USESO 2021

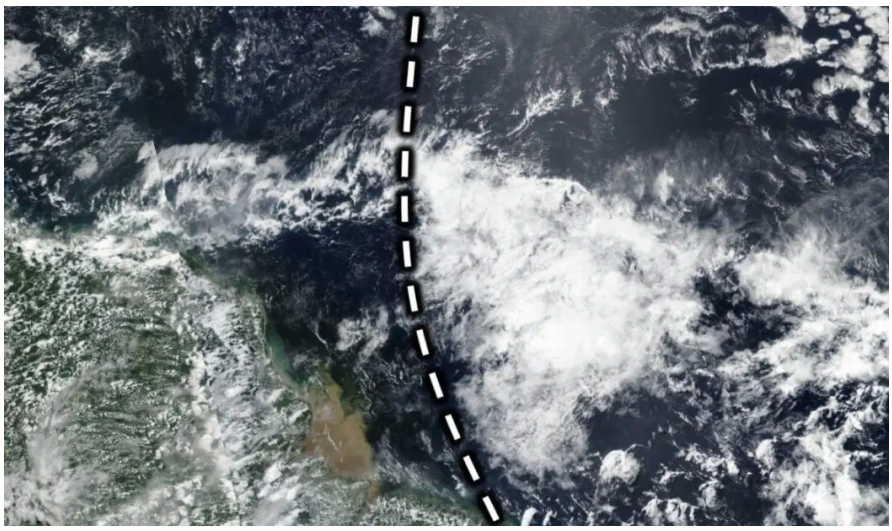
Atmosphere KEY

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 non-graphing, non-programmable calculator is allowed; show all work for calculations.
- Recommended time management: 30 minutes on each section.

Section I

1. (2 points) Below is satellite imagery of a developing storm system in the Northern hemisphere with a white dashed line marking the region of a pressure trough.



(a) In which direction will the pressure trough move?

A. West

B. East

(b) This imagery is most associated with what weather phenomenon?

A. Hurricane

B. Mid-latitude cyclone

C. Tornado

Solution: This is an example of a tropical wave, which generally moves from east to west with the African Jet (and trade winds). Tropical waves have an inverted-v signature with convergence occurring on the right and divergence on the left, and are often associated with hurricanes. If winds were moving east, convergence/clouds would occur on the left side.

2. (2 points) Pictured below is an atmospheric optical phenomenon caused by a strong temperature contrast. Select the most accurate description of the image.

A. The image shows a superior mirage, which is stable

B. The image shows a superior mirage, which is not stable

C. The image shows an inferior mirage, which is stable

D. The image shows an inferior mirage, which is not stable

Solution: Inferior mirages appear below actual objects, as shown in the image, from a temperature inversion caused by the hot road. Since these inversions have relatively dense air above less dense air, inferior mirages are not stable.

3. (2 points) Surface weather observations for multiple cities were recorded in a table.

City	Relative humidity (%)	Wind speed (m/s)	Barometric pressure (hPa)	Observed cloud types, if any
A	75	1.5	1028	cirrus
B	30	7.5	1030	none
C	90	7.5	1008	nimbostratus
D	65	4.5	1020	stratus
E	40	1.5	1010	altocumulus

Assume that all cities have the same temperature and pollutant output levels, and that the only significant source of pollution is from within the city. Which city is most likely to experience low visibility and severe air pollution?

A. A

B. B

C. C

D. D

E. E

Solution: High relative humidities reduce visibility and may contribute to haze. High barometric pressure, a stable atmosphere, and low wind speeds limit the dispersal of air pollutants. Sunlight also catalyzes the formation of air pollutants such as ozone and contributes to photochemical smog. While recipitation (from nimbostratus or stratus clouds) may reduce visibility, it removes pollutants from the air. Thus, City A is most likely to experience low visibility and severe air pollution.

4. (2 points) In a particular region, one finds that the heat exchange between the sea surface and the air varies primarily because of changes in surface wind speed. Which of the following interactions is most likely responsible for this variation?

A. Heat is conducted in low latitudes from the sea surface to the atmosphere

B. Heat is conducted in the mid-latitudes as warm surface currents cool

C. Atmospheric circulation convects warm air overlying the ocean

D. The ocean radiates heat as longwave radiation into the atmosphere

E. Latent heat is transferred to the atmosphere as water vapor

Solution: Latent heat fluxes are one of the primary ways heat is transferred from the ocean to the atmosphere. Surface wind speed is associated with the amount of water evaporated, and hence the amount of energy exchanged as water vapor.

