~ ATSC 2000 ~

INTRODUCTION TO METEOROLOGY

LAB MANUAL

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UNIVERSITY OF WYOMING

Fall 2008

ATSC2000: INTRODUCTION TO METEOROLOGY

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Except if otherwise noted, the lab sessions meet in EN 6085.
The 'computer labs' are held in EN 1039 and EN 1041 for this semester.

Lab Schedule

Section 10 (S1): EN 6085 - Mondays (3:00 - 5:00 PM)
Section 11 (S2): EN 6085 - Thursdays (3:00 - 5:00 PM)

Dates (S1, S2)	Lab	Lab Content
08/25, 08/28	-	Introduction, Procedures, and Grading
09/04, 09/08	1	Surface Weather Observations
09/11, 09/15	2	Temperature Structure of the Lower Atmosphere
09/18, 09/22	3	Radiative Energy Transfer
09/25, 09/29	4	The Greenhouse Effect *(Take Home Lab)*
10/02, 10/06	5	Humidity Variables
10/09, 10/13	6	Thermodynamic Diagrams
10/16, 10/20	7	Static Stability and Clouds
10/23, 10/27	8	Freezing of Water: Ice Nucleation
10/30, 11/03	9	Interpreting Weather-Satellite Images *(Take Home Lab)*
11/06, 11/10	10	Force Balance and Atmospheric Motion
11/13, 11/17	11	Frontal Disturbances - Part I: Surface Charts
11/20, 11/24	12	Frontal Disturbances - Part II: The Jet Stream and Surface Weather
12/01, 12/04	-	No Labs

Take Home Labs are scheduled for the session beginning **25 September** and **30 October**. Students wishing to receive guidance for the completion of these labs are invited to visit with their lab TA at the beginning of their normally scheduled lab period during those two weeks. Students preferring to forego guidance do not have to attend the lab session, but must turn in their lab assignment to their TA ***no later than at the start of the first class following their normally scheduled lab session*.**

LATE ASSIGNMENTS WILL NOT BE ACCEPTED.

Table of Contents

ATSC 2000 Lab I   Section: Mon. / Thurs. (Circle)   **Name:**

1. Surface Weather Observations

Before the Lab: Read pages 16 – 24 of Chapter 1 in *Meteorology - Understanding the Atmosphere* by S. A. Ackerman and J. A. Knox and this lab assignment. Refer to Appendix A-2 for further assistance.

I. Introduction

Computers are vital to the collection, analysis, and display of weather data. Each hour, thousands of weather observations are taken across the globe. These observations are in many different forms. Conditions at the surface are measured at many airports and weather offices around the world. Weather balloons measure the conditions above the surface. Weather satellites and radars measure conditions remotely. Computers are able to ingest these observations and present them in ways that are easier for people to assimilate.

Over the years there has been an explosion in the amount of data available on the internet through the World Wide Web (WWW), a system developed by Dr. Tim Berners-Lee (knighted for his scientific and information technology contributions) at CERN in Switzerland. In this laboratory, you will look at some of the weather observations made near the surface of the Earth. Access to this data is available via the web server provided by the Department of Atmospheric Science at the University of Wyoming, http://weather.uwyo.edu.

Lab Goals:

1. Learn about conventions for time measurement and time zones.
2. Appreciate the extent and accessibility of observational weather data on the internet.
3. Learn how to interpret observational weather data and how to both interpret and construct a 'station model'.
4. Explore correlative relationships between some of the reported weather parameters.

II. Accessing the Web

In this lab you will use the computer labs in the Engineering Building (Rooms 1034 or 1041). You will need to log in to these computers. Your user name is the first eight letters of your last name. If you have a common last name, it may be modified and will have a number appended, such as SMITH14. Ask your TA if you do not know your login name. The password for your *initial* log-in consists of your "W number", which can be found on your student ID or on the WYOWEB page. Follow the onscreen instructions to revise your password. After logging in, click on the 'Start' button and open the Internet Explorer web browser, found under 'Communications'. If there are problems logging in, ask your TA for assistance.

Please bookmark the University of Wyoming's weather page, **http://weather.uwyo.edu**.

III. Observation Times

As mentioned in Chapter 1 of your textbook, weather observations are made across the world at nearly the same time. Problems can arise when reporting the time at which an observation was made, since different locations may be located in different time zones. To avoid this difficulty, meteorologists report all weather observations with a standard time, called Universal Time Coordinates or simply UTC. Another (shorter) name for this time is Z time. This standard time corresponds to the time at Greenwich, England, located at 0° longitude.

To convert between local time (the time where you live) and Z time you need to determine how many hours difference there is between your location and Greenwich, England. In winter, Laramie, in the Mountain Time Zone, is 7 hours behind Greenwich, England, so if it is noon at Greenwich, it will be 5 AM in Laramie. When we are using daylight savings time (during the summer months) we adjust our clocks ahead one hour, making the difference between local time in Laramie and Z time, 6 hours.

One additional item to note is that meteorologists use a 24 h clock instead of the commonly used 12 hour clock. This means that midnight is 0000, noon is 1200, and 11:59 p.m. is 2359.

