Atmospheric Sciences 101
Second Midterm Exam - Solutions and discussion

1. a) Name the type of cloud for each cloud displayed on the overhead projector.

cloud #1:	cumulus	
cloud #2:	cirrus	
cloud #3:	cumulonimbus	
cloud #4:	lenticularis	*(Hint: The mountain has an altitude of 3 km)*

b) For each cloud in part (a), decide if it is a high cloud, a middle cloud, or a low cloud, and also whether it is composed of liquid water or ice crystals. Circle your answers below. Note that some of the clouds may occupy more than one level and also might contain both liquid water and ice, so you might have to circle more than one answer for each cloud.

cloud #1:	low	*cloud #1:*	liquid
cloud #2:	high	*cloud #2:*	ice
cloud #3:	high / middle / low	*cloud #3:*	liquid / ice
cloud #4:	middle	*cloud #4:*	liquid

c) For each cloud in part (a), decide if you would expect to experience precipitation at the surface of the Earth if you were standing underneath the cloud. Circle your answers below and state what type of precipitation you would expect on the ground underneath each cloud (if any).

cloud #1:	no precipitation	
cloud #2:	no precipitation	
cloud #3:		precipitation: rain, possibly hail
cloud #4:	no precipitation	

Comments:

cloud #1: Fair weather cumulus clouds are low, "puffy" looking clouds composed of liquid water. They have relatively shallow vertical extent (or they would be called cumulus congestus or cumulonimbus), and they almost never produce any precipitation.

cloud #2: Cirrus clouds are high clouds, and since the air is very cold aloft, they are composed of ice crystals. The crystalline structure of ice and the thin vertical extent of the cloud gives cirrus their characteristic "wispy" appearance. A "cirrostratus" cloud would be more uniform (less definition) and would cover most or all of the sky. Also, note that "cirriform" is a general cloud type (i.e. high ice cloud) and not a specific name of a cloud.

cloud #3: This cloud displays the typical shape of a cumulonimbus cloud, with its generally puffy appearance, large vertical extent, and anvil-shaped top (cumulus congestus, the intermediate stage between a low level cumulus and a cumulonimbus, has a "cauliflower head" instead of an "anvil" head). This type of cloud typically extends all the way from the lower atmosphere to the tropopause; consequently, both liquid droplets and ice crystals are present. Cumulonimbus clouds are generally associated with intense and violent weather: they almost always produce rainfall, and often hail (but not "drizzle").

cloud #4: Lenticular clouds appear when air is deflected in a wavelike fashion by the top of a mountain. As air is deflected upwards, it might reach saturation, forming cloud droplets by condensation. They have shallow vertical extent and will not produce precipitation. A "cap" cloud or "pileus" cloud, although formed through a similar mechanism, appears on top of a cumulus (or congestus or cumulonimbus) cloud. The hint stated that the top of the mountain was at 3,000 meters, so this lenticular cloud is a middle cloud; it may or may not have ice crystals (we accepted either answer), but it definitely has liquid droplets.

d) What is the *most important* *difference between a "stratus" cloud and a "nimbostratus" cloud?*
"Nimbo-" means "rain producing". The most important difference is that a nimbostratus produces rain (or drizzle), whereas a stratus cloud does not. We often have stratus clouds over Seattle without precipitation (okay, we also have a lot of rain, but that just means that we have a lot of nimbostratus!). We gave you partial credit for saying that a nimbostratus produces "more" rain than a stratus cloud (although this is a bad use of the terminology), or for saying that a nimbostratus cloud extends higher up in the atmosphere (you could, however, have a non-precipitating stratus cloud with deep vertical extent or a relatively shallow nimbostratus cloud).

e) Typical liquid water cloud droplets have a diameter of 20 micrometers (0.020 millimeters), but typical raindrops have a diameter of 2 millimeters. Explain how raindrops of this size develop inside a cloud composed of typical liquid water droplets.
Cloud droplets grow by ***collision*** and ***coalescence*** in clouds with vertical air motion. Your book and the lecture notes both contain a good description of this process. You need upward motion within the cloud for the droplets to collide with each other and coalesce. This is why clouds with deep vertical extent (which implies significant vertical velocity), like cumulonimbus clouds, produce larger raindrops than more shallow clouds, like nimbostratus. "Collision" by itself is not a sufficient answer, because cloud droplets can bounce off each other and not coalesce. Also, note that although the 20 micrometer cloud droplets develop by *condensation* of water vapor onto cloud condensation nuclei (CCN), the process of condensation is much too slow to produce rain droplets with diameters of 2 millimeters.

