USESO 2022

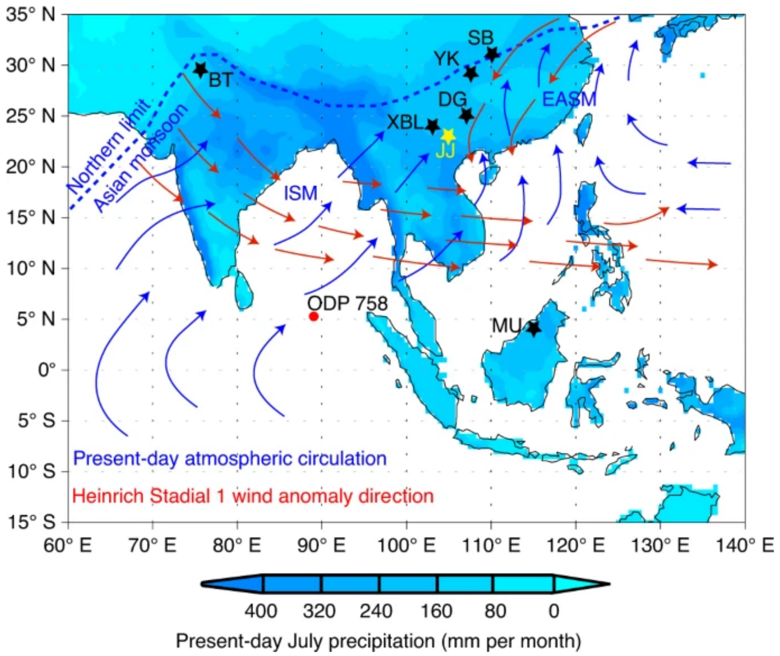
Atmosphere
KEY

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

Solution: The Indian Summer Monsoon (ISM in figure) typically brings precipitation to India by blowing from the sea to land. The reversal of this pattern during Heinrich events would likely result in a decrease in precipitation. The lighter ^{16}O isotope is more common in precipitation than ^{18}O, so a decline in precipitation is generally associated with a decline in ^{16}O and a corresponding increase in ^{18}O.

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.

Solution: The air parcel must fulfill two requirements to become unstable: 1) the environmental lapse rate must be greater than the adiabatic lapse rate, and 2) the parcel temperature must be greater than or equal the environmental temperature. This solution demonstrates one approach to finding the minimum elevation that fulfills these requirements.

Because the environmental lapse rate is less than the DALR but greater than the WALR, the atmosphere is conditionally unstable. At the surface, the air parcel is stable by the condition of being unsaturated (notice that the dew point is lower than the parcel temperature—adiabatic cooling follows the DALR and the parcel will be colder than the environment). The parcel becomes saturated at the height at which the parcel temperature reaches the dew point, and thereafter the environmental lapse rate will be lower than the adiabatic lapse rate following the WALR. To find this height h_1, we equate expressions for the dew point and parcel temperature at h_1:

$$26^\circ\text{C} - h_1 \times 10^\circ\text{C/km} = 14^\circ\text{C} - h_1 \times 2^\circ\text{C/km}$$

$$h_1 = 1.5\text{ km}$$

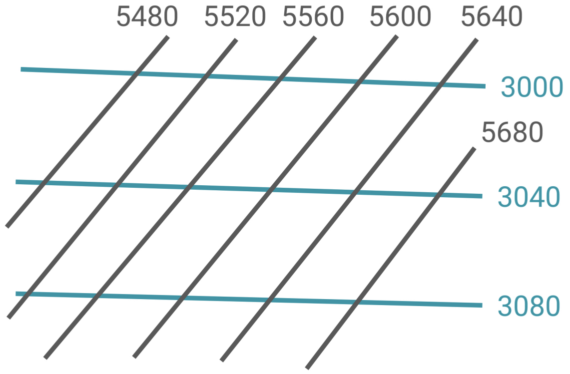
The first requirement has been fulfilled, but at 1.5 km the parcel temperature (11°C) is still less than the surroundings (16°C). To find the additional height h_2 that the parcel must be raised, we equate expressions for the parcel temperature (now cooling at the WALR) and environmental temperature at h_2:

$$11^\circ\text{C} - h_2 \times 6^\circ\text{C/km} = 16^\circ\text{C} - h_2 \times 8^\circ\text{C/km}$$

$$h_2 = 2.5\text{ km}$$

Finally, adding these two heights yields 4 km. This is the height at which a parcel will continue rising in a conditionally unstable atmosphere, also known as the *level of free convection.*

