USESO 2022

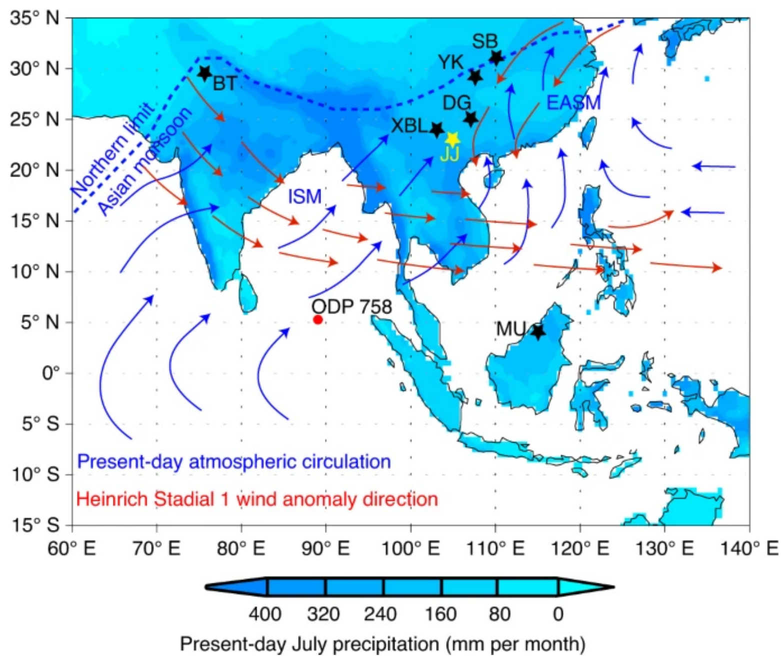
Atmosphere

Instructions:

- Section I consists of 10 multiple choice questions, with each question worth 2 points. There is only one correct option on multiple choice questions
- Section II consists of 2 multipart free response questions
- A calculator is allowed; show all work for calculations unless otherwise stated
- Recommended time management: 30 minutes on each section

Section I

1. The figure below shows present-day monsoon wind directions (blue) and during Heinrich events (red), where a weakened AMOC (Atlantic Meridional Overturning Circulation) shifted global wind patterns. Proxies from these events can help us understand the effects of modern climate change.



Researchers use oxygen-18 isotope concentrations as a proxy to determine the amount of precipitation at a certain time. Compared to modern records of ^{18}O, which of the following would one expect to observe in records from Heinrich events near India?

A. More ^{18}O due to more precipitation

B. More ^{18}O due to less precipitation

C. Less ^{18}O due to more precipitation

D. Less ^{18}O due to less precipitation

2. A parcel of air starts at sea level with a temperature of 26 °C and a dew point of 14 °C. The environmental lapse rate is 8 °C/km with a temperature of 28 °C at sea level. At what height would the parcel need to be raised to become unstable? Assume a dry adiabatic lapse rate (DALR) of 10 °C/km, wet adiabatic lapse rate (WALR) of 6 °C/km and dew point lapse rate (DLR) of 2 °C/km.

A. 1.5 km

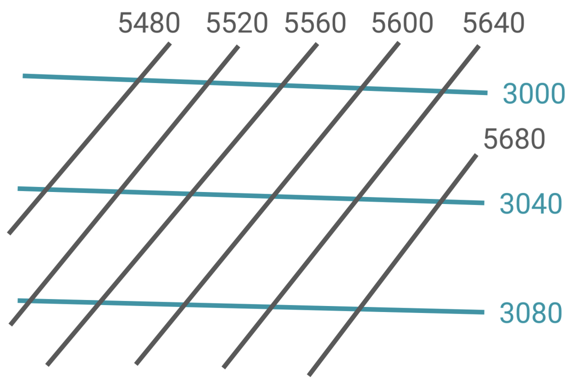
B. 3.4 km

C. 4 km

D. It is absolutely stable.

E. It is already unstable at the surface.

3. Consider the upper-level map below, showing overlapping sets of height contours at two different pressure surfaces (represented by different colors). All elevations are given in meters, and assume winds are in geostrophic balance.



Select the choice that best completes the following: ______ air advection is occurring aloft, which ______ chances of severe weather. Winds are ______ with increasing height, which ______ chances of severe weather.