2. a) Define "dry adiabatic lapse rate" (in your answer, include an approximate numerical value for this lapse rate with the appropriate sign).
The dry adiabatic lapse rate is the rate at which the temperature of a parcel decreases (increases) as the parcel rises (sinks) in the atmosphere, if the parcel is not saturated **and** if no heat exchange takes place between the parcel and the environment (ex: if the parcel receives energy from the sun through radiation, then the process is non-adiabatic). You may work your way around this definition by explaining that the decrease in temperature as the parcel goes up in the atmosphere is due to the expansion of the parcel as pressure decreases; the expansion of the parcel requires work, which implies a reduction of the kinetic energy of the air molecules in the parcel and thus a decrease in temperature (which is a measure of the average kinetic energy of the molecules). An approximate value for this lapse rate in the Earth's atmosphere is -10°C/km.

b) Indicate an approximate numerical value for the *moist* *adiabatic lapse rate in the lower troposphere and explain why it is different than the dry adiabatic lapse rate.*
When an air parcel rises in the atmosphere, its temperature decreases, as explained in part (a). Because its temperature is decreasing, its saturation vapor pressure (or saturation mixing ratio, or the amount of water vapor the air can hold) decreases also. If the parcel of air is ***saturated***, then as it rises it is able to hold less and less water vapor. The excess water vapor immediately condenses and forms liquid water droplets, and this process releases latent heat. This latent heating offsets some of the cooling of the parcel due to expansion, so the moist adiabatic lapse rate is always less than the dry adiabatic lapse rate. The "moist" adiabatic lapse rate is typically between -4°C/km and -6°C/km in the lower troposphere, depending on atmospheric conditions, the temperature of the parcel, and the air pressure. Note that this explanation may be reversed for an air parcel going down in the atmosphere, where some of the energy gained by compression (adiabatic warming) is now used to evaporate liquid water droplets (assuming they have not rained out), reducing the rate at which the air parcel warms on its way down.

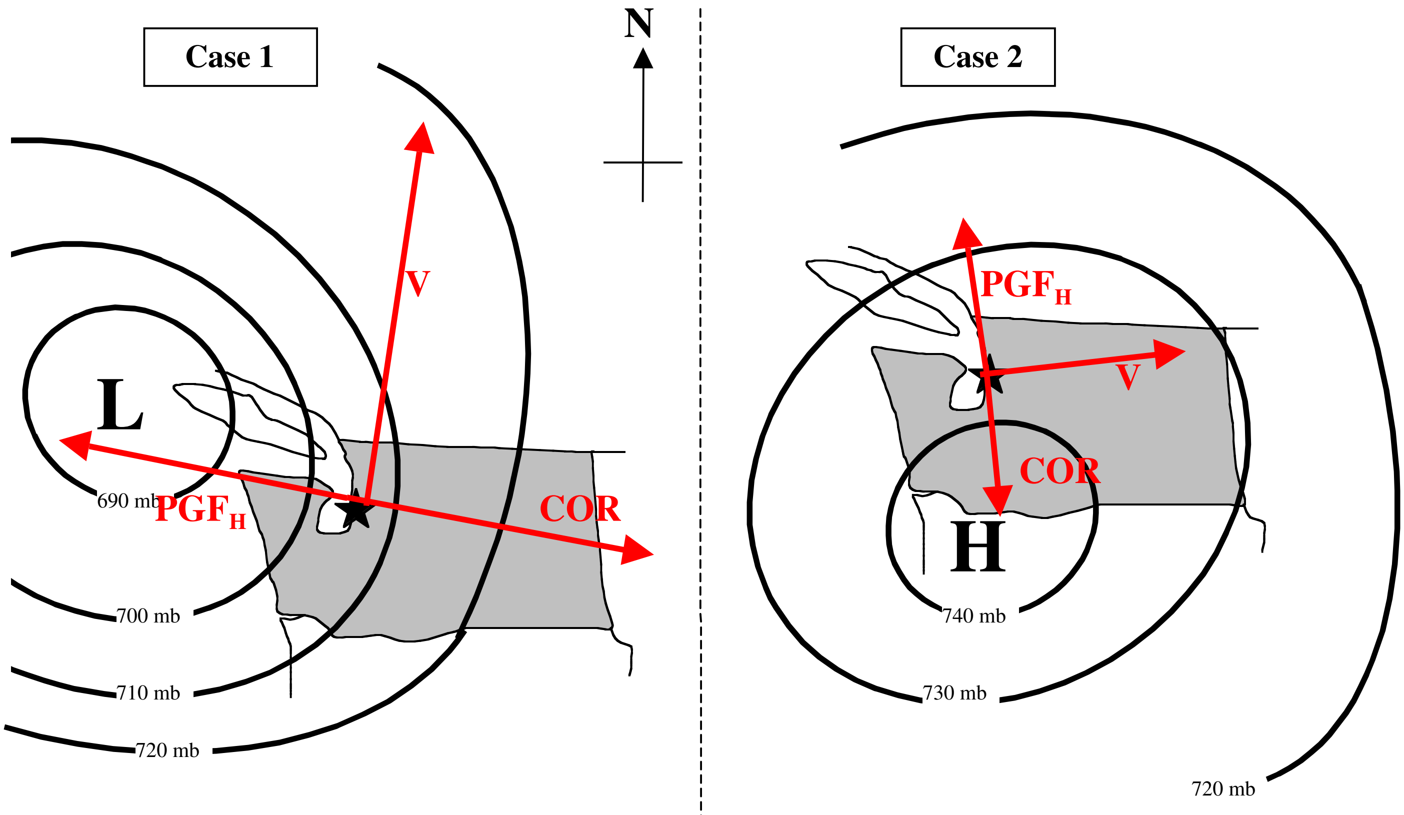
c) The figure below shows the motion of air as it is blown over point A, lifted upward as it encounters a mountain (points B and C), and then sinks back down to the surface on the other side of the mountain (point D). As air is lifted up from the surface, condensation takes place at an altitude of 1 km (point B) and a cloud forms above this height. The black arrows represent the path followed by the air. Consider a parcel of air starting near the surface at point A that follows the flow of air over the mountain. If ***the temperature of the parcel at point A is 26°C****, determine the temperature of the parcel as it moves through points B, C, and D. Also, indicate the relative humidity of the parcel at points B and C. Assume that all of the condensed water falls out of the cloud as precipitation before the air descends on the lee side of the mountain. Use the values you indicated in parts (a) and (b) for the dry and moist adiabatic lapse rates.*