5. (2 points) The planetary boundary layer (PBL) is an atmospheric layer in the troposphere in which wind is influenced by contact with the planetary surface, often creating turbulence. Temperature inversions cap the PBL, and the height of an inversion (along with PBL thickness) depends on many factors. Which of the following would lead to a decrease in the thickness of the PBL?

   A. Mountainous terrain, since rough terrain increases influence of friction on wind and leads to greater turbulence

   B. Nighttime radiative cooling of the surface, since air temperature decreases, leading to a smaller vertical temperature gradient and less depth of convective mixing

   C. Warm water underlying cold air, since air temperature increases, leading to a larger vertical temperature gradient and greater depth of convective mixing

   D. Large city location, since plentiful city buildings decrease the influence of friction on wind and leads to less turbulence

   E. Thick stratus clouds, since air temperature decreases, leading to a smaller vertical temperature gradient and less depth of convective mixing

Solution: PBL depth increases with larger temperature differential and greater friction from terrain. Thick stratus clouds would decrease solar heating, meaning a smaller temperature differential between the surface and above the PBL. A, B, C, and D, respectively, are incorrect because: greater turbulence increases thickness of PBL, radiative cooling of ground increases air temperature, greater depth of convective mixing = increase thickness of PBL, and city terrain is typically not flat.

6. (2 points) Shown below is a Doppler radar image of some thunderstorms and a table of winds at the 500 mb and 1000 mb isobaric surfaces of three possible environments in knots (kt).

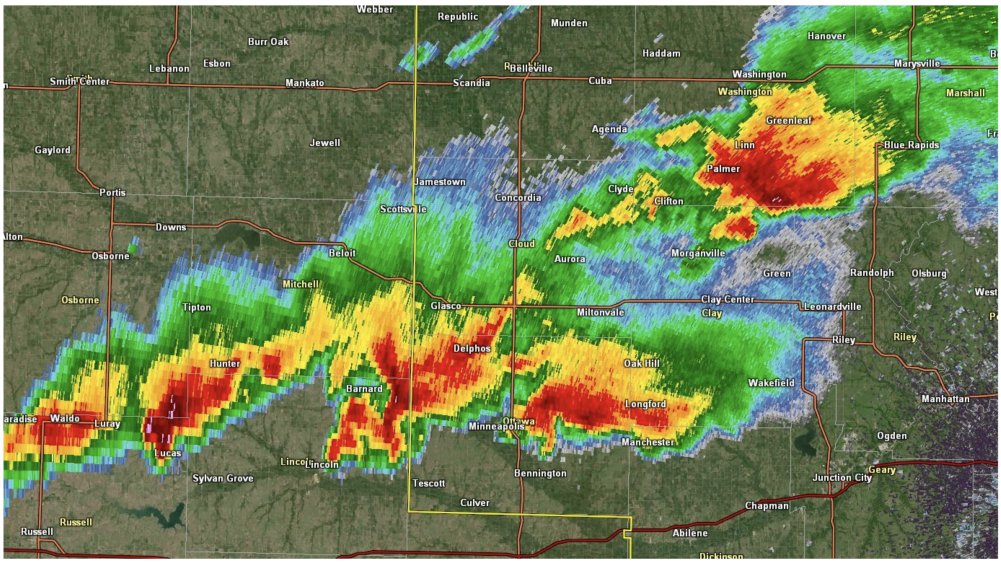


Image credit: National Weather Service

Isobaric surface	Environment X	Environment Y	Environment Z
500 mb	southwest, 35 kt	west, 45 kt	southwest, 25 kt
1000 mb	southwest, 15 kt	southeast, 5 kt	south, 20 kt

(a) Which environment most favors the pattern of storms shown in the radar image?

A. Environment X

B. Environment Y

C. Environment Z

(b) Which of the following offers the best interpretation of the radar image?

A. The storms form a squall line producing damaging winds and flooding

B. The storms are supercells producing large hail and tornadoes

Solution: The storms in the radar image are supercells, which are individual cells with characteristic "hook echo" shapes indicative of mesocyclones and possible tornadoes. On Doppler radar, squall lines are more linear than supercells. Wind shear, shown by a change in wind direction and speed with increasing height, is essential to supercell development and is most evident in Environment Y. Also, while hail, flooding rain, damaging winds, and tornadoes are possible with both supercells and squall lines, large hail and tornadoes are generally more likely and significant in supercells.