A. Warm; increases; stronger; increases

B. Warm; decreases; weaker; decreases

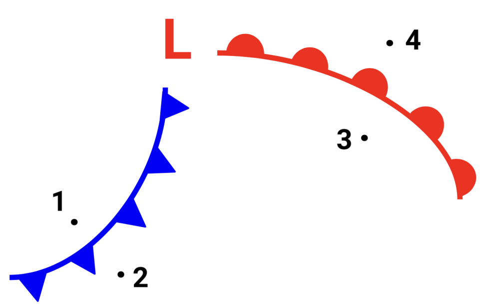
C. Cold; increases; stronger; increases

D. Cold; decreases; weaker; decreases

E. Neither warm nor cold; does not affect; stronger; increases

F. Neither warm nor cold; does not affect; weaker; decreases

4. Elevated convection is responsible for the formation of storms due to unstable air parcels away from the ground, typically above a stable boundary layer or inversion. This can occur near both cold and warm fronts. Given the surface map below, elevated convection is most likely to occur at which locations?



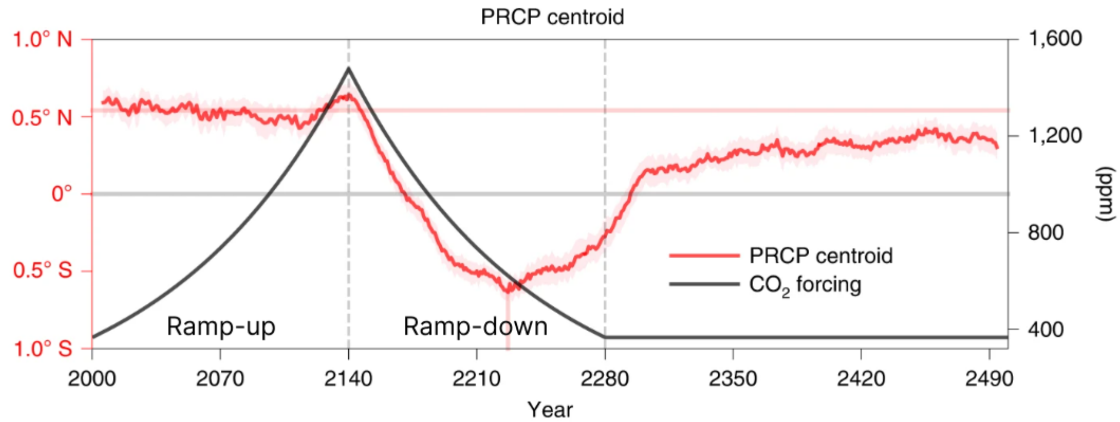
A. 1 and 3

B. 1 and 4

C. 2 and 3

D. 2 and 4

5. Some components in the climate system exhibit hysteresis, meaning they can exist as one of multiple stable states within the same climate. To study the hysteresis of the Intertropical Convergence Zone (ITCZ), a climate model is run such that the CO_2 concentration is slowly raised, lowered at the same rate, then held constant at the pre-industrial level. The precipitation centroid, a diagnostic for average ITCZ latitude, is plotted below in red.



Which of the following could explain this behavior? (*Hint: consider the role of atmospheric heat transport in setting the ITCZ position*)

I) The Southern Hemisphere becomes warmer than the Northern Hemisphere during the ramp-up period due to the heat capacity of the Southern Ocean

II) The AMOC continues to weaken at the beginning of the ramp-down period, causing the Northern Hemisphere to cool faster than the Southern Hemisphere

A. I only

B. II only

C. I and II

D. None

6. The stratospheric polar vortex is a large-scale ______ circulation that is typically strongest in the Southern Hemisphere during ______.

A. Cyclonic; January

B. Cyclonic; April

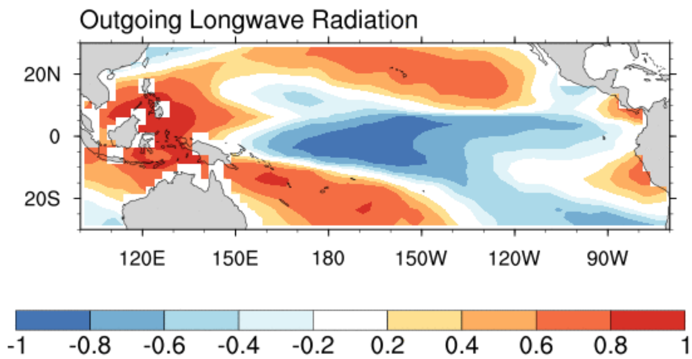
C. Cyclonic; July

D. Anticyclonic; January

E. Anticyclonic; April

F. Anticyclonic; July

7. The map below shows the spatial variation of the correlation coefficient between the Multivariate ENSO Index (MEI) and the outgoing longwave radiation anomaly.