Using -10°C/km for the dry adiabatic lapse rate and -4°C/km for the moist adiabatic lapse rate:

Point	temperature of the parcel (°C)	relative humidity (%)
B	16	100
C	8	100
D	38	

From A to B, the air is not saturated, so the temperature decreases by 10°C.
From B to C (note this is an altitude change of 2 kilometers), the air is saturated (RH=100%), so the temperature decreases by (2km × 4°C/km = 8°C) to a value of 16°C - 8°C = 8°C.
From C to D (3 kilometers altitude change), the air is not saturated (since all the condensed water fell out of the parcel as precipitation), so the temperature increases by 30°C to 38°C.
The relative humidity is 100% anywhere in the cloud (if it was not, then the cloud droplets would evaporate right away until the vapor pressure equals the saturation vapor pressure).
We gave you credit if your lapse rates in (a) and (b) were wrong but your calculations were correct. We also gave you credit if your temperature at A and/or B was wrong, but the subsequent calculations of the temperature change were correct.

d) List <u>all</u> of the information that you would need to calculate the relative humidity of the parcel at point D:
You need to know the actual water vapor content of the air parcel at point D (vapor pressure or mixing ratio) **and** the maximum amount of water vapor the parcel can hold at point D (saturation vapor pressure or saturation mixing ratio). Note that you can determine the saturation vapor pressure and/or the saturation mixing ratio from the temperature of the parcel (which you computed in part (c)).
Alternatively, if you know the actual water vapor content of the parcel at point C, then it would stay the same as the parcel descends to point D. Or, if you know the amount of water vapor contained in the parcel at point A, and the amount of precipitation lost by the parcel during its ascent, you could determine the amount of water vapor remaining in the parcel at point D.