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

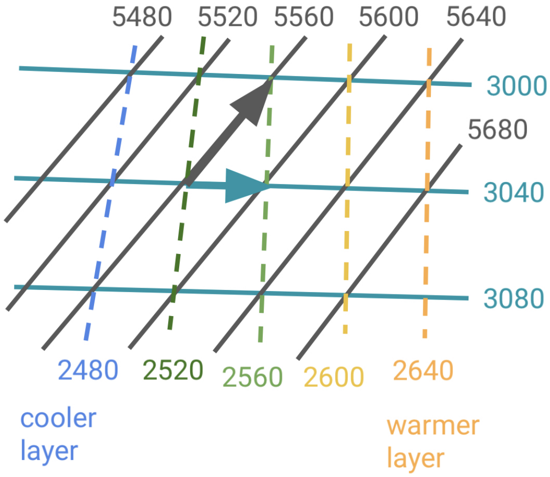
C. Cold; increases; stronger; increases

D. Cold; decreases; weaker; decreases

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

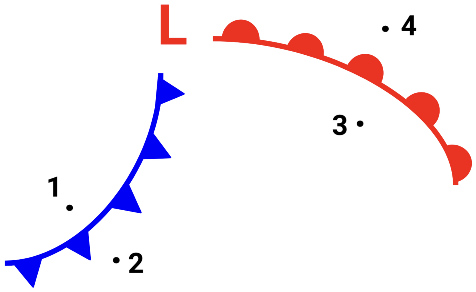
F. Neither warm nor cold; does not affect; weaker; decreases

Solution: The gray set of contours (5480 to 5680) is part of a pressure surface with a higher elevation than the teal set of contours (3000 to 3080). The layer thickness between the two surfaces (or the height difference between the two pressure surfaces) generally decreases going westward (shown with the dashed lines in the figure below). Since layer thickness is proportional to mean layer temperature, smaller thicknesses correspond to colder temperatures (the dashed lines are lines of equal thickness, but can be thus approximated as isotherms). Geostrophic winds at each pressure level would advect (transport) cooler air into warmer locations (shown with the wind vectors in the figure below). Cold air advection aloft increases the environmental lapse rate and reduces atmospheric stability, increasing the chance of severe weather. Also, since the pressure gradient is tighter at the more elevated pressure surface, geostrophic winds increase with increasing height. This indicates vertical wind shear and helps support tilting updrafts, which also increases the chance of severe weather.



Alternative solution: The concept of thermal wind/advection turning may be helpful but is not necessary to infer the type of advection. Since wind is backing (turning counterclockwise with increasing height), it may be known that cold air advection is occurring.

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

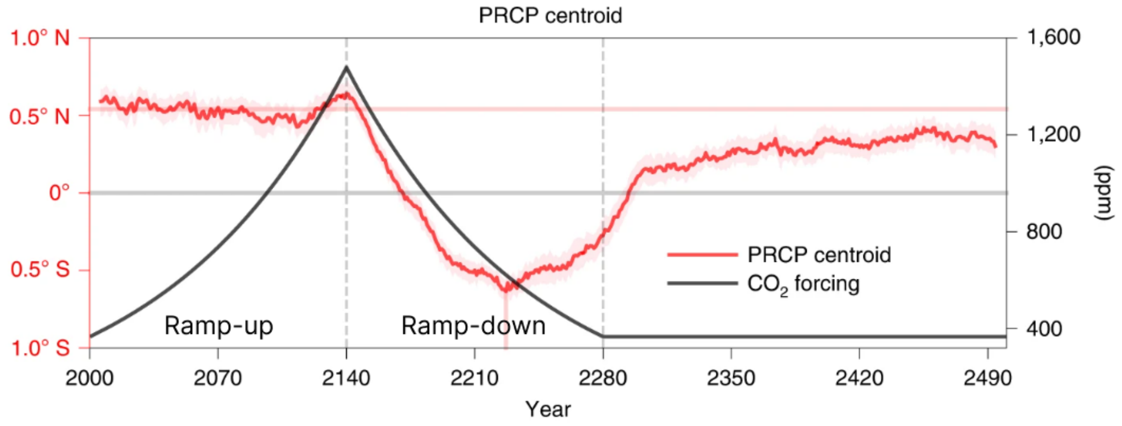
B. 1 and 4

C. 2 and 3

D. 2 and 4

Solution: Considering the vertical cross-section of a cold front, the area just behind a cold front (point 1) has a cold, shallow, and relatively stable layer near the surface. The frontal boundary separates this surface layer from relatively unstable air above which can support elevated convection. Point 2 is ahead of the cold front, so convection is likely to be surface-based (air is unstable even at/very near the surface). Similarly, the area ahead of a warm front (point 4) has a shallow stable layer near the surface; such a layer is absent behind the warm front (point 3).