7. (2 points) Air lifted by mountains often produces clouds and precipitation on the windward side and descending foehn winds on the lee side. For any given elevation, air on the lee side is warmer than air on the windward side because:

A. The dry adiabatic lapse rate (DALR) is greater than the moist adiabatic lapse rate (MALR)

B. The dry adiabatic lapse rate is less than the moist adiabatic lapse rate

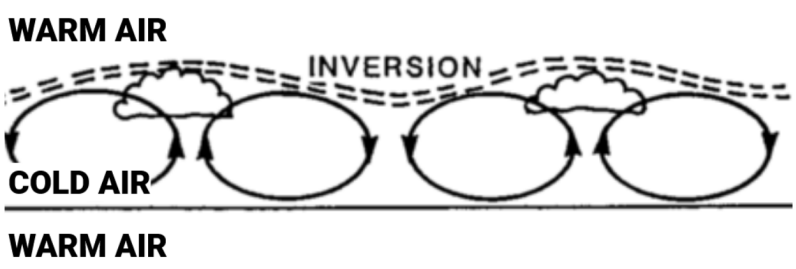
C. The environmental lapse rate is greater than both the DALR and MALR

D. The environmental lapse rate is less than both the DALR and MALR

E. The environmental lapse rate is between the DALR and MALR

Solution: Air cools and warms adiabatically as it ascends and descends, respectively. Since air on the lee side of the mountain is warmer than it is at the same elevation on the windward side, air must have warmed more than cooled. This can be attributed to ascending air eventually saturating, which results in condensation and the release of latent heat. The MALR is less than the DALR for the same reason.

8. (2 points) On the left is a diagram of cloud street formation in a cold air mass bounded by warm air, and on the right is an example of cloud streets.



Imagine that the entire configuration experiences a downward force such that existing vertical air movement is enhanced or limited. What arrangement would the clouds in the cold air mass take, and why?

A. Stratus, since downward motion flattens cloud street convection cells into only horizontal air movement

B. Hexagonal cells with cloud centers/cloud-free borders, since net vertical motion changes convection cell shape and adiabatic heating gives more energy for cloud formation

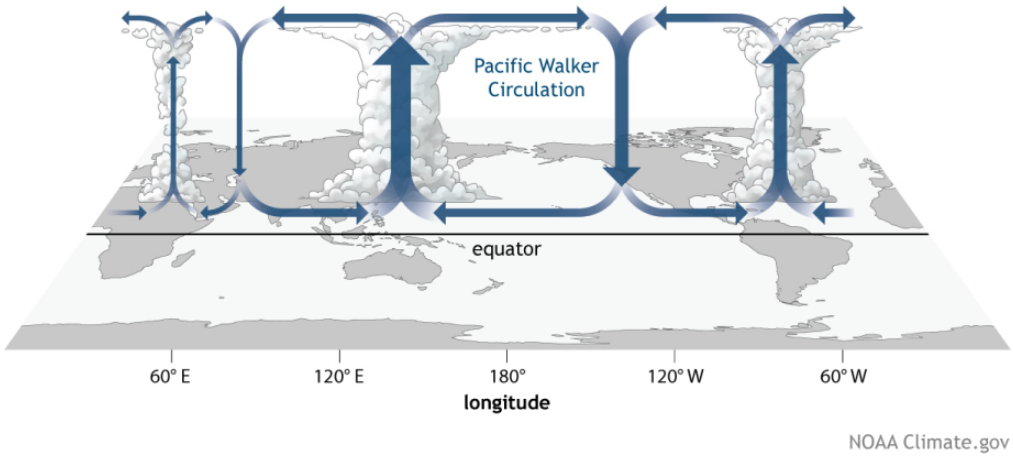
C. Hexagonal cells with cloud-free centers/cloud borders, since net vertical motion changes convection cell shape and downward motion thins out clouds

D. Extended vertical cloud columns, since downward motion elongates cloud street convection cells

E. No change, since downward motion won't affect cloud appearance within an air layer, only its relative position

Solution: This is an example of mesoscale cellular convection. Net vertical motion changes convection cell shape from 2D Rayleigh-Benard convection (rolls) to 3D (hexagons). Downward motion dominates, the net downward motion discouraging cloud formation by inhibiting any extensive vertical development.