You can use the formulae below to convert between local time in Laramie and Z time:

Standard Time (winter)	**Daylight Savings Time**
Time (Laramie) = Time (Z) - 7 h	Time (Laramie) = Time (Z) - 6 h
Time (Z) = Time (Laramie) + 7 h	Time (Z) = Time (Laramie) + 6 h

1. What is the corresponding local time in Laramie, WY, for yesterday's weather observation reported at 2300 Z?

2. A weather observer at Denver International Airport (located in the Mountain Time Zone) makes a weather observation today at 11 a.m. local time. What Z time would she indicate when reporting the weather observation?

3. What is the difference between Z time and local standard time on the east coast of the United States, where the local time is two hours ahead of that in Laramie?

IV. Surface Weather Observations

Weather observations at the surface of the Earth are made each hour by meteorologists around the world. These observations are typically taken at airports, in support of aviation operations. Appendix B of your textbook describes the weather elements that are observed and descriptions of the instruments used to make the measurements are found throughout the text. Typically, surface observations include measurements of the temperature, humidity, cloud cover, visibility, wind speed and direction, air pressure, and the present weather (precipitation, fog, etc.).

First we will look at these observations for Laramie, WY. From http://weather.uwyo.edu, select **Surface Observations**, and then **Global Surface Observations**. A map of the western US will be displayed together with boxes in which you can choose the type of output you require. The default settings in these boxes should indicate that the data about to be retrieved is current data, in American units, and that it will be displayed as a Listing. (If this is not the case, change the descriptor settings accordingly). Now click on the point for Laramie on the map to display the table of data.

The observations for KLAR are arranged chronologically, with the most recent observation at the top of the page and the oldest observation at the bottom. The data that is displayed represents the weather at Laramie Regional Airport over the last 24 h (note that some observations may be missing). Across the top of the table are column headers that describe the type of data given in each column of the table.

VIS: (Visibility) The visual range is given in miles (mi).

PMSL: (Sea level pressure) The atmospheric pressure (corrected to the equivalent pressure at sea level) is given in hecto-pascals (hPa; hundreds of Pascals) and is numerically identical to pressures expressed in millibars (mb). Standard sea level pressure is 1013.25 mb.

TMP: (Temperature) The temperature is given in degrees Fahrenheit. A reported value of –99 represents no data. Recall that the normal melting point of ice and the boiling point of water at sea level are 32°F and 212°F, respectively.

DEW: (Dewpoint) The value of the dewpoint (or dewpoint temperature) reflects the humidity of the air. We will explore the relationship further in the fifth lab.

DIR: (Wind Direction) The wind direction is reported in degrees with 360° representing a wind *from* the north, 90° representing a wind *from* the east, 180° representing a wind *from* the south, and 270° representing a wind *from* the west. Intermediate values are used to represent a wind which is coming from a direction other than the four cardinal directions (for example, a southwest wind would be reported as 225°).

RH: (**Relative Humidity**) The relative humidity gives the amount of water vapor in the air as a percentage of the maximum possible at the prevailing temperature.

SPD: (Wind Speed) Wind speed is reported in *knots* (kts), a unit with which you may not be familiar. A knot is a nautical mile per hour. (1 knot = 1.15 miles per hour)

GUS: (wind gust speed) Also in knots (kts).

CLOUDS: (Cloud Cover) Cloud cover is reported as a variety of categories, such as CLR or OVC. The actual amount of cloud cover for each of these categories is described on page 19 of the text. When clouds are present their height is often given in hundreds of feet by a three digit appendix to the three letter descriptor. Thus SCT036 means that there are scattered clouds at 3600 feet.

1. What is the current observation time (give both Z time and local time)?

   Z time: Local time:

2. What were the maximum and minimum temperatures reported for Laramie during the past 24 h? When were these temperatures reported? Use the temperature column (headed **TMP**) to determine these values. Give your answers in *local* time.

   Maximum temperature: Minimum temperature:
   T_{max} was measured at T_{min} was measured at

3. What are the current temperature, dewpoint, and relative humidity (RH)?

   Current temperature: Current dewpoint: RH:

4. At what *local* time(s) during the last 24 hours was the difference between the temperature and the dewpoint (called 'the dew point depression') a minimum?

   The minimum dew point depression ($T - T_{dew}$) occurred at

5. At what *local* time(s) during the last 24 hours was the difference between the temperature and the dewpoint (the 'dew point depression') a maximum?

   The maximum dew point depression ($T - T_{dew}$) occurred at

6. At what *local* times during the last 24 hours was the relative humidity a maximum and a minimum?

   Relative Humidity maximum occurred at ; Relative Humidity minimum occurred at

7. How do your answers to question 6 compare with those to questions 4 and 5? Do they suggest that small dew point depression values are associated with high relative humidity?

8. What is the current reported sea level pressure? (Make sure that you include the appropriate units). How has it varied over the last 24 hour period?

9a. What cloud cover category is currently indicated?

9b. What fraction of the sky is covered by clouds, based on your answer to part 9a?

9c. At what height are these clouds?

10a. What is the current wind direction? Give the wind direction in both degrees and as a compass direction.

10b. What is the wind speed in knots?

10c. What is the wind speed in miles per hour?

10d. Were any wind gusts reported in the previous 24 h? If so, list the gust speeds (knots) and the local times that the gusts were reported.

11. Is *significant* weather currently being reported and, if so, what is it? (Note, if the **Weather** column has no entry it implies that no *significant* weather is occurring, not that there is *no* weather occurring).