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

Solution: Due to the unequal heating of the Earth, the Hadley circulation transports energy poleward. The position of the ITCZ is thus closely related to the position of the "energy flux equator", which is where the poleward atmospheric heat transport equals zero. The fact that the energy flux equator, and hence the ITCZ, is not at the geographic equator suggests that there is, on average, an interhemispheric temperature difference that must be compensated by a cross-equator heat flux.

During the ramp-up, the NH remains warmer than the SH, as implied by the northward extent of the ITCZ. As dynamical changes in ocean circulation can lag changes in forcing, the AMOC contributes to the hysteresis of the ITCZ by causing the NH to cool faster than the SH during the ramp-down. This results in a southward shift of the ITCZ. The interhemispheric difference of effective heat capacity, as caused by the distribution of continents, also plays a major role in this hysteresis.

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

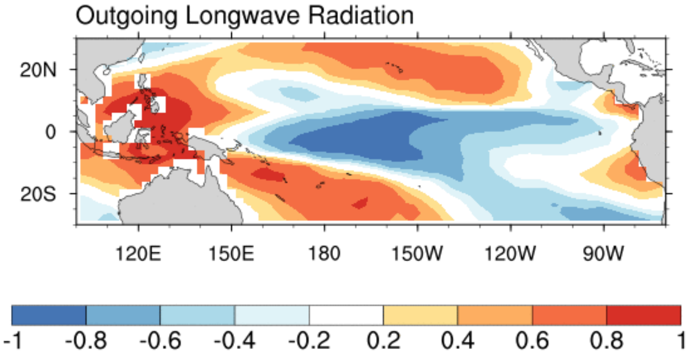
    D. Anticyclonic; January

    E. Anticyclonic; April

    F. Anticyclonic; July

Solution: The stratospheric polar vortex is a cyclonic circulation that is strongest during winter months due to the strengthened meridional temperature gradient.

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

Solution: We see in the map that when the MEI is positive, there is a correlated negative longwave anomaly in the central tropical Pacific. This is true during El Niño, since the change in Walker circulation and the associated eastward shift of deep convective clouds (which have very cold cloud tops) would decrease the outgoing longwave in the central tropical Pacific. Accordingly, the central tropical Pacific is also wetter during El Niño.

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

Solution: With a lower base of the negative region of a cloud (i.e. its freeze zone), more cloud-to-ground lightning can occur, decreasing the lightning flash rate - I is false. At lower latitudes, the freezing elevation is higher, which increases the lightning flash rate - II is true. Lightning occurs more often over land because its lower heat capacity allows faster heating, warming the air above and resulting in convection and thunderstorms - III is true. Thus, choice $\boxed{\text{E}}$ is the answer.

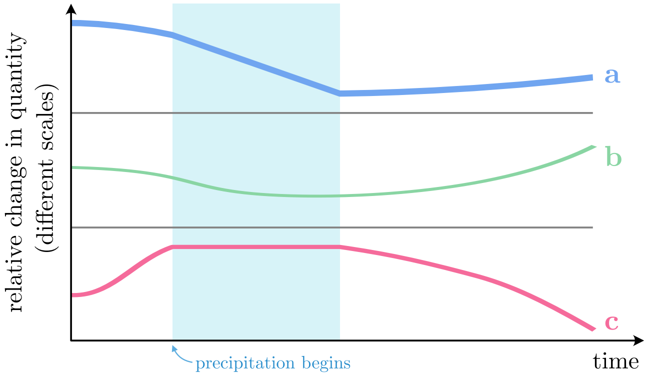
9. The most destructive hurricanes to the US Gulf Coast tend to form near the west coast of Africa, since that provides the longest path over warm ocean to increase the strength of the hurricane. Fortunately, many of these hurricanes do not make landfall. Which of the following conditions in the eastern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

   I) Strong vertical wind shear
   II) Dry easterly winds from the Sahara Desert

   A. I only
   B. II only
   C. I and II
   D. None

Solution: Vertical shear destabilize hurricanes and can cause them to weaken. Dry winds can prevent condensation of water vapor and the growth of a hurricane.