3. On the two figures above, the pressure field over Washington State <u>at an altitude of 3 km</u> above sea level has been sketched for two different cases. The location of Seattle is represented by a black star on both figures. Note that the contour interval is the same for both cases.
a) Assuming that the wind is in geostrophic balance, estimate the direction of the wind at 3 km over Seattle for both cases (Make sure you use the appropriate terminology for meteorology):

(case 1) southerly (or southwesterly or south-southwesterly)
(case 2) westerly (or southwesterly or west-southwesterly)

One common error: the terms "cyclonic" and "anticyclonic" are used to indicate the sense of rotation around a low or high pressure center, but **not** the direction of the wind at a specific location. Also, in meteorology the direction of the wind expresses where the wind comes **<u>from</u>**.

b) State if you would expect to experience stronger winds at 3 km above Seattle during case 1 or during Case 2. Give a physical reason for your answer in terms of the forces driving the geostrophic balance.
The winds are stronger in case 1. Since the contour interval for the isobars is the same in both cases, the horizontal pressure gradient over Seattle is greater in case 1 because the isobars are closer together. This means that there is a stronger horizontal pressure gradient force over Seattle in case 1, which is balanced by a stronger Coriolis effect since the winds are in geostrophic balance. Also, since the wind speed is proportional to the pressure gradient force (and also the Coriolis force, which makes sense if these two forces are balanced), the winds will be stronger in case 1. Note that describing the isobars is not a sufficient answer: it does not explicitly say anything about "the forces driving the geostrophic balance."

c) For each case, draw arrows that indicate the direction and strength of the pressure gradient force (label it PGF), the Coriolis force (label it COR), and the wind speed (label it V) at 3 km above Seattle. Use the same scale for your arrows on both cases (e.g. draw a larger PGF arrow on the case with the larger PGF, etc.). Remember that there is essentially zero friction at 3 km.

Here are a few important features to check:
(1) The tail of your arrows should be over Seattle (the black star).
(2) The PGF and the Coriolis force should have the same magnitude and should be pointed in opposite directions. Both arrows should be perpendicular to the closest isobars to the black star.
(3) The wind arrow should be at a right angle with respect to the forces, with the Coriolis force to the right of the wind arrow and the PGF to the left of the wind arrow.
(4) <u>All</u> three arrows should be twice as big in case 1 as they are in case 2. Since the isobars are twice as close together in case 1, the PGF is twice as strong. Since we are in geostrophic balance, the Coriolis force must balance the PGF, so it must also be twice as large. And since both of these forces are proportional to the wind speed, the wind arrow should also be twice as long!

4. a) Circle all of the optical process(es) that make each of the following optical phenomena possible in the atmosphere.

Rainbows	refraction / reflection
Crepuscular Rays	scattering
Blue sky	scattering
Glory	diffraction / reflection
Twinkling	refraction

Some people argued that scattering IS reflection. However, scattering refers to the <u>random</u> reflection of light off of the surfaces of a collection of water droplets or air molecules. "Scattering," without a modifier, refers to reflection of radiation by a collection of molecules without a favored direction. Scattering is what enables you to "see" a cloud in the sky, or to see dust particles in a crepuscular ray, or to seethe blue sky outside.
Reflection, on the other hand, refers to light bouncing off of a substance in a particular manner, for example: light bouncing off of the rear interior surface of a rain drop or cloud droplet to produce a rainbow or glory. Note that some of the light that strikes water drops is scattered by the droplets (so you see a cloud), but a small percentage is reflected internally off of the rear of the raindrop at a particular angle and (after refracting as it leaves the raindrop) reaches your eye as a rainbow. (We gave you partial credit if you confused these two terms).

b) You look up at the sky and observe that it is entirely covered by a thin cloud layer. You can see the Sun through the cloud, although it is somewhat dim. You also notice a ring of light around the Sun at an angle of 22 degrees.

What type of cloud are you looking at? cirro**stratus** (note that it covers the <u>entire</u> sky)
What is its composition? (be specific!) column-type **ice** crystals (diameter < 20 microns)
What optical phenomenon are you observing? 22° **halo**
What makes this phenomenon possible? refraction

5. You are standing on a stationary ship in the middle of the North Pacific Ocean and you know that a front is approaching the ship from the West, as shown on the picture below.