12. Use the current observation at Laramie to make a station plot of the data. Include the temperature, dewpoint, wind speed and direction, cloud cover, and pressure in your station plot. Make sure that you use the proper coding techniques when plotting the data. Appendix B and chapter 14 gives information on how to plot the data.

Help with plotting the station model:

You can get some practice at interpreting station model plots by first visiting
http://cimss.ssec.wisc.edu/wxwise/station/page5.html or
http://profhorn.meteor.wisc.edu/wxwise/station_model/sago.html).
Normal values for sea level pressure range from about 950 mb to 1050 mb. Standard sea level pressure is 1013.25 mb. On station plots the reported sea level pressure is coded as a *three* digit number. To convert the pressure value to a coded value just take the last three digits and omit the decimal point. Thus pressure values of 1010.6 mb, 1004.8 mb, and 993.2 mb become 106, 048, and 932 when coded. To reconstruct the actual sea level pressure from a coded value, just reverse the procedure, i.e., put the decimal point back in between the last two digits and add either a 10 or a 9 before the three digits. Choose either 10 or 9 following this manner; if the three digit number is greater than 500 place a 9 in front of the numbers and if the set of number is less than 500, place a 10. This method allows the reconstructed pressure to fall within the range 950 – 1050 mb. If it is outside this range, you made an incorrect choice. For example, if the coded value is 879, the decoded value must be 987.9 mb, not 1087.9 mb which is impossibly high. Similarly, 104 becomes 1010.4 mb, not 910.4 mb, which is too low.

Now click **Weather Data for Wyoming** and then on **Graphics** under Weather at the University of Wyoming. A three-panel graph will appear that displays conditions on the roof of the Engineering Building over the last 48 hours. The detailed description of the plot is available if you are having trouble interpreting it.

13a. The top panel of the graph shows temperature and relative humidity data. At what time of day yesterday (local time) were the minimum and maximum temperature values observed? The time scale (date/hour (Z time)) is at the bottom of the plots, under the lowest of the three panels. **GIVE ANSWERS IN LOCAL TIME.**

Temperature maximum occurred at *; temperature minimum occurred at*

13b. At what local time were the relative humidity values at their maximum and minimum values yesterday?

Relative humidity minimum occurred at *; relative humidity maximum occurred at*

13c. How do your answers to questions 13a and 13b relate to your answer to question 7?

The center panel shows the time trace of the readings from a pyranometer, which measures the intensity of sunlight (solar radiation) striking the Earth's surface. Clear skies result in maximum penetration of the sun's rays, whereas clouds diminish the intensity of the solar radiation reaching the surface.

14. Does the shape of the pyranometer trace indicate anything to you about how cloudy it was yesterday, and if so, what? When was the intensity of sunlight at a maximum yesterday?

The local time when sunlight was at its maximum intensity was

How does your answer compare to the time when the maximum temperature was observed (question 13a)?

15. Wind data are plotted in the lower panel. During what period(s) was(were) the wind(s) at its(their) calmest yesterday? When did they tend to be strongest? Give your answers in local time.

Return to the **Global Surface Observations** page and select the map for any region of your choice. Change the default setting in the 'Type of Output' box to 'All Observations', but leave the 'Current' default settings in the Date and Hour boxes. Now click on a station in your region of choice. A table of the latest observations for all the stations in that state/country will appear. **MAKE SURE YOU CHOOSE A LOCATION WITH AT LEAST TWO OBSERVING STATIONS.**

16. Which state/country have you chosen to look at, and at what time were the observations made?

17. What are the warmest and coldest temperatures currently being reported in this state/country, and at which stations ? (The names of the stations are displayed below the map as you move the cursor over them).

18. Are any stations reporting significant weather? What type of weather is occurring and where?

Note: ***Be sure to complete the Post-lab assignment, as well as Lab 2 Pre-lab Questions in preparation for the next Lab Session!***

V. Take-home Exercise for Lab I Section: Mon. / Thurs. (circle) **Name:**

Post-Lab Assignment: from Weather to Climate

(Hand this in for grading at the beginning of the next lab together with the Pre-lab for lab 2)

This assignment aims to collect and interpret daily weather observations at a few places with distinct climates. You will gain familiarity with raw weather data, learn about the variability of *weather*, and, based on a very small dataset, draw inferences about the *climate* that characterizes these places.

We look at 3 places: Laramie (LAR), Sacramento (SAC) in California's Central Valley, and Quillayute (UIL) along the coast of Washington. We collect key weather data for just five days of your choice between now and the due date. Temperatures and other weather variables typically have a daily cycle, due to the Earth's rotation, and the minimize the variability due to the diurnal cycle, we need to take the observations at the same time each day. Let us pick 21 Z.

1. What is the local time at 21 Z? SAC and UIL are in the western timezone (WST=UTC-8, WDT=UTC-7).

- at LAR? ______________________________
- at SAC and UIL? _____________________________

2. Go to http://weather.uwyo.edu
click on **Observations and Images**
Under "region" in the upper-right box, pick **Northwest US**
Under "observations", pick **Station Id** and try to find our three sites (LAR, SAC, and UIL)
Then click on **Topography**
Under "observations", pick **Temperatures**
Under **Hour**, pick 21 Z.

Then fill out the table below. Data from the past 5 days should be available under **Date**. To calculate the average of 5 numbers, you can import them in Excel, or, with a calculator, you sum the 5 numbers and divide the total by 5.