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

Solution: a is dew point, b is temperature, and c is relative humidity. I is false because dew point is more dependent on moisture content and pressure/volume than air temperature. Since the parcel decreases in pressure and increases in volume as it rises, it cools adiabatically. In a precipitation-free scenario, it would warm the same amount adiabatically when returning to the same elevation, but the condensation of water releases latent heat—II is true. Finally, while this latent heat partially contributes to the reduction in relative humidity, III is false since most of the drop is attributed to adiabatic warming.

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. All components are in thermal equilibrium.

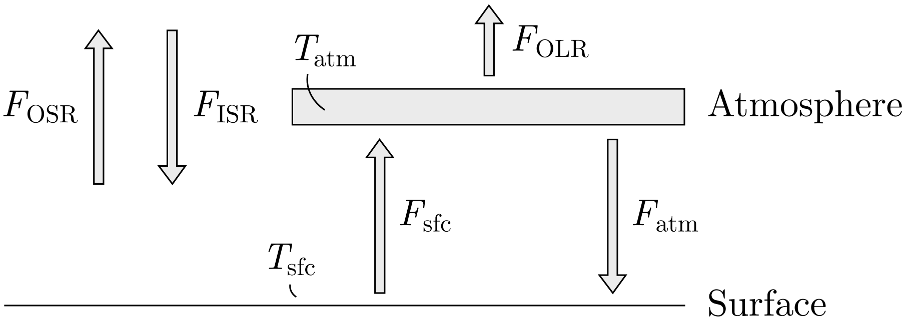


Figure 1: Schematic of model atmosphere. F denotes radiative flux, in W m^{-2}. OSR: outgoing (reflected) shortwave radiation; ISR: incoming shortwave radiation; sfc: outgoing longwave emitted from surface; atm: incoming longwave emitted from atmosphere; OLR: outgoing longwave emitted from atmosphere. **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.

   Solution: Greenhouse gases in the atmosphere radiate energy back to the surface, effectively trapping longwave radiation that would fully escape to space. So $F_{sfc} > F_{atm}$ and $T_{sfc} > T_{atm}$. The emission temperature T_e is equal to the temperature of the atmosphere in this model.

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 (W m^{-2} 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?*)

   Solution: For the planet to be in equilibrium, all outgoing fluxes must balance all incoming fluxes. Hence $F_{OLR} = F_{ISR} - F_{OSR}$. Since the atmosphere is radiating away all absorbed radiation, by definition, its temperature must be equal to T_e.

   (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)	5.67×10^{-8} W m^{-2} K^{-4}

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

Solution: The incoming and outgoing fluxes at the surface must be equal since it is in thermal equilibrium:

$$F_{sfc} = F_{atm} + F_{ISR} - F_{OSR}$$

$$F_{sfc} = F_{OLR} + (1 - \alpha)F_{ISR}$$

But we know from the previous question that $F_{OLR} = F_{ISR} - F_{OSR} = (1-\alpha)F_{ISR}$, since the atmosphere must be radiating away all absorbed incident energy. Hence,

$$F_{sfc} = 2(1 - \alpha)F_{ISR}$$

$$T_{sfc} = \left(2(1 - \alpha)\frac{F_{ISR}}{\sigma}\right)^{1/4}$$

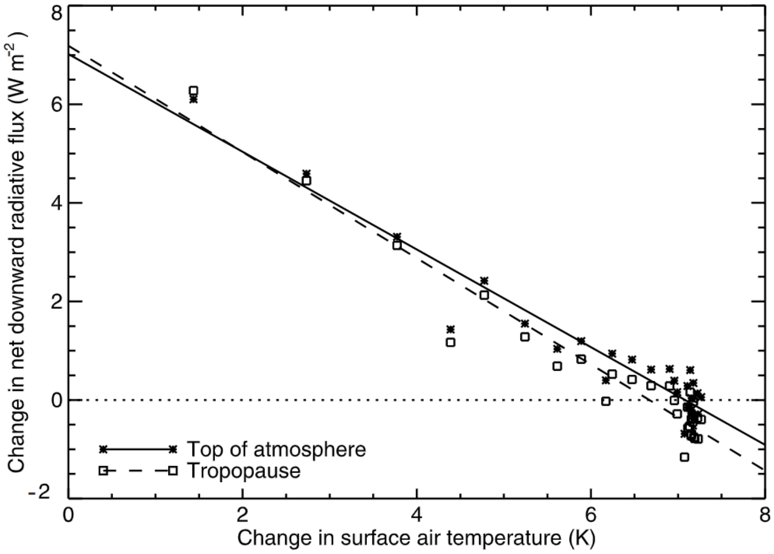
Plugging in all numbers, we get $T_{sfc} = 303$ K.