a) What type of front is this? cold front

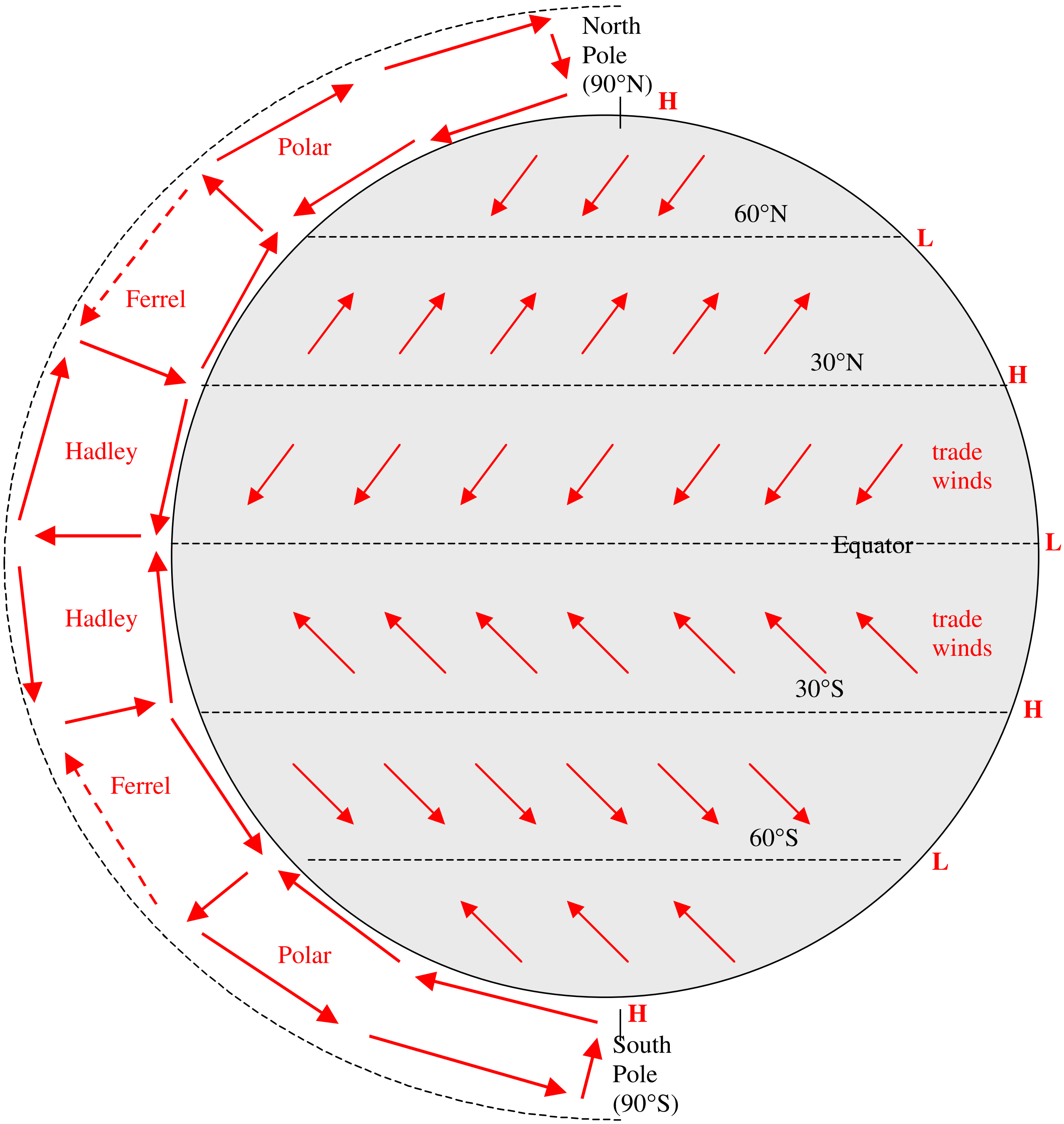
*b) Assuming that the surface front will be at the ship in 12 hours, provide a forecast of the weather at the ship **in 6 hours** by making the following predictions (circle your answers):*
*temperature (relative to **current** temperature):* about the same (you will still be located in the warm sector, where the temperature is typically quite uniform).
*pressure (relative to **current** pressure):* lower (both warm fronts and cold fronts are referred to as pressure "troughs", because the pressure is lowest when the front is overhead; the pressure decreases as the front approaches, which is why you can predict the weather using a barometer to monitor the change in pressure).
wind direction at the surface: Southerly or Southwesterly
Name the clouds you might see overhead in 6 hours (if any): cirrus or cirrostratus clouds blown off of the top of the approaching frontal clouds by the jet stream aloft; you might also see some fair weather cumulus clouds, and perhaps fog because you are in the warm, humid sector. Or you might see no clouds at all.

*c) Briefly describe the clouds and precipitation you expect over the ship **in 12 hours** (if any):*
The cold front will be directly overhead in 12 hours. Deep cumulonimbus clouds, with heavy rain and/or hail are possible. Often these clouds are accompanied by nimbostratus clouds near the surface and/or cirrus clouds aloft (but you would probably not see either of these cloud types in isolation). You might also see regular cumulus clouds, cumulus congestus clouds, or altocumulus clouds.