Complete the following statements:

(a) The MEI is positive during ______.

A. El Niño-like conditions

B. La Niña-like conditions

(b) The central tropical Pacific becomes ______ during El Niño.

A. Anomalously wet

B. Anomalously dry

8. Lightning flash rate is defined as the ratio between the sum of the rates of intra-cloud and cloud-to-cloud lightning, and the rate of cloud-to-ground lightning. Choose all of the following that are true about lightning.

I) The lower the base of the negative region of a cloud, the higher the lightning flash rate

II) Lightning flash rate decreases with increasing latitude

III) Lightning occurs more often over land than water

A. I only

B. II only

C. III only

D. I and II

E. II and III

F. I, II, and III

9. The most destructive hurricanes to the US Gulf Coast tend to form near the west coast of Africa, since that provides the longest path over warm ocean to increase the strength of the hurricane. Fortunately, many of these hurricanes do not make landfall. Which of the following conditions in the western Atlantic may disrupt these hurricanes making landfall on the US Gulf Coast?

I) Strong vertical wind shear

II) Dry easterly winds from the Sahara

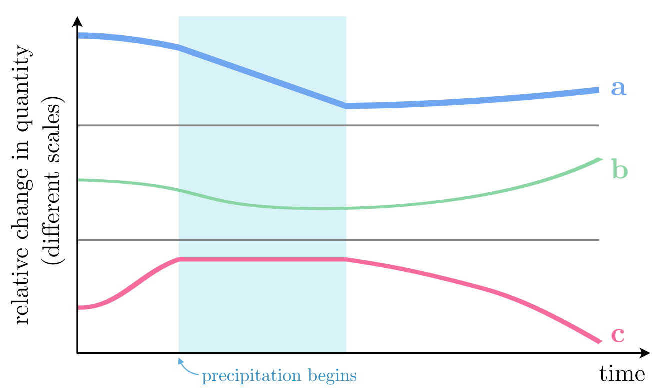
A. I only

B. II only

C. I and II

D. None

10. An air parcel rises over a mountain range, during which water condenses and precipitates at a constant rate until reaching a maximum elevation, and then descends back to the same elevation it began at. Consider the simplified representation of changes in three physical quantities of this air parcel in the figure below. Which of the following statements is true regarding these quantities?



I) Changes in dew point are primarily caused by changes in b.

II) Without water condensing, the end amount of b would be equal to its starting amount.

III) The addition of latent heat accounts for most of the decrease in c during the descent.

A. I only

B. II only

C. III only

D. I and II

E. II and III

Section II: Problem 1

Question	1	2	3	4	5	Total
Points	1	3	5	4	2	15 (30%)

You may recall from the Open Exam that a planet's emission temperature T_e is defined as its temperature if it were a blackbody radiating away all absorbed incident energy. This underestimates Earth's temperature because it fails to account for the greenhouse effect.

We can model the greenhouse effect by assuming Earth is fully covered by a single layer atmosphere that is transparent to shortwave radiation and opaque to longwave radiation.

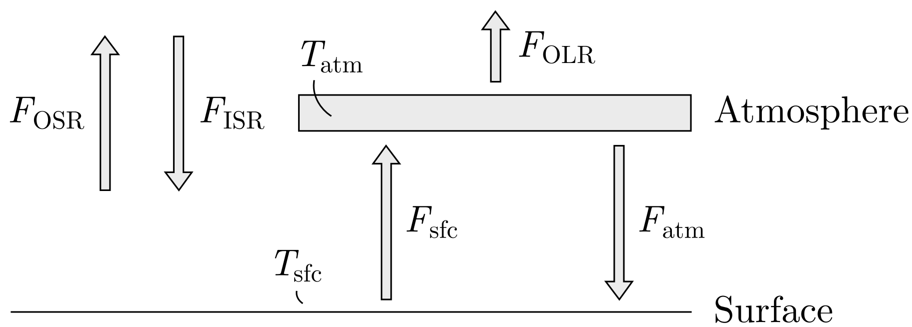


Figure 1: Schematic of model atmosphere. F denotes radiative flux, in W m^{-2}. OSR: outgoing (reflected) shortwave radiation; ISR: incoming shortwave radiation; sfc: outgoing longwave emitted from surface; atm: incoming longwave emitted from atmosphere; OLR: outgoing longwave emitted from atmosphere. **Arrows are not to scale.**

1. (1 point) Using the radiative flux terms in the schematic above, briefly explain why the greenhouse effect causes surface temperatures to be greater than the emission temperature.