Repeat the same for two other "observations": **dewpoint** and **wind speed**. The dewpoint is a measure of the amount of water vapor in the air, as will be discussed later in class. The higher the dewpoint, the more humid the air is, and the heavier the precipitation can be.

variable	**date**	**Laramie (LAR)**	**Sacramento CA (SAC)**	**Quillayute WA (UIL)**
temperature (ºF)				
average	**5 days**			
dewpoint (ºF)				
average	**5 days**			

variable	**date**	**LAR**	**SAC**	**UIL**
wind speed **(kts)**				
average	**5 days**			

3. Next, interpret these <u>weather</u> observations, in terms of weather events, and in terms of <u>climate</u> differences between these 3 places.

a. Indicate which place is the warmest, the coldest, *on average*, for the five days; the most dry and the most humid; the most and the least windy:

warmest: ____________________ coldest: ____________________

most humid air: ____________________ driest air: ____________________

windiest: ____________________ least windy: ____________________

b. Now summarize what the weather was like at these 3 places. Do this as if you had visited the places and you wanted to tell about how one place was different from the others.

Laramie: ____

____

Sacramento: ____

____

Quillayute: ____

____

c. Indicate the dominant type of *air mass* that affected each of these 4 places during the three days that you took observations. You can choose between 4 types of air masses:

- Continental Polar (cP): cold and dry
- Maritime Polar (mP): cold and wet
- Continental Tropical (cT): warm and dry
- Maritime Tropical (mT): warm and humid.

Laramie: ______ Sacramento: ______ Quillayute: ______

d. (extra credit) Discuss whether your observations are typical, or whether there was an unusual spell of weather at any of these three places. Of course this assumes a knowledge of what is typical of these places at this time of the year. In other words, you need to know something about the *climatology* of the place. Because this question is more advanced, it can only give you extra credit. If you need more space, write on the back of this page.

ATSC 2000 Lab II Section: Mon. / Thurs. (Circle) **Name:**

2. Temperature Structure of the Lower Atmosphere

Pre-lab Assignment

Before the Lab: Read pages 16 –17 of Chapter 1 in *Meteorology - Understanding the Atmosphere* by S. A. Ackerman and J. A. Knox and this lab assignment. Answer the ***pre-lab questions*** on this page and turn in this page at the beginning of your lab period.

Pre-Lab Questions
Answer these questions based on the information given in the text of this lab assignment.

1. What is the name of the instrument that is used to provide the data for this lab assignment that measures vertical profiles of temperature, dewpoint, and wind?

2. What is the vertical resolution (the vertical distance between *successive* observations) of the measurements made by this instrument?

3. At what Z time are these type of measurements typically made around the world?

4. What are the two lowest layers of the atmosphere called?

5. What is the name of the boundary that separates the layers named in question 4?

ATSC 2000 Lab II Section: Mon. / Thurs. (Circle) Name ……………………………

2. Temperature Structure of the Lower Atmosphere

Main Lab Assignment

I. Introduction

The vertical profile of atmospheric temperature, dewpoint (a measure of the moisture content of the air), and wind speed and direction can be measured using an RS-80 radiosonde carried by a helium-filled rubber balloon. The photograph in Figure 5.6 on page 133 your text shows a balloon and radiosonde being launched. The radiosonde measures pressure, temperature, and humidity directly. The temperature and humidity are measured with two small devices on the "silver tongue" of the instrument. The pressure is measured with an aneroid barometer located inside the instrument. Winds are calculated by receiving long wavelength radio transmissions from several stations located around the Earth. As the instrument is in flight these data are reported back to the ground station using radio telemetry, broadcasting at approximately 403 MHz. The data are received every 30 s during flight, corresponding to a measurement approximately every 150 m, by a MicroCora receiving station, which calculates the balloon altitude from the temperature and pressure data using an equation called the hydrostatic equation.

Instruments of this type are flown twice a day at some 60 locations around the United States and at 600 locations worldwide. The flights are all made at the same time 0000 and 1200 Z, corresponding to 1700 and 0500 MST (Mountain Standard Time) or 1800 and 0600 MDT (Mountain Daylight Time). The soundings in Wyoming are made at Riverton. The data from all of these soundings are collected within a matter of hours at a central location. In the United States this is the National Centers for Environmental Prediction in Camp Springs, Maryland. These data are then used to provide information for mathematical descriptions of the atmosphere that computationally simulate atmospheric behavior and give forecasts of the weather.

II. Objectives

This Lab’s goals are:

(1) to explore how values of the pressure (p), temperature (T), and other parameters that characterize the state of the atmosphere vary with height.
(2) to understand how to import data in EXCEL, and how to generate scatterplot charts.
(3) to understand the temperature *‘lapse rate’* and determine how it varies with height.
(4) to use observational data to identify the boundary between the two lowest layers of the atmosphere.

III. Data collection and display

You will obtain recent radiosonde data at Key West, Florida, import the data into EXCEL, and plot the temperature, dewpoint, winds, and pressure as a function of altitude. Then you will identify the troposphere, the tropopause, and the lower stratosphere. You will then be able to calculate the temperature lapse rate (the rate at which temperature changes as a function of altitude) for the troposphere and the stratosphere.