9. (2 points) The Atlantic Niño is the warm phase of a coupled ocean-atmosphere variability in the equatorial Atlantic, akin to its "brother" in the Central Pacific. It can affect the Central Pacific (CP) El Niño by perturbing the Walker Circulation, shown below.



Which of the following is **not** true about the Atlantic Niño?

A. Atlantic Niño is associated with anomalously strong West Africa summer monsoon rainfall

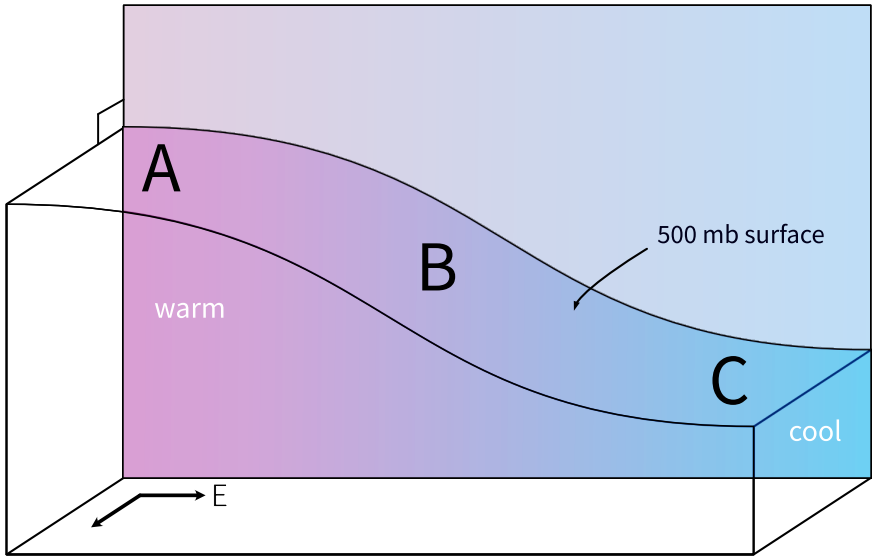
B. Atlantic Niño generates anomalous surface convergence in the western equatorial Atlantic

C. A strong Atlantic Niño initiates El Niño conditions in the CP

D. The influence of the CP El Niño on the Atlantic Niño is significantly limited by the topographic prominence of the Andes Mountains

Solution: The equatorial variabilities in the Atlantic and Pacific are linked through Walker Circulation, as seen in the diagram. A strong Atlantic Nino is associated with extension of a warm SST anomaly into the western equatorial Atlantic. This reinforces Pacific Walker Circulation, which will probably not lead to El Nino conditions.

10. (2 points) Below is a representation of a constant pressure surface in the atmosphere in the Northern Hemisphere.



(a) At which location is the wind speed at the 500 mb level likely the highest?

A. A

B. B

C. C

Solution: The slope of the isobaric surface, and therefore the pressure gradient force (PGF), is the greatest at B.

(b) Assume wind at this altitude is in geostrophic balance. In which direction would wind flow?

A. North

B. East

C. South

D. West

E. Between two of the above

Solution: Geostrophic winds balance the PGF with the Coriolis force, flowing parallel to isobars. In the Northern Hemisphere, the Coriolis effect "deflects" wind to the right, and wind achieves geostrophic balance at 90° to the right of the PGF. The eastward PGF in the diagram creates southward wind.

Section II: Problem 1

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

The energy driving surface processes and life on Earth is almost entirely derived from incoming solar radiation, or insolation. The balance of energy entering and exiting, sometimes referred to as Earth's heat budget, is highly relevant in climate studies.