2. In our model, all components are blackbodies and their radiative fluxes F can be expressed as $F = \sigma T^4$, where T is its temperature (K) and σ is a constant ($\text{W m}^{-2}\ \text{K}^{-4}$).

   (a) (2 points) Explain why the temperature of the atmosphere T_{atm} is equal to the emission temperature T_e. You do not need to perform any numerical calculations. (*Hint: if the planet is in equilibrium, what must be true of the incoming/outgoing fluxes?*)

   (b) (1 point) Using the data in the table below, calculate T_{atm} in K. You **do not** need to show your work.

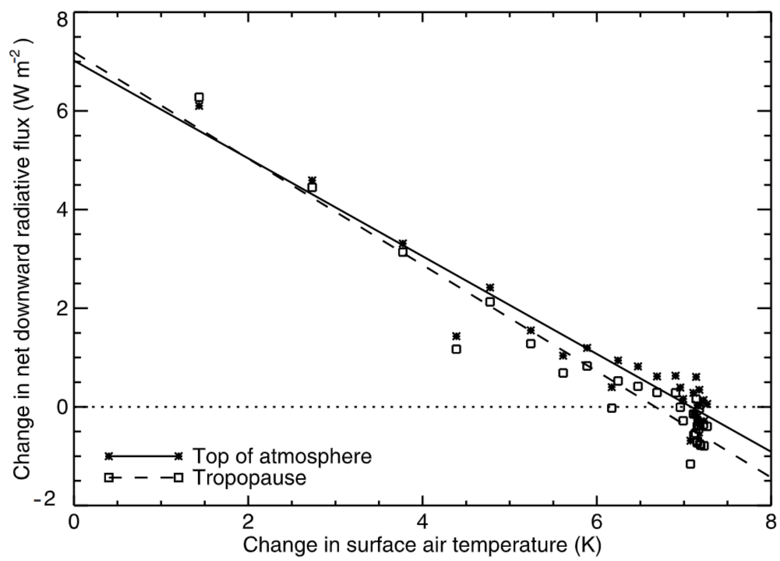
Average albedo of the Earth	0.300
Incoming shortwave radiation (F_{ISR})	341 W m^{-2}
Stefan-Boltzmann constant (σ)	$5.67 \times 10^{-8}\ \text{W m}^{-2}\ \text{K}^{-4}$

3. (a) (3 points) Calculate the temperature of the surface T_{sfc} in K. **Show your work.** (*Hint*: $F_{OLR} = F_{atm}$)

   (b) (2 points) The global average surface temperature averaged over 1951 to 1980 was 14 °C. Was our calculation an overestimate or underestimate? Propose two reasons for this discrepancy.

When the climate system is perturbed by a radiative forcing, it will readjust to a new equilibrium via climate feedback. This can be thought of as an opposing radiative flux response generated by climate feedbacks that cancels out the original forcing. The temperature dependence of this feedback-driven radiative flux response is quantified by the climate feedback parameter λ (units W m^{-2} K^{-1}).

In an idealized climate model experiment, the atmospheric CO_2 is doubled from pre-industrial levels. The change in surface temperature and change in top-of-atmosphere (TOA) radiative flux are plotted below.



(Gregory et al., 2004)

4. Let N be the net TOA radiative imbalance and F be the initial radiative imbalance (i.e., initial forcing).

   (a) (2 points) Using the TOA linear fit shown above, write an algebraic expression relating N, F, and any other relevant variables. **Do not include any numerical values.**

   (b) (2 points) Determine the climate feedback parameter, in W m^{-2} K^{-1} for the experiment above.

5. (2 points) The climate feedback parameter itself can be temperature-dependent, owing to the temperature-dependence of various climate feedbacks. Give one example of climate feedback and explain why it is temperature-dependent.

