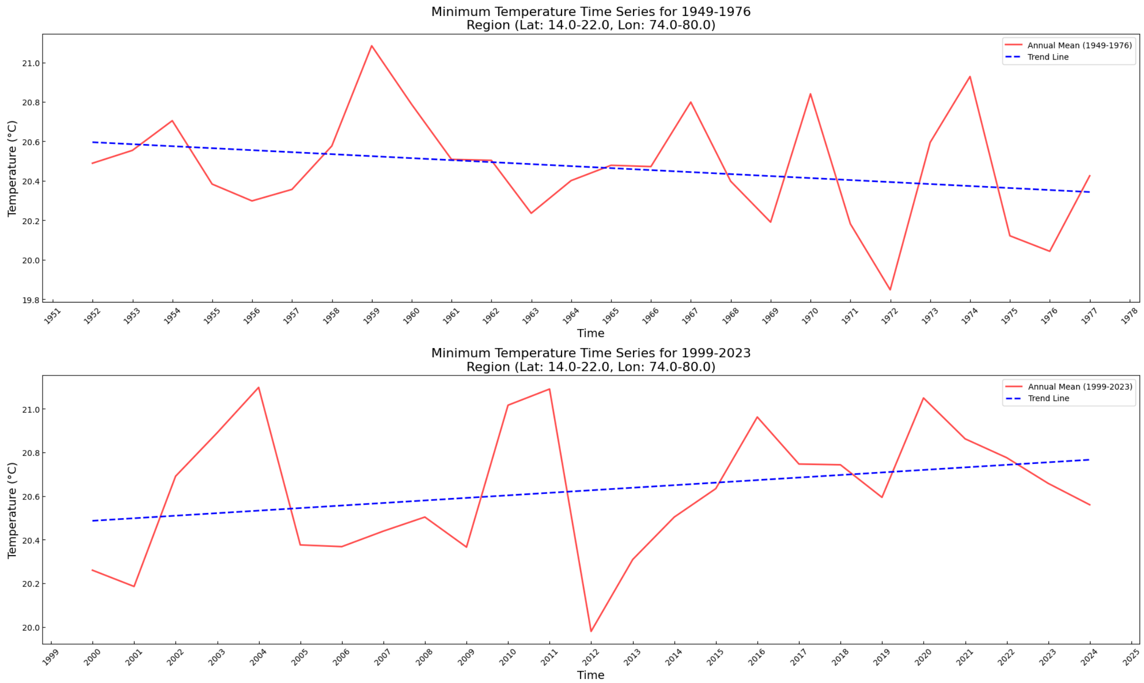


For the Northern region, it being near the Himalayas and having a relatively cooler climate as compared to the Indian average, the effect of global warming had a significant effect on both the annual mean maximum temperature and the annual mean minimum temperature. In both the cases, the slope of the curve becomes zero from being negative which is due to the fact that the region being cooler, gets affected in a way similar to that of a cold region.