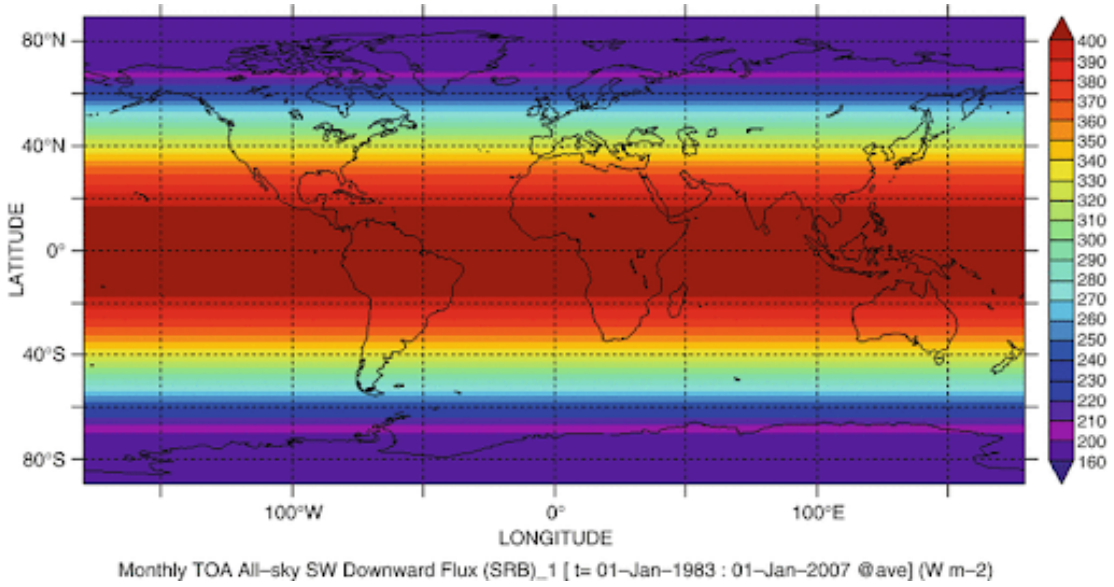


Figure 1: Top of atmosphere (TOA) insolation.

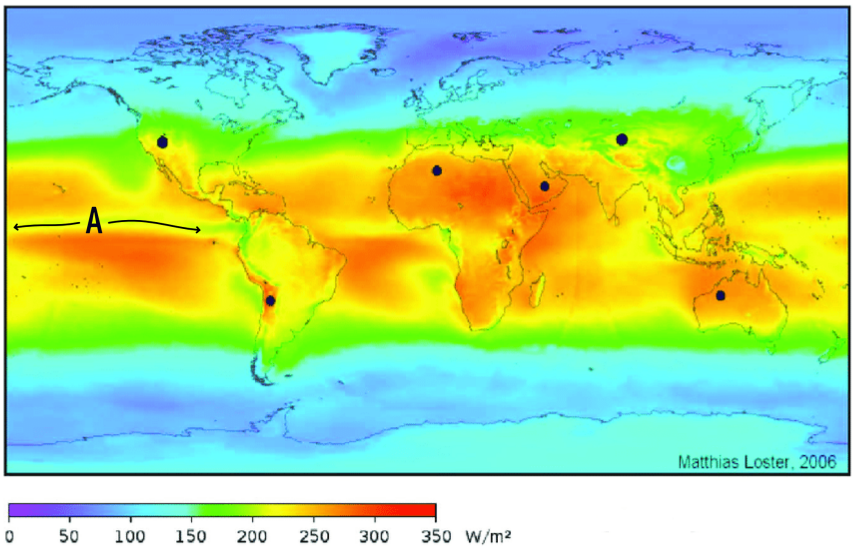


Figure 2: Surface insolation

1. Compare the solar insolation in Figures 1 and 2. Note that the two heatmap color scales are not the same. Units for both figures are in watts per square meter.

   (a) (1 point) Give a brief reason for each of the following:

   I) The overall insolation is lower at the surface compared to the TOA.

   II) The difference between TOA and surface insolation is non-uniform.

   Solution: Incoming solar radiation must pass through the atmosphere, where it is at least partially scattered, reflected, and absorbed, before reaching the surface. Therefore, surface insolation will be less than the insolation incident on the top of the atmosphere. Circulation patterns in the atmosphere and ocean influence the degree of absorption locally.

   (b) (2 points) Based on your knowledge of the atmosphere, provide one reason for the long region of relatively low insolation at Location A.

   Solution: Location A coincides with the intertropical convergence zone, where the lower limb of Hadley circulation rises near the equator and forms a band of frequent thunderstorms. These dense clouds reflect light, preventing much of it from reaching the surface.