*d) Provide a forecast of the weather at the ship **in 18 hours** (after the passage of the surface front) by making the following predictions (again, circle your answers):*
*temperature (relative to **current** temperature):* cold (you will be located in the cold sector)
*pressure (relative to pressure **12 hours from now**):* higher
wind direction at the surface: Westerly or Northwesterly (note the wind shift)
Name the clouds you might see overhead in 18 hours (if any): perhaps some fair weather cumulus clouds (since there is usually clearing after a cold front and solar heating of the surface might initiate some shallow convection over the moist ocean water) or stratocumulus clouds (which form when cold air overrides a warmer surface below). Generally, there is clearing after a frontal passage, so "none" is also an acceptable answer.

6. The figure below is a sketch of the Earth with a cross section of the troposphere on one side (note that the tropopause height is NOT to scale in this figure). The horizontal dashed lines represent latitude circles at the Equator, 30° North and South, and 60° North and South. Consider the idealized circulation model that we developed in class to describe the horizontal winds, average surface pressure, vertical motions, and weather characteristic of each latitude "band."

(Question 6 is continued on the next page.)



(Question 6, continued.)
a) Using arrows, indicate on the figure the average direction of the <u>*surface*</u> *winds in the six latitude bands in between the dashed lines. Also label the "trade winds" in both Hemispheres.*
Many people correctly represented the bands of westerly and easterly winds, but they neglected to include the large-scale effects of friction near the surface, which cause convergence into surface low pressure centers near the equator and 60°N, and divergence from high pressure centers in the subtropics and polar regions.

b) At 0°, 30°, 60° and 90°, in both the Northern and Southern Hemispheres, indicate on the figure if the pressure <u>*at the surface*</u> *is higher (label "**H**") or lower (label "**L**").*

c) In the cross section of the troposphere, sketch the "Polar Cell," the "Hadley Cell," and the intermediate mid-latitude cell (which is called the "Ferrel Cell"). Label each cell with its name and draw arrows to indicate the direction of circulation in each of these meridional cells.

d) The Earth's major rain forests are located around the equator (0° latitude). The Earth's major deserts are located around 30°S and 30°N. Using your knowledge of the general circulation, briefly explain why the rain forests are near the equator and the deserts are in the subtropics?
At the equator, there is low pressure at the surface, and due to surface friction there is **convergence** or air in the vicinity of the equator across much of the globe (see the general circulation diagram on the preceding page, which shows that the trade winds generally have a North-South component as well as the expected easterly flow). This surface low pressure center and surface convergence (i.e. the ITCZ, or inter-tropical convergence zone) is generally associated with **rising motion** in the vicinity of the equator (i.e. the rising "arm" of the Hadley cell). Under conditions of large scale rising motion, the lifting of surface air is enhanced, and thus convection, and the associated processes of condensation, cloud formation, and precipitation, are all favored. Rain forests thrive under these conditions of enhanced precipitation. Moreover, the warm, moist air in the rain forests and surrounding ocean regions provides an excellent source of energy and moisture for convection (this is an example of a positive feedback mechanism).
In the subtropics, which experience generally higher surface pressures, **air is generally sinking** as part of the descending "arm" of the Hadley cell. It is very difficult for convection to occur in the vicinity of 30 degrees latitude because any lifting mechanism must overcome the large-scale sinking motion. Thus convection and the associated condensation, cloud formation, and precipitation are all suppressed. Subtropical regions therefore do not experience a large amount of rainfall, and deserts may form if the underlying soil characteristics and regional climatology are favorable. Note that although desert air is quite dry near the surface, the surface is so warm (especially during the day) that the air near the surface has a very low density. In this situation, convection would happen freely if not for the large scale *subsidence* (sinking motion) retarding upward motion. In reality, convection is limited to a shallow turbulent layer near the desert surface.
Note that "low pressure at the equator and high pressure at the subtropics" is not a sufficient answer to this question because it does not explain **why** these surface pressure centers should be associated with enhanced or diminished rainfall. Also, it is important to link the rising/sinking motion to precipitation via the appropriate physical processes, and then link the precipitation amount to the expected surface climate.

e) Explain why the jet stream blows from West to East ***and*** *why it is located near the tropopause.*