Your instructor will help you with the four steps involved in plotting the data:

A. *Collect the data*. Go to http://weather.uwyo.edu/ . Click on **Upper air observations**, then on **Soundings**. Pick today’s 12 UTC sounding at Key West (labeled EYW on the map) at the bottom end of Florida. Make sure that the type of plot is set at: **Text:List**. The textfile will pop up. When saving this file select “Text File.txt” under **save file as**. Save this file on your desktop as **sounding.txt.** Delete the text above and below the measurements so that when it is imported into excel, the data can be easily converted to columns.

B. *Import the data into Excel*. Open EXCEL, go to **Data**, then click on **From text.** An **Import text file** window pops up. Then navigate to and click on the file **sounding.txt**. At step 2 of 3; scroll down to make sure that enough placement has been allowed for the entire **Height** column. This can be done by clicking and holding the arrow under the digit 10 and sliding it left to 9. Then follow the default data import options of the wizard (click on **next** each time, till you see **finish**). You should have all the sounding variables in separate columns. Let's identify what they are.

- PRES (hPa): air pressure
- HGHT (m): height above sea level
- TEMP (ºC): air temperature in Celsius
- DWPT (ºC): dewpoint temperature, or dewpoint for short, also in Celsius: it is the temperature at which the air becomes saturated
- RELH (%): relative humidity, a relative measure of the water vapor content in the air. It is expressed as a percentage of the maximum (saturation) amount of water vapor in the air.
- MIXR (g/kg): the water vapor mixing ratio, the amount of water vapor (in grams) present in each kilogram of dry air)
- DRCT (deg): the wind direction: northerly (or from the north) is zero, an easterly wind is about 90, a southerly wind about 180, and a westerly wins is about 270. A northeasterly wind has DRCT of about 45 degrees, etc.
- SKNT (knots): the wind speed

The three remaining columns (THTA, THTE, THTV) are not relevant to this lab.

D. *Plot temperature and dewpoint vs. height (scatterplot).* In EXCEL, go to **insert**, then **Scatter**, then **Scatter with Smooth Lines and Markers**. Then right click on the graphics window and click on **Select data**, and click on **Add**. Click on the small icon to the right of **x values**. This allows you to select the column in the spreadsheet pertaining to your x-axis. Then choose temperature for your x-axis (highlight all values in the TEMP column), and height for the y-axis (highlight all values in the HGHT column) using the same procedure in selecting HGHT values as you did TEMP. Give this series a name ('temperature') and **add** a second series. This time plot dewpoint (DWPT) on the x-axis, and again height (HGHT) on the y-axis. **Next** you can label the x- and y- axis and you can take various steps to improve the layout of the chart. Then right click on the chart and click on **Move chart**, then click on **New sheet**. You can give the two lines different colors, but that is not needed. They can both be black. If you desire, you can change the background color from grey to white to save some printer ink!

E. *Print your temperature & dewpoint profile* (ask the instructor with the choice and location of the printer if there are troubles). **YOU MUST INCLUDE THIS PRINT-OUT IN THIS ASSIGNMENT. MAKE SURE TO INCLUDE YOUR NAME ON THE GRAPHS**.

IV. Analysis of the plotted data

1. Label the troposphere and stratosphere on your temperature profile graph, using brackets to denote the entire layer. Also, label the one height that best corresponds to the tropopause.

2. How did you identify the tropopause from your graph of temperature versus altitude?

3. Could you have identified the tropopause based on a graph of pressure versus altitude alone? Why or why not?

4. Calculate the rate of cooling with increasing height (the 'lapse rate' or LR, expressed in °C per km), for the segments of the sounding listed below. Use the following formula for the rate of cooling with altitude (Z):

$$LR = \frac{-1000 * (T_{upper} - T_{lower})}{Z_{upper} - Z_{lower}}$$

Here T is temperature (TEMP) and Z height (HGHT). For instance, let's calculate the LR from the surface to 4 km. Here 'upper' refers to 4 km (or as close as possible to it) and 'lower' to the first row listed near the surface. Within EXCEL you can calculate the LR. Just pick and empty box below the data, and type in:
=-1000*(click-click)/(click-click)
where each 'click' refers to a mouse-click on the box in the EXCEL sheet that contains the number you are looking for, starting with TEMP @ 4 km. Ask your instructor if you get stuck.

As always, add the UNITS to your numerical answer.

4a. *LR* (surface to 4 km):

4b. *LR* (surface to tropopause):

4c. *LR* (tropopause to the top of the sounding):

4d. How do the lapse rates calculated above in questions 4b and 4c compare with that discussed in the section entitled *Dividing Up the Atmosphere* in your textbook (pages 16 to 17)? Does your temperature profile correspond to the lower part of the graph in Figure 1.14?

4e. A positive lapse rate implies that the air temperature <u>decreases</u> with height. How could you determine the sign of the lapse rate by just looking at your temperature profile (without doing any calculations)?

4f. Look at the temperature and dewpoint profiles on your print-out. Does the dewpoint at any height exceed the air temperature for the same height? Discuss what would happen if the dewpoint was larger than the temperature.

5a. Repeat EXCEL step D above: now generate a new XY (scatter) plot, but plot pressure (PRES) on the x-axis, and height (HGHT) on the y-axis. Again label the x- and y-axes of the plot appropriately, and draw a smooth line connecting the dots. Print this sheet and **INCLUDE THE PRINTOUT** in this assignment.