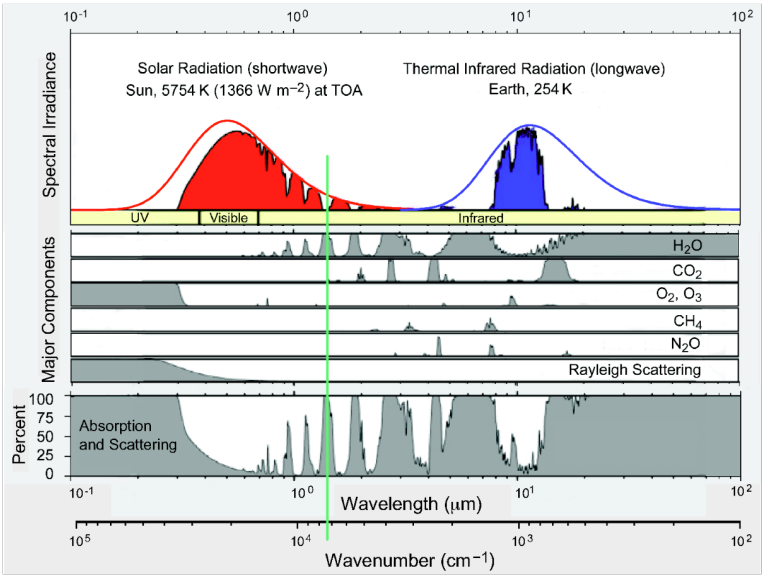


Figure 3: Spectra of radiation from the Sun and Earth (top), absorption spectra of a few atmospheric components (water vapor, carbon dioxide, etc.) (mid), and total absorption spectrum of the atmosphere (bottom).

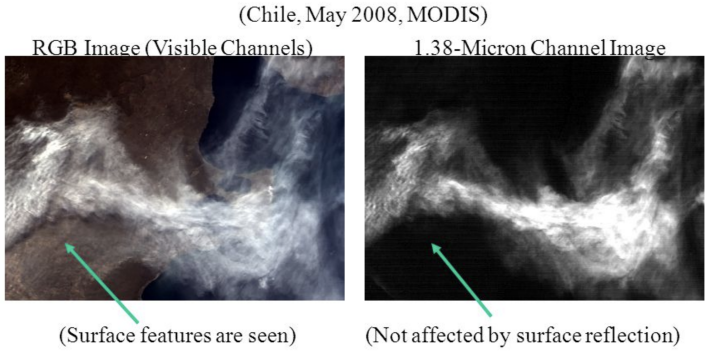


Figure 4: Example of images taken in the visible and 1.38 micrometer band after a volcanic eruption.

2. The role of clouds in climate change is one of the most complex and uncertain in climate modeling. For instance, different types of clouds differ in interaction with radiation.

   (a) (1 point) Cirrus clouds tend to have a warming effect as a result of the absorption spectrum of ice. With this information, give an approximate range of wavelengths (in micrometers) for the atmospheric window that cirrus clouds act to partially close.

   Solution: About 8-12 micrometers. Cirrus clouds, composed primarily of ice crystals, absorb longwave radiation that would escape to space in their absence.

   (b) (2 points) The detection of cirrus through satellite remote sensing is difficult in the visible range. One technique used to image these thin clouds utilizes the 1.38 micrometer band (i.e., images are taken of light with wavelength 1.38 micrometers), shown as a green line in Figure 4. What gas(es) is/are opaque to this wavelength, and how does its/their vertical distribution allow cirrus clouds to be imaged? Note that ice is reflective at 1.38 micrometers.

   Solution: Water vapor is opaque at 1.38 micrometers since it completely absorbs light at that wavelength. Since most water vapor occurs below the high elevations cirrus clouds typically form at, the 1.38 band effectively obscures the Earth's surface and all lower-level clouds, leaving cirrus clouds visible.

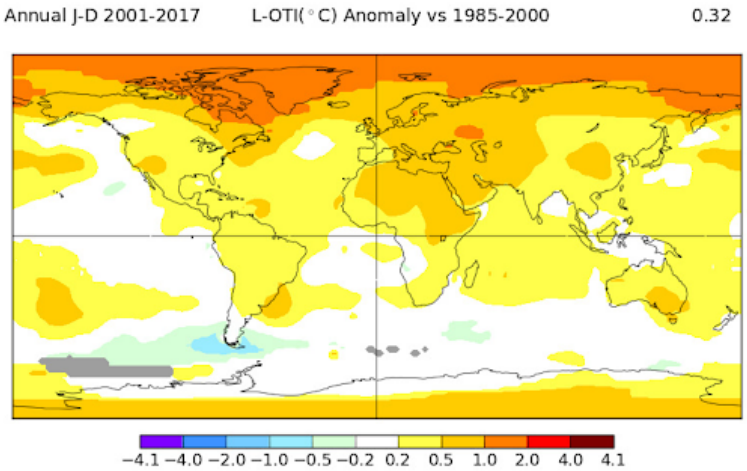


Figure 5: Map of Land-Ocean Temperature Index (L-OTI) anomaly in degrees Celsius.