2. **South (74–80°E, 14–22°N)**

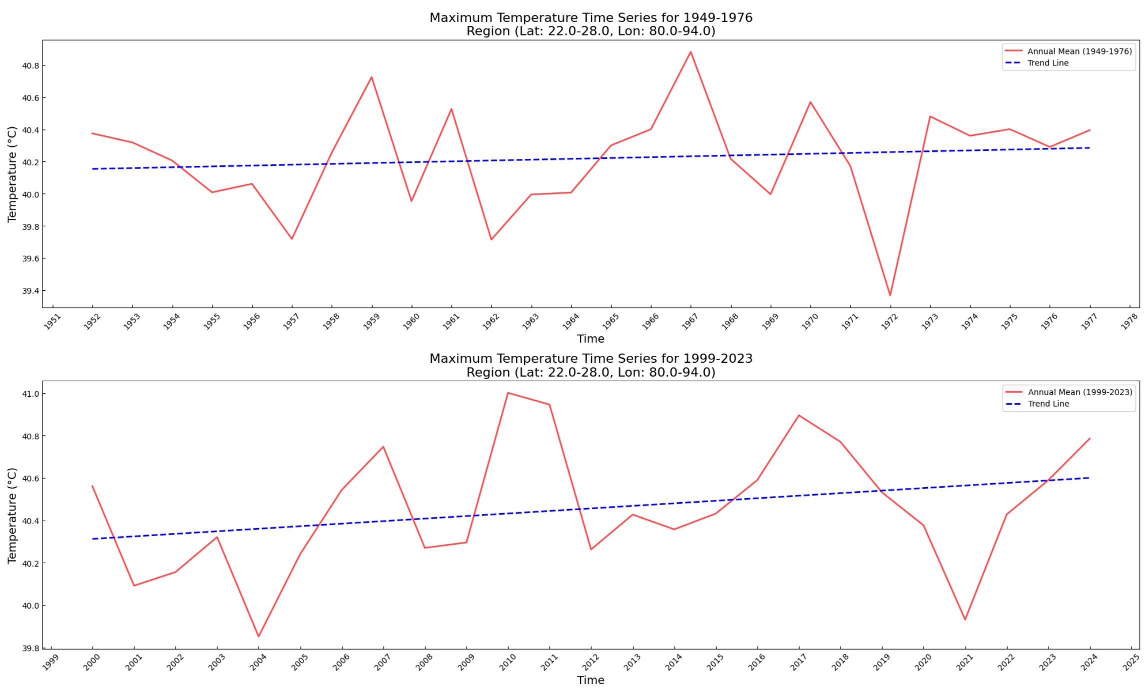


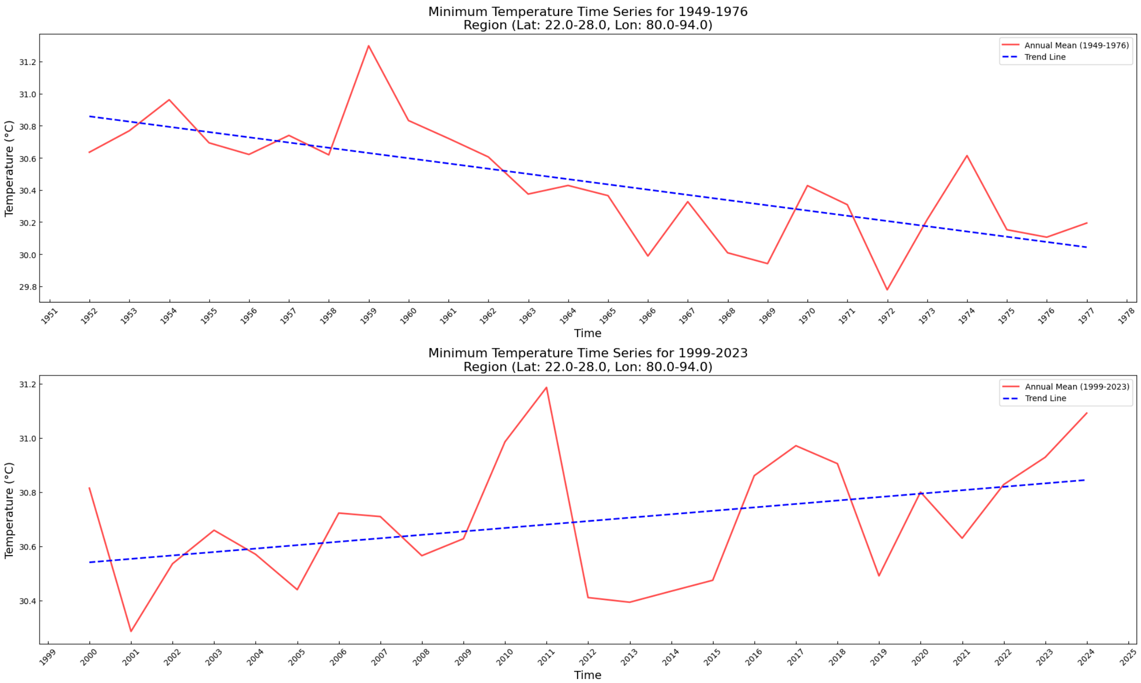




For the Southern region, the maximum temperature had an overall positive gradient during the period from 1950 - 1975 but it has become constant during the period 2000 - 2023. This might be due to the climate change over that region. Also, the minimum temperature series was declining prior to 2000 but afterwards, it has been consistently growing and doesn't seem to stop.