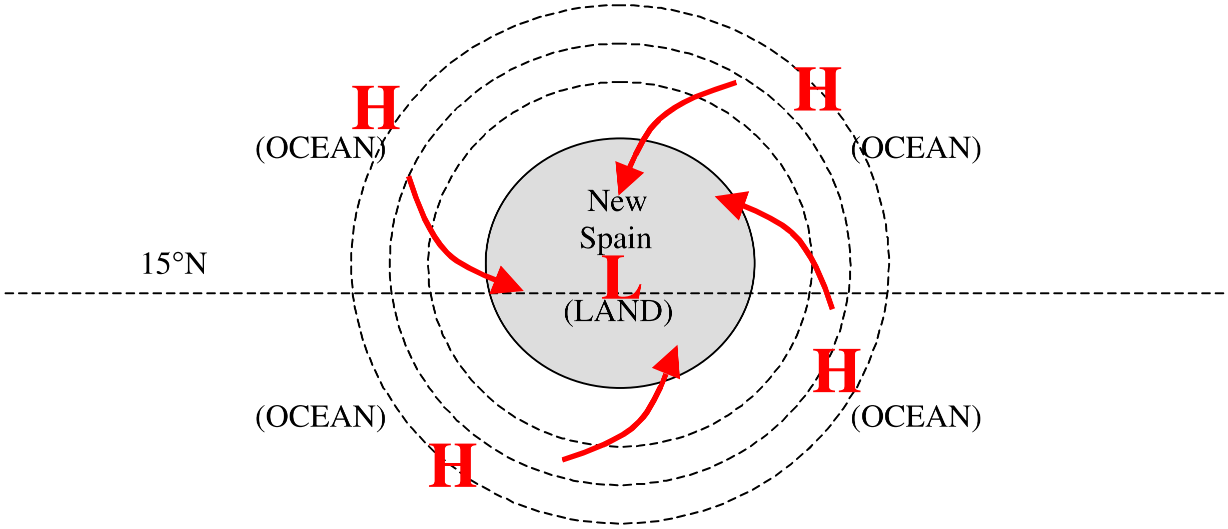
Due to differential heating from the sun, the tropics are warmer than the mid-latitudes and the poles. Air pressure decreases faster with height in the colder regions (as per our discussions of land/sea breeze), so aloft (say near the tropopause), there is a horizontal pressure gradient force from the tropics (relatively high pressure aloft) towards the poles (relatively low pressure aloft). This pressure gradient tends to push air out of the tropics and towards the extratropical regions. However, this entire process is taking place on a rotating reference frame (the Earth). As air moves towards the poles, it tends to be deflected eastward (to the right in the Northern Hemisphere, to the left in the Southern Hemisphere) to conserve angular momentum about the Earth's axis of rotation. Since there is relatively little friction near the tropopause, the resulting wind (the jet stream) tends to be close to geostrophically balanced (i.e. PGF points away from equator, Coriolis force points towards equator, wind points to the east--a westerly wind).

The main reason that the jet stream is located near the tropopause is because the difference in pressure between the warm tropics and colder polar regions increases with height. At the tropopause, you are essentially "adding up" all of the pressure differences in the layers below you (and there is relatively little temperature variation in the stratosphere above you). In addition, the air near the tropopause is not very dense, so it is easier for the pressure gradient force to "push" this less dense air around. Although it is true that there is relatively little friction at this height, this is not one of the main reasons that the jet stream is located aloft. If there were no friction near the surface, a jet stream would not form near the surface because the pressure gradient is not as strong and the air is much more dense.

A complete answer to this question needed to include a discussion of the thermal contrast between the equator and the poles, an evaluation of the resulting pressure differences aloft, a description of the horizontal pressure gradient force aloft, the Coriolis effect, the resulting geostrophic balance that produces the westerly jet stream, and also the two main factors that make the winds stronger near the tropopause than at the surface.

Many people noted that the book distinguishes two different "jet streams": a subtropical jet stream located near the sinking "arm" of the Hadley cell at 30° latitude, and a polar jet stream that is located where the cold polar air and the warm tropical air meet, i.e. the "polar front" in the vicinity of 60° latitude. The subtropical jet forms above the sinking "arm" of the Hadley cell, as air moving away from the equator is deflected eastward by the Coriolis effect. On the other hand, the mid-latitudes (in the vicinity of the "polar front") is the region of the strongest horizontal change in temperature, so it is also the region with the strongest pressure gradient force aloft. Hence, there is also a wind maximum above the polar front.

In reality, it is difficult to distinguish between these two jet streams. One reason for this is that the circulation in the top half of the mid-latitude Ferrel cell (between 30° and 60° latitude) is weak (hence it is drawn in dashed arrows on the figure in the preceding page). Also, the relative speeds of the subtropical jet and the mid-latitude jet change with the seasons. However, the explanation of the jet stream given above works for either of these two jets.