3. (a) (2 points) Using the information given in the header and legend of Figure 5, interpret the meaning of the orange shading that covers Greenland and much of the Arctic. Include units and relevant timeframe(s).

   Solution: The orange covering Greenland corresponds to a 1.0°C to 2.0°C increase from the average temperature in 1985-2000 to the average temperature in 2001-2017.

   (b) (2 points) The ice-albedo feedback is an often-cited cause of polar amplification. Feedbacks are responses to climate forcings, changes in conditions external to the system such as greenhouse gas emission increasing global average temperature. Describe one other forcing to the Arctic system that contributes to decreases in ice cover. Why is subsequent ice melt not a forcing?

   Solution: (Multiple possible answers)Soot from burning biomass is an anthropogenic forcing that decreases the average albedo of the Arctic. Ice melt is a response internal to the system, so by definition it is not a climate forcing.

4. Planck feedback, the highest-magnitude feedback on changes to Earth's temperature, is a less often discussed but necessary component in modeling climate feedback. The parameter for Planck feedback, which connects a change in temperature to its effect on radiation flux, has a magnitude of 3.2 W/m^2K. This feedback can be illustrated by the Stefan-Boltzmann law, where the power of the radiation the planet emits is related to surface temperature.

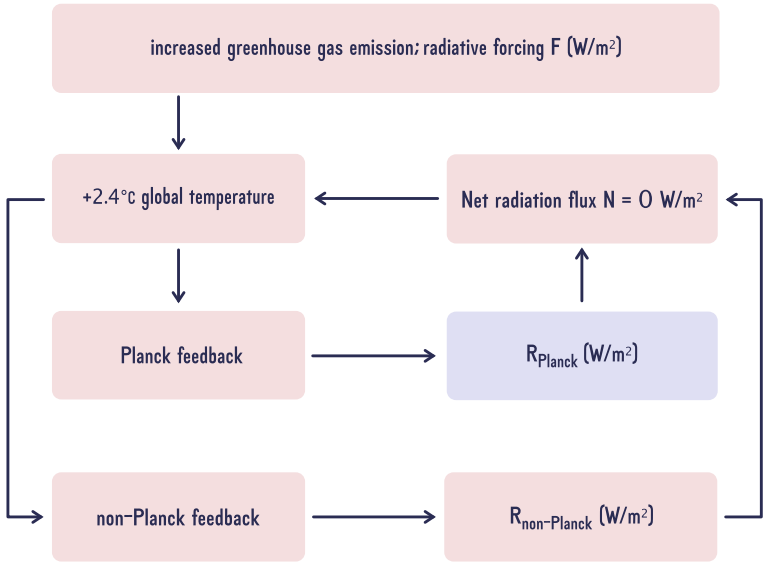


Figure 6: Diagram representing the global climate feedback (Planck feedback + all other feedbacks) in a simplified 2.4°C warming scenario.

(a) (2 points) Identify whether Planck feedback is positive or negative. Briefly explain using the feedback mechanism (diagram not needed for this part).

Solution: Planck feedback is negative. An increase in surface temperature also increases the power of outgoing longwave radiation, which would limit further change to temperature.

(b) (1 point) Find and interpret the value for R_{Planck} given the scenario in the diagram.

Solution: 2.4 K * -3.2 W/m^2K = -7.68 W/m^2. Outgoing radiation increases by 7.68 W/m^2 from Planck feedback considered alone.

(c) (2 points) Consider the fact that the Earth is not undergoing the 'runaway greenhouse effect.' Which of the following best describes the total sum of all non-Planck feedback?

A. Negative and less than -3.2 W/m^2K

B. Negative and greater than -3.2 W/m^2K

C. Positive and less than 3.2 W/m^2K

D. Positive and greater than 3.2 W/m^2K

Solution: The Earth in its current state has a small net negative feedback in response to temperature change. Planck feedback is strongly negative but is made up for by positive feedbacks such as water vapor and ice-albedo feedback.