Section II: Problem 2

Question	1	2	3	Total
Points	5	5	5	15 (30%)

The tropopause, the boundary between the troposphere and the stratosphere, is an important feature in Earth's atmosphere.

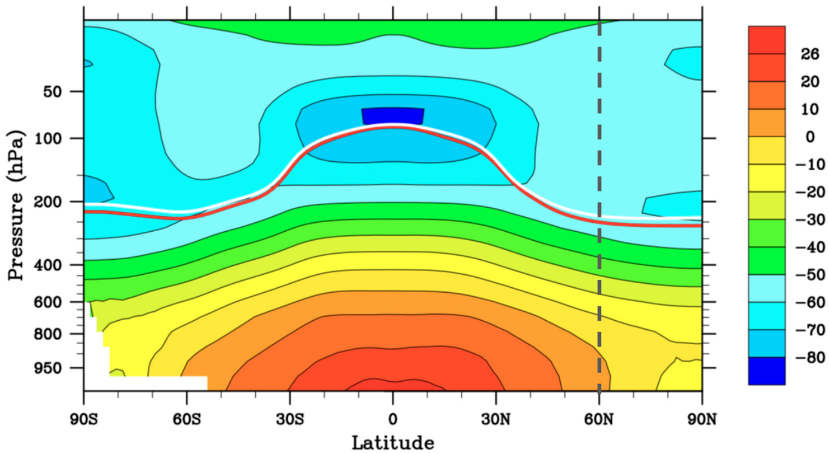


Figure 1: Plot of average temperatures in °C shaded on a graph of pressure vs. latitude. The red line shows the modeled tropopause under pre-industrial CO_2 levels, and the white line shows the modeled tropopause under 2x pre-industrial CO_2 levels (modified from Graversen et al., 2014).

1. (a) (1 point) Which of the following are true statements according to the figure above?

   I) The greatest change in tropopause pressure versus change in latitude occurs near the subtropical jets

   II) Constant-pressure surfaces are generally less steep than constant-temperature surfaces

   A. I only

   B. II only

   C. I and II

   D. None

   (b) (2 points) A student claims that, according to the figure, the tropopause height is around the same at 60°N (dashed line) compared to 90°N. What specific error, if any, did the student make? Justify your answer.

   (c) (1 point) Suppose you want to test the hypothesis that deep convection (associated with thunderstorm activity) in the tropics pushes the tropopause slightly higher near the equator. Which of these, coinciding with areas of strong convection, would support your hypothesis? (*Hint: consider Figure 1.*)

   A. Positive precipitation anomalies, positive tropopause temperature anomalies

   B. Positive precipitation anomalies, negative tropopause temperature anomalies

   C. Negative precipitation anomalies, positive tropopause temperature anomalies

   D. Negative precipitation anomalies, negative tropopause temperature anomalies

   (d) (1 point) To test your hypothesis, you release a radiosonde rising at constant speed from the surface to the tropopause. The air inside the radiosonde balloon is in hydrostatic equilibrium. Identify the force (besides gravity) acting on this air AND indicate if the force increases, decreases, or remains constant with increasing height.

While the dynamics of the stratosphere and troposphere are often treated as separate, stratosphere-troposphere exchange (STE) can significantly affect atmospheric chemistry and hence radiative balance.

2. (a) (1 point) One mechanism of STE is via overshooting tops, which are protrusions from the top of the anvil of a thunderstorm. In one or two sentences, briefly explain why clouds may overshoot despite reaching a level of neutral buoyancy.

   (b) Another mechanism of STE is a gradual upward air flux above the tropical tropopause due to wave-driven circulation. A remarkable piece of evidence for this is known as the "tape recorder" effect (Figure 2), where water vapor anomalies at the tropopause are recorded as that air moves upwards into the stratosphere.