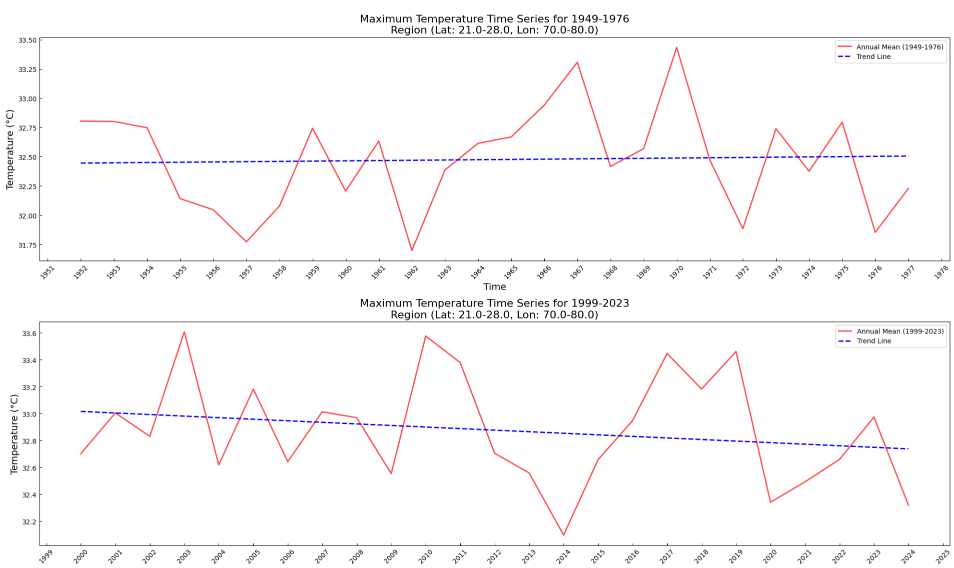
3. **East (80–94°E, 22–28°N)**

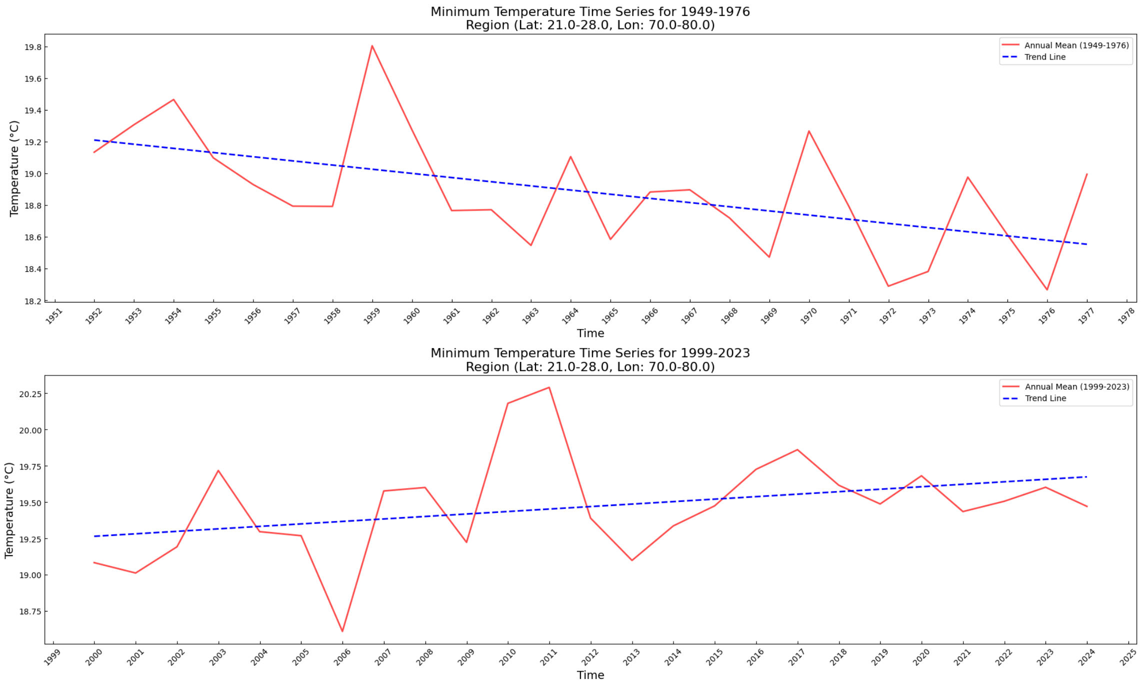




For the Eastern region, the maximum temperature has been increasing steadily over the years with slight ups and downs, but the general trend is consistent with the global warming theory. Meanwhile, the minimum temperature curve has changed its gradient from negative to positive suggesting that during the period 1950-1975, the minimum temperature was decreasing but after 2000, it began increasing. This portrays that the effect of global warming is more on the regions with lower temperatures than at those with higher temperatures.

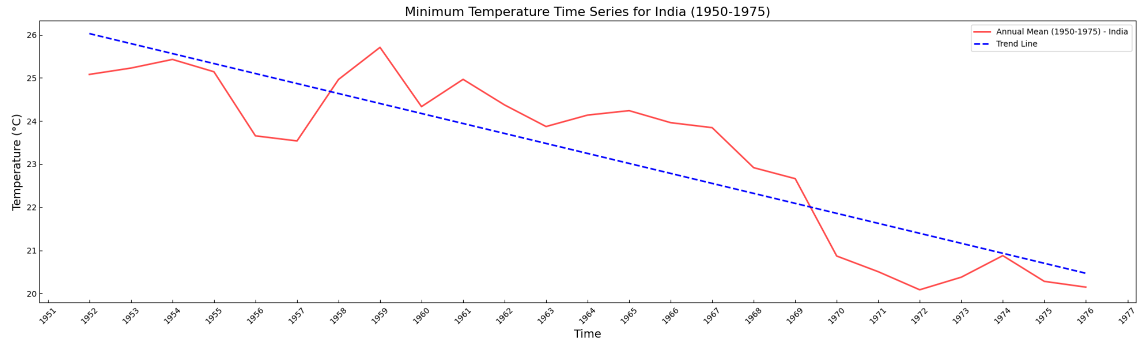
4. **West (70–80°E, 21–28°N)**

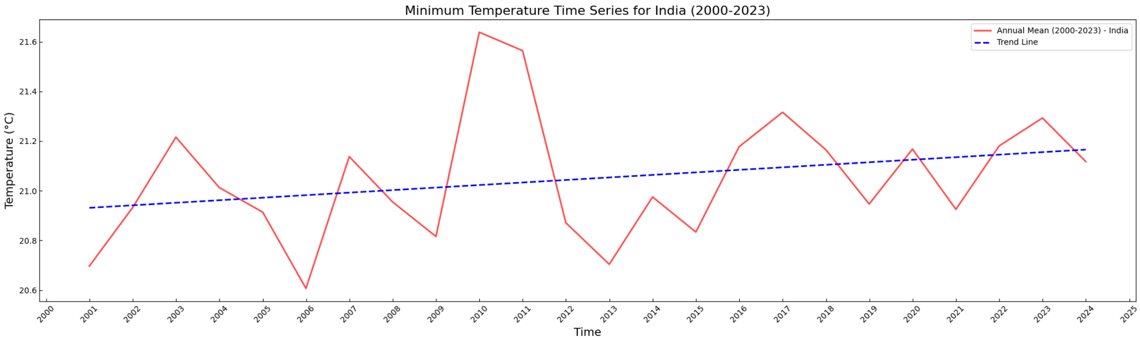




For the Western region, the maximum temperature curve is abundant with highs and lows while maintaining a slightly negative otherwise constant gradient over the years. But the trend for the minimum temperature has changed its directions whereas earlier it was decreasing but now it has started increasing because of global warming.

5. **India**





First of all, the Indian average was calculated by averaging over the four regions provided earlier to take into account every significant change possible.

Now regarding the annual mean maximum temperature, during the period 1950-1975, it was decreasing but after 2000 it has remained constant but with major jumps in individual years. Meanwhile the annual mean minimum temperature has gone from having a negative slope to a positive slope complining to the effects of climate change.

All the above observations clearly showcase the effects of climate change over the years with the annual mean minimum temperature being the most affected.