Section II: Problem 2

Question	1	2	3	Total
Points	4	7	4	15 (30%)

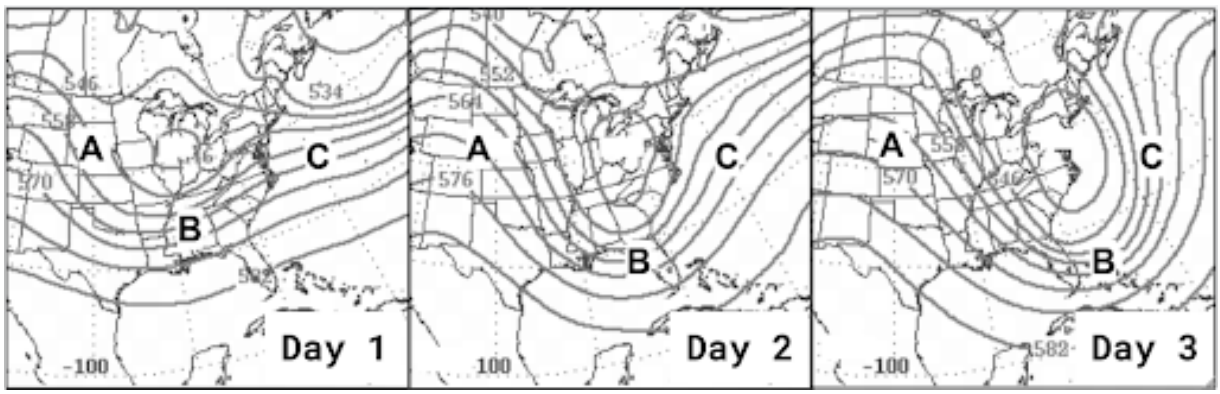


Figure 7: three 500 millibar upper-level maps depicting a recent storm system, including timestamps (lower right) and locations labeled A, B, and C. Grey lines are height contours of the pressure surface in meters.

1. (a) (2 points) On which day are you most likely to find a(n):

   I) Stationary front?

   II) Occluded front?

   Solution: I) **Day 1**. The early stages of mid-latitude cyclone formation involve a wave forming in the stationary front between the polar and Ferrell cells. II) **Day 3**. The cyclone dissipates soon after the cold front overtakes the warm front, which occurs on the third day in the map.

   (b) (2 points) Describe any surface-level pressure systems at C. Include any development over time.

   Solution: C has a surface low, which deepens and intensifies over time.

2. The measure of spin for air parcels is known as vorticity. The faster something spins, the greater its vorticity; air spinning counterclockwise has positive vorticity. For this question, assume that Earth's rotation has no effect on vorticity.

   (a) (1 point) At which location and on which day does vorticity reach its maximum?

   Solution: Day 3, Location B. In these upper level maps, wind is approximately geostrophic and flows parallel to contours. The greatest curvature of contour lines is present at the southernmost extent of the trough on Day 3.

   (b) (2 points) Just as air can be advected, vorticity (and its values) can be advected, too. On Day 3, between which letters, if any, does positive vorticity advection (PVA) occur? Negative vorticity advection (NVA)?

Solution: Negative vorticity advection occurs from A to B. Positive vorticity advection occurs from B to C. Negative advection corresponds with a negative to positive gradient (i.e. negative vorticity is being moved into regions of greater positive vorticity), while positive advection corresponds with a positive to negative gradient (i.e. positive vorticity is being moved into regions of greater negative vorticity).

(c) (1 point) Would a strip of positive vorticity advection from locations A to C on Day 2 hinder, improve, or have no effect on the development of the storm?

Solution: It would hinder storm development.

(d) (3 points) Give justification for your answer to (c). Include any surface-level and upper-level changes.

Solution: In PVA, high vorticity moves to a place of lower vorticity and the vorticity gradient goes from high to low. The band of PVA would disrupt the otherwise NVA occurring to the left of the trough, offsetting upper-level convergence since decreasing vorticity is associated with divergence. This means the relationship between surface-level divergence and upper-level convergence weakens. Storm development would be disrupted.

3. Upper-level jet streams play an important role in storm development. Their strength varies on a multitude of factors, including ENSO phase.

(a) (1 point) Considering the relative strength of trade winds, would an El Niño phase correspond to a stronger or weaker Pacific jet stream?

Solution: Stronger. Weaker trade winds are associated with a stronger Pacific jet stream.

(b) (1 point) Assume that the given upper-level maps correspond to a neutral ENSO phase. How would the intensity of the storm change if it took place during an El Niño, accounting for the role of the jet stream?

Solution: The storm would be more intense.

(c) (2 points) Give justification for your answer in (b).

Solution: The jet stream is stronger, meaning stronger upper-level convergence and divergence. This therefore intensifies mid-latitude cyclones.

END OF EXAM