Calculate the rate of decrease of pressure with height (dp/dz, expressed in hPa per km), using a similar formula as used for problem 4, but replacing the temperature values with pressure values:

$$\frac{dp}{dz} = \frac{1000 * (p_{upper} - p_{lower})}{(Z_{upper} - Z_{lower})}$$

5b. ${}^{dp}\!/_{dz}$ (1 km to 2 km, or the closest HGHT values to these):

5c. ${}^{dp}\!/_{dz}$ (9 km to 10 km, or the closest HGHT values to these):

5d. Does the sign of the rate of decrease of pressure change with height?

5e. How does the magnitude of the rate of change of pressure change with height?

5f. Would you call the decrease of pressure with height in the 12 UTC Key West sounding <u>a smooth linear decay, a smooth exponential decay, or an irregular decay</u> (like the dewpoint for instance, see your dewpoint profile)?

5g. How do your answers to the questions 5a-5f above fit within the context of the discussion of the rate of pressure change with height in the textbook (pp. 14 to 16)?

6a. Repeat EXCEL step D above: now generate a new XY (scatter) plot, but plot mixing ratio (MIXR) on the x-axis, and height (HGHT) on the y-axis. Again label the x- and y-axes of the plot appropriately, and draw a smooth line connecting the dots. Print this sheet, and **INCLUDE THE PRINTOUT** in this assignment.

How does the water vapor mixing ratio vary with height above the surface up to the tropopause and above?

6b. How much more water vapor is there near the surface, compared to layers in the upper troposphere? Hint: look at the column ‘MIXR’ in the EXCEL spreadsheet and find the highest value of MIXR, at or near the surface, as well as the lowest value near the tropopause.

highest value:

lowest value:

ratio (lowest / highest):

6c. Clearly the upper troposphere is an extremely dry environment: there is hardly any water vapor. Now if the air were to rise from near the surface to the upper troposphere, and if it were to cool following the temperature profile that you plotted, its dewpoint would have to decrease accordingly. What happens to all the water vapor that has to condense?

6d. Look at the column of relative humidity values (RELH). Does the relative humidity decrease as rapidly with height as the mixing ratio? Describe how the relative humidity varies: does the change in relative humidity mirror changes in mixing ratio, or do you still find high values of relative humidity at some levels in the middle and/or upper troposphere?

7a. Describe how the *wind speed* (SKNT) **generally** varies with height from the surface up to the top of the sounding. In what region of the atmosphere does the sounding indicate the highest wind speeds?

7b. **Generally** describe the changes in *wind direction* (DRCT) above the surface, referring to wind direction by the conventional points of the compass (e.g., a north-west wind is from the northwest, the angle is about 315 degrees).

Extra Credit: Numerical weather prediction relies on the frequent measurement of temperatures, winds, and humidities in the middle and upper troposphere. Higher accuracy can be achieved by releasing radiosonde balloons more frequently, and from more locations. What do you think the principal drawback is of relying solely on this strategy?

IV. Take-home Exercise for Lab II Section: Mon. / Thurs. (circle) **Name:**

Post-Lab Assignment

(Hand this in for grading at the beginning of next week's lab together with the Pre-lab for lab 3)

For this section of the lab you will need to use an online computer. Go again to: http://weather.uwyo.edu.

Click on the **Upper Air Observations** button. Now click on **Soundings** to display a map of North America. Above the map are boxes to select the format of the desired product you wish to view. The default settings in the year/month/time boxes should allow the latest information to be obtained. Select **GIF:Stuve** for the Type of Plot and view the latest sounding from Rapid City, SD, by clicking on RAP on the map.

1. The displayed sounding shows the temperature (°C) and dewpoint profiles for RAP. Remember, for every height, the air temperature is never less than the dewpoint. Note that the temperature is plotted as a function of pressure instead of height. This is a common format used by meteorologists for sounding data. Meteorologists will then refer to a height in the atmosphere by a pressure rather than an actual height. What is the pressure (P_{trop}, hPa) and temperature (T_{trop}, °C) at the tropopause for this sounding? (Also list the Z time and date of the sounding).

RAP Sounding Date: Time: P_{trop}: T_{trop}:

2. Now view the soundings for Brownsville, TX, (BRO), on 4 July of last year and Barrow, Alaska (PABR), on 25 December of last year. What is the pressure (P_{trop}, hPa) and temperature (T_{trop}, °C) at the tropopause for each of these soundings? (Again, be sure to list the time and date of the sounding).

BRO Sounding Date : 4 July 20__ Time : 00 UTC P_{trop}: T_{trop}:

PABR Sounding Date:25 Dec 20__ Time : 00 UTC P_{trop}: T_{trop}:

3. Typically, the tropopause height is lower for observations made closer to the poles and higher for observations made in the tropics. We might therefore expect that the pressure at the tropopause would decrease as we go from PABR to BRO. How does P_{trop} vary for the three soundings you have viewed? How do the three tropopause temperatures vary?

4. Describe the temperature lapse rate (LR) at the three soundings examined above, in the lower troposphere (say from the surface to 700 mb). Indicate whether the **LR is high** (rapid cooling with height, which may imply thunderstorms), **medium**, or **low** (little cooling with height, i.e. it is stable). An extreme case, even more stable than the low LR case, is an **inversion** (temperature increases with height).