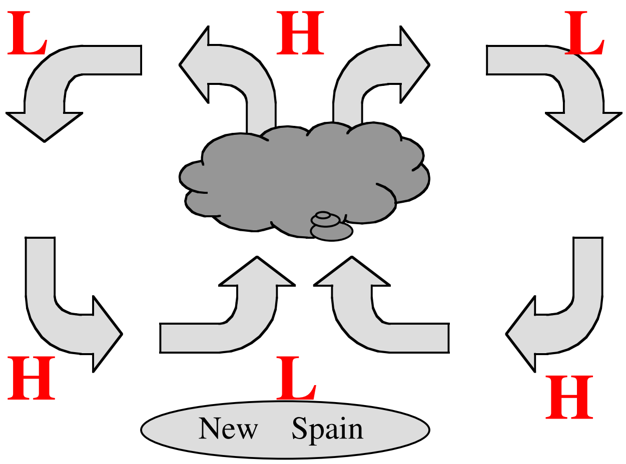


7. Dr. Saramago, the internationally famous geologist, has predicted that (in a rather remarkable event) Spain will soon separate from the European continent and drift into the tropical Atlantic. Dr. Saramago has estimated that Spain will grow in size by accumulating ocean sediment as it slides along, and ten years from now it will stop in the central Atlantic Ocean at about 15°N. So in ten years, "New Spain" will be a large island (roughly 500 kilometers across) located in the middle of the Atlantic Ocean.

*a) Assuming that the energy output from the sun and the concentration of greenhouse gases in the atmosphere do not change during the next ten years, indicate the location of average <u>summertime</u> high (label "**H**") and low (label "**L**") sea-level pressure in the vicinity of New Spain on the map above. Also, draw the average summertime <u>surface</u> wind field (use arrows). Keep in mind that the summer lasts for several months, so the timescale involved in this circulation will be long compared to the rotation rate of the earth.*
We have also sketched in (with dashed lines) the approximate surface pressure field (isobars).

b) What kind of weather (clouds and precipitation) would you expect to experience in New Spain during the summer months?
Clouds, in particular convective clouds like cumulus and cumulonimbus, and probably periods of heavy rain.

c) Explain your answers to parts (a) and (b). Concentrate on the physical processes involved in setting up this circulation system. Use the back of this page if you run out of space below.
This is similar to the classical "Monsoon" situation. You can reconstruct the pressure field through a sea-breeze type reasoning. Averaged over the summertime, the land surface will be warmer than the surrounding ocean. By conduction and convection, the air above New Spain will also be warmer than the surrounding air over the ocean. The warmer air column expands, creating a pressure difference aloft: higher pressure <u>aloft</u> over New Spain, lower pressure <u>aloft</u> over the oceans around New Spain. This drives an upper-level circulation from the land toward the ocean, and induces higher pressure <u>at the surface</u> over the ocean as air molecules are blown from the land over the ocean aloft. This surface pressure contrast in turn creates a sea-breeze where the surface winds blow in from the surrounding ocean toward New Spain. (See the diagram below, which is a vertical cross-section across New Spain and the surrounding ocean.)



However, this circulation takes place over large distances (500 km) and is averaged over several months, so the Coriolis effect must be taken into account. In the Northern Hemisphere, the effect of the Coriolis force is to deflect the sea-breeze (or monsoon) winds to the right. If the surface winds were in perfect geostrophic balance, then they would just circle the island of New Spain in a counterclockwise (cyclonic) direction. However, the effect of surface friction means that the winds will actually have a component **into** the surface low pressure center over the island. This will produce a convergence of surface winds over the island, and the circulation will look like the one depicted in the diagram at the beginning of this problem.

By conservation of mass (and the fact that the air cannot go into the ground), the converging air rises over New Spain, expands, cools, and may reach saturation, forming clouds (in particular, clouds with significant vertical velocity like cumulus) and possibly rain. Conversely, the air sinks over the ocean, preventing the formation of clouds around the island. During the summer months, we would thus expect clouds over New Spain and possibly rain.

Note that at 15°N we are neither at the ITCZ nor in the subtropics, so you would not expect an enhancement or suppression of convection and precipitation due to the effects of the large-scale circulation. Also, since we are surrounded by warm water there is an abundant supply of energy and moisture for precipitation so surface convergence could produce heavy rainfall.