(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.

Solution: Overestimate. We assumed the atmosphere has a perfect greenhouse effect that absorbs all outgoing longwave radiation, which is not the case. We also did not account for clouds, which may decrease the absorbed incident shortwave.

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.**

   Solution: $N = F - \lambda(\Delta T)$ where λ is a constant representing the climate feedback.

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

   Solution: Given the linear fit between N and ΔT, we can infer that the radiative response due to climate feedback (which we'll call ΔR_f) is linearly dependent on temperature. The climate feedback parameter would hence be the slope of N versus ΔT. We get $\lambda = -1.0$W m^{-2} K^{-1}.

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.

   Solution: The water vapor feedback is temperature dependent, because the increase in saturation vapor pressure is exponential with temperature. The percent change in saturation vapor pressure increases with increasing temperature, so water vapor feedback is stronger in a warmer climate.

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.

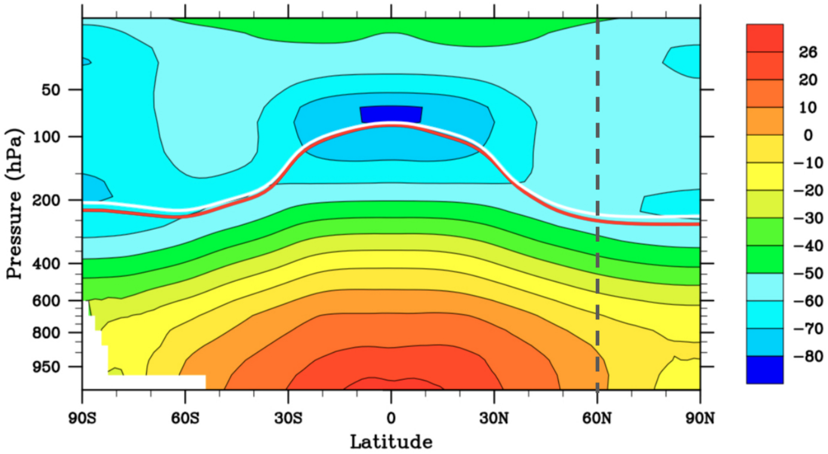


Figure 1: Plot of average temperatures in °C shaded on a graph of pressure vs. latitude. The red line shows the modeled tropopause under pre-industrial CO_2 levels, and the white line shows the modeled tropopause under 2x pre-industrial CO_2 levels (modified from Graversen et al., 2014).

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

   Solution: From the figure, the tropopause is steepest around 30°N and 30°S, which corresponds to the approximate location of the two subtropical jets. As the isotherms on the plot cross over multiple pressure levels, this implies that constant-pressure surfaces are less steep than constant-temperature surfaces.

   (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.

   Solution: The tropopause height is actually higher at 60°N than at 90°N. Though the tropopause is at the same pressure level, the mean troposphere temperature is higher at 60°N than at 90°N, so the pressure surface is higher at the lower latitude.

   (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

Solution: Strong convection is associated with heavy rains, which would result in higher than average precipitation amounts. A slight increase in tropopause height would result in lower temperatures at 0° latitude, according to Figure 1.

(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.

Solution: Pressure gradient force (PGF), decreases

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.

Solution: The momentum of a rapidly ascending updraft can carry it above the equilibrium level, allowing it to protrude above the anvil top.

(b) Another mechanism of STE is a gradual upward air flux above the tropical tropopause due to wave-driven circulation. A remarkable piece 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.

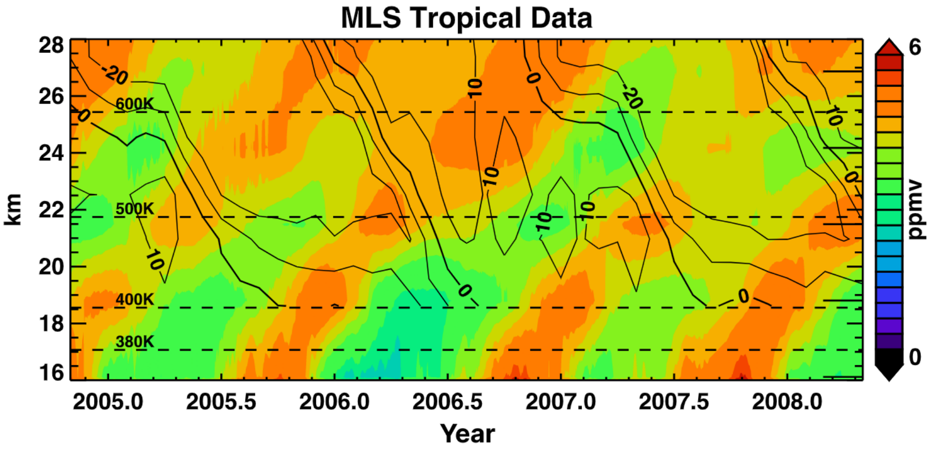


Figure 2: Height-time plot of water vapor concentration at the equator. (Schoeberl et al., 2008)