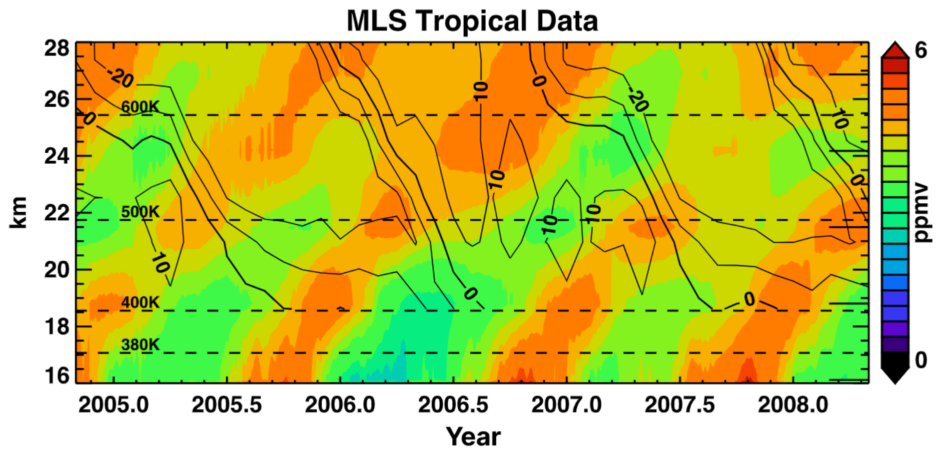


Figure 2: Height-time plot of water vapor concentration at the equator. (Schoeberl et al., 2008)

i. (2 points) Estimate the upward tropical STE velocity, in m/s. You **do not** need to show your work.

ii. (2 points) The "tape recorder" effect relies on the consistent annual cycle of water vapor in air entering the tropical stratosphere. This cycle is thought to be driven by the seasonal cycle of tropopause temperature. Answer the following two true/false questions.

$\longrightarrow$ T/F: Air entering the stratosphere must be near ice saturation

$\longrightarrow$ T/F: Horizontal eddy transport near the tropical tropopause is weak compared to the upward transport

Global warming affects the temperature profile in the troposphere and the stratosphere, with important consequences for lapse rates and atmospheric chemistry.

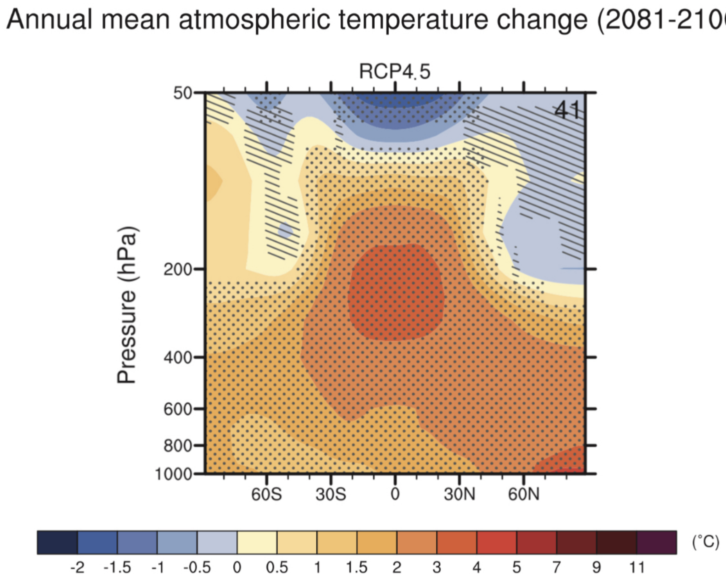


Figure 3: Modeled annual mean temperature changes as a function of pressure and latitude in 2081–2100 compared to 1986–2005 (IPCC, AR5).

3. (a) (1 point) Which best describes the trend in lapse rate in the 1000–200 hPa layer in the tropics? (DALR = dry adiabatic lapse rate)

   A. Increasing towards the DALR

   B. Increasing away from the DALR

   C. Decreasing towards the DALR

   D. Decreasing away from the DALR

   (b) (2 points) Transport of moisture to the upper levels of the atmosphere will increase in a warmer atmosphere. Describe two ways in which this can result in enhanced warming in the tropical upper troposphere.

   (c) (2 points) Changes in the atmospheric lapse rate cause a feedback due to differing changes in outgoing longwave radiation. Select the **two** true statements out of the statements listed below.

   I) The sign of the lapse rate feedback, ignoring water vapor, is positive in the tropics and negative in the high latitudes

   II) The sign of the lapse rate feedback, ignoring water vapor, is positive throughout all latitudes

   III) An increase in CO_2 concentrations would result in a greater negative temperature change in the tropical stratosphere

   IV) Gradually recovering ozone levels near the South Pole could explain the positive temperature change in the southern polar stratosphere

   V) Given Figure 3 alone, it is impossible that the tropopause above the equator stays at a constant height