PABR:

RAP:

BRO:

Don't forget to complete the Pre-lab Exercises for Lab 3 before next week!

ATSC 2000 Lab III Section: Mon. / Thurs. (Circle) **Name:**

3. Radiative Energy Transfer

Pre-lab Assignment

Before the Lab: Read all pages of Chapter 2 in *Meteorology - Understanding the Atmosphere* by S. A. Ackerman and J. A. Knox of the textbook, and this lab assignment. Answer the ***pre-lab questions*** below.

Pre-Lab Questions

Answer these questions after you've read the text of this lab assignment (NEXT TWO PAGES) and the recommended readings. *Turn in this page at the **beginning** of lab.*

1. What is the source of the Earth/atmosphere system's energy?

2. How does *longwave* radiation differ from *shortwave* radiation?

3. If we conduct the experiment described in this lab for a long enough period of time the temperature of the plate will eventually remain constant. Why?

4. List four factors that determine the energy *input* to the plate for the experiment described in this lab.

5. List two energy loss processes for the plate in the experimental set-up.

ATSC 2000 Lab III Section: Mon. / Thurs. (Circle) Name ……………………………

3. Radiative Energy Transfer

Main Lab Assignment

I. Introduction

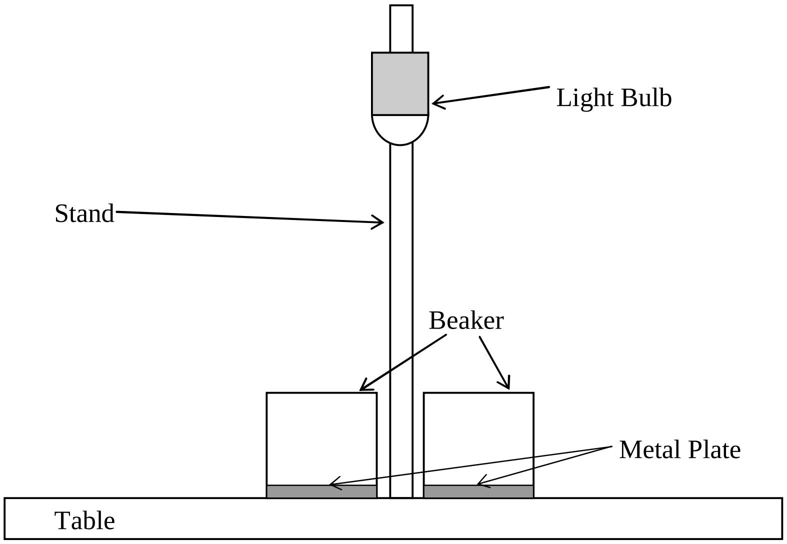
The Earth/atmosphere system receives almost all of its energy as so-called 'shortwave' radiation from the sun. This energy input is approximately balanced by the loss of energy to space from the Earth/atmosphere system by emitted 'longwave' radiation. Other forms of energy transfer such as conduction, convection, and evaporation, which occur between the Earth and the atmosphere, are not possible between the Earth/atmosphere system and space due to the lack of a medium for energy transfer.
In this lab we perform an experiment to illustrate the impact of shortwave radiation on a system. We also explore the role of other energy transfer processes.

Lab Goals:

(1) Learn about factors that affect how objects both acquire and lose energy.
(2) Understand how the rate of temperature change of an object depends on both the rates of energy input and loss from the object (the *energy budget* of the object).
(3) Gain more experience in drawing logical conclusions from experimental observations, and in performing experiments to illustrate physical concepts.

II. Lab Set-up

In this lab we use a light bulb to provide radiant energy, which is primarily in the form of visible light. The radiant energy from the light bulb heats a metal plate, which, in turn, heats the air above the plate. Below is a sketch of the experimental setup.



A thermometer is inserted into a hole in the edge of each metal plate, so that changes in the temperature of the plate with time can be recorded. If the plate were somehow to be perfectly insulated, and not lose energy or heat to the surroundings, we might expect its temperature to continue to rise steadily as it absorbs more and more radiant energy from the light bulb. However, this is not the case because other forms of energy transfer occur. In particular, sensible heat (as defined on pg. 30 of the text) and longwave radiation are lost from the plates, in addition to the input of energy via visible light absorption. These energy loss processes cause the heating rate to vary with time. Initially we might expect that the rate of temperature increase of our plates will be nearly constant since the energy loss processes will be minor. However, as the sample warms up, the energy loss processes will become increasingly significant as the temperature differences between the plates and the surroundings become larger, so that the rate of temperature increase of the plates will decrease. Eventually a balanced state will occur where the energy input to the plate is exactly equal to the energy loss from the plate. When this *equilibrium* (a balanced state) is reached, the temperature of each plate will remain constant. We do not have enough time during the lab period for this to happen, but we should be able to notice a change in the heating rate with time.

Several factors influence the energy input to the plates, as follows:

1. The energy output from the light bulb, which is related to the wattage of the bulb.

2. The distance of the light from the sample. Increasing the distance decreases the amount of energy being received by the plate, because the same amount of energy is being spread over an ever increasing area as the distance between the light and the sample increases.

3. The amount of visible light reflected. If the surface of the plate is white, then a significant fraction of the incoming energy will be reflected, in the same way that a snow covered surface with a high albedo reflects much of the incident sunlight. Alternatively, if the plate is black, very little of the incoming energy is reflected.