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

Solution: The STE velocity can be determined by the slope of positive/negative water vapor anomalies. The positive anomalies are clearer and travel roughly 8 km per year. This translates to about $\boxed{2.5 \times 10^{-4}\text{ m/s}}$, or 0.25 mm/s.

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.

⟶ $\boxed{\text{T}}$/F: Air entering the stratosphere must be near ice saturation

⟶ $\boxed{\text{T}}$/F: Horizontal eddy transport near the tropical tropopause is weak compared to the upward transport

Solution: Since the water vapor cycle is dictated by the temperature cycle, the air must be near saturation. Further, since the upward-moving "tape recorder" signals can be preserved for months, we can infer that horizontal eddy circulation must be weak such that those anomalies do not get transported away horizontally.

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

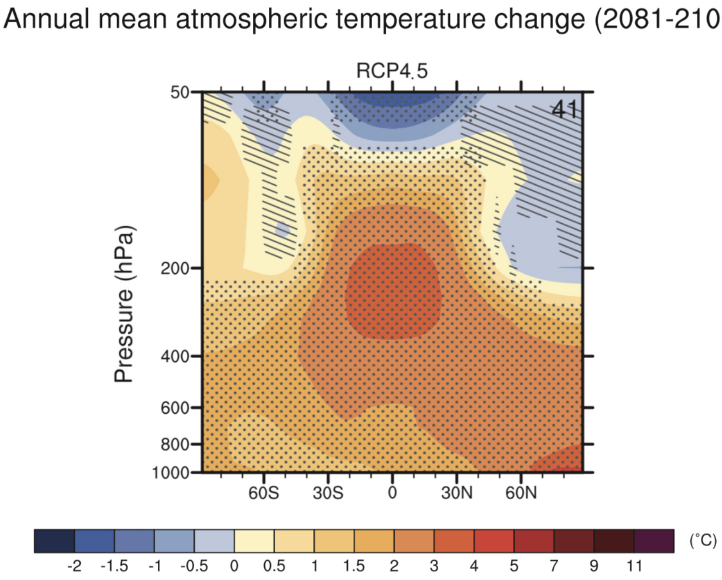


Figure 3: Modeled annual mean temperature changes as a function of pressure and latitude in 2081–2100 compared to 1986–2005 (IPCC, AR5).

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

Solution: Since upper atmospheric temperatures (near 200 hPa) are warming more than lower atmospheric temperatures, the lapse rate (change in temperature with height) is decreasing. Also, because the MALR (moist adiabatic lapse rate) is always less than the DALR, and it is improbable that the initial lapse rate was greater than the DALR (which would make an absolutely unstable atmosphere), choice $\boxed{\text{D}}$ is most accurate.

(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.

Solution: The increased concentration of water vapor (a greenhouse gas) strengthens the greenhouse effect. Also, as water vapor condenses in the upper atmosphere, latent heat release also contributes to upper atmosphere warming.

(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

Solution: The lapse rate feedback is negative in the tropics and positive at the poles. The strength of the greenhouse effect is proportional to the lapse rate. In the tropics, a weaker lapse rate and a warmer upper atmosphere results in a net increase in outgoing longwave radiation (OLR), counteracting the warming. A contrasting temperature profile occurs near the poles with stronger surface-based warming, resulting in a positive lapse rate feedback - I and II are false. Increased CO_2 blocks most OLR from the earth, so less OLR is absorbed in the stratosphere. Higher CO_2 increases its emissivity, which exceeds absorption and results in a net cooling - III is true. Ozone levels have been recovering from previous lows, and ozone absorbs UV and infrared radiation from the troposphere, increasing stratospheric temperature - IV is true. Finally, a warming below the initial tropopause and a cooling above (as shown in Figure 3) will result in an upward shift of the tropopause - V is false. Thus, the answer is $\boxed{\text{III and IV}}$.