4. The angle at which the light strikes the plate surfaces. If the light is directly overhead, then the radiation is spread over a small area. As the angle increases the area illuminated also increases, and the amount of energy received by a fixed area decreases. This principle also applies to the illumination of the Earth's surface by the sun. Thus, a given area of the Earth's surface receives less solar radiant energy in winter when the elevation angle of the sun is low and the sun's rays strike the surface at an oblique angle. This is one of the two principal factors that give rise to seasonal variations in climate. The second factor concerns the number of hours of daylight. Fewer hours of daylight result in a reduced energy input.

How does the system lose energy?

1. All objects emit radiation. The amount of radiation emitted increases as the temperature of the object increases, in accordance with the Stefan-Boltzman Law. For objects with temperatures similar to those experienced on the Earth, this radiation is *longwave*, infrared radiation (Wien's Law). The sample therefore emits longwave radiation.

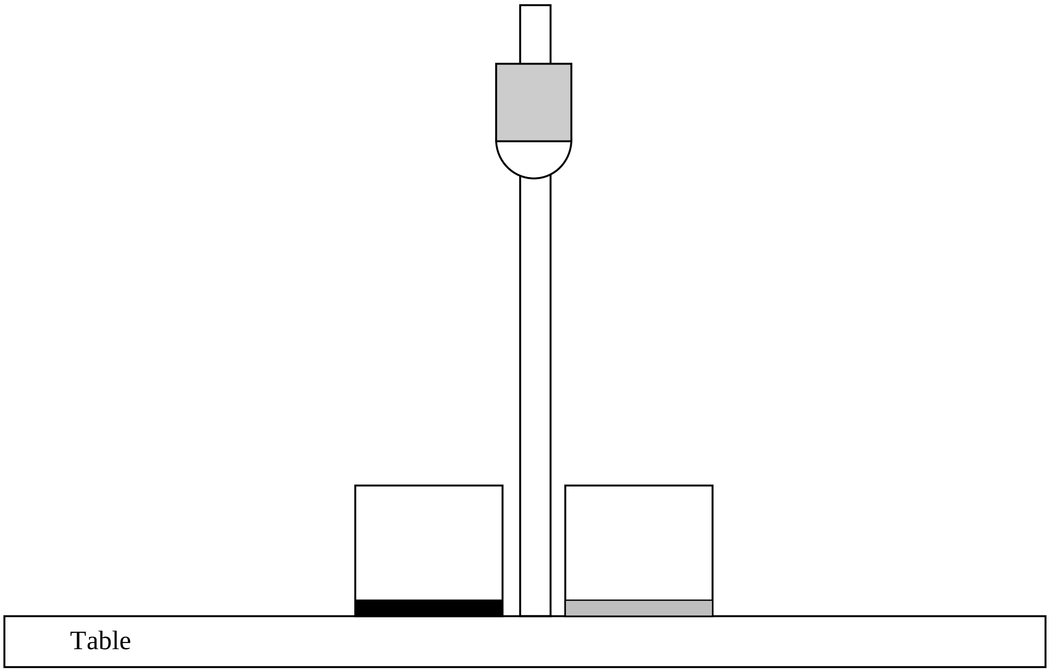
2. If the temperature of the plate differs from the surroundings (the air, the table, etc.) then energy will be transferred from the warmer object to the colder object by conduction and also, for fluids (e.g., air), by convection. The rate of energy transfer by these processes increases as the temperature difference increases.

III. Exercises

In the table below keep a record of the changes in temperature of the plates with time during the experiment. You should record a new temperature and time every minute for each plate so that you can subsequently produce a smooth graph. Start by recording the black plate temperature after 0.5 minutes. While you are recording this data you may be able to start to answer the questions on the next page.

TIME	TEMPERATURE (°C)			TIME	TEMPERATURE (°C)	
MINUTES	BLACK	WHITE		MINUTES	BLACK	WHITE
0				10.5		▨
0.5		▨		11.0	▨	
1.0	▨			11.5		▨
1.5		▨		12.0	▨	
2.0	▨			12.5		▨
2.5		▨		13.0	▨	
3.0	▨			13.5		▨
3.5		▨		14.0	▨	
4.0	▨			14.5		▨
4.5		▨		15.0	▨	
5.0	▨			15.5		▨
5.5		▨		16.0	▨	
6.0	▨			16.5		▨
6.5		▨		17.0	▨	
7.0	▨			17.5		▨
7.5		▨		18.0	▨	
8.0	▨			18.5		▨
8.5		▨		19.0	▨	
9.0	▨			19.5		▨
9.5		▨		20.0	▨	
10.0	▨					

1. Add arrows to the sketch of the experimental setup, to illustrate the fluxes of energy to and from the plates. Label each of the fluxes represented by the arrows according to the type of energy being transferred.



2. How do the various energy fluxes change with time? List fluxes that stay constant during the course of the experiment and those that change during the experiment.

3. How would you know if the energy input was being balanced by the energy output?

4. Graph the values of temperature versus time on the next page. The slope of the line is a measure of the *net* rate of energy input to the plate. A slope that is more perpendicular to the x-axis indicates significant change over time whereas a slope more parallel to the x-axis indicates a slower rate of change.

4a. Is the net (incoming less outgoing) rate of energy input constant during the experiment? How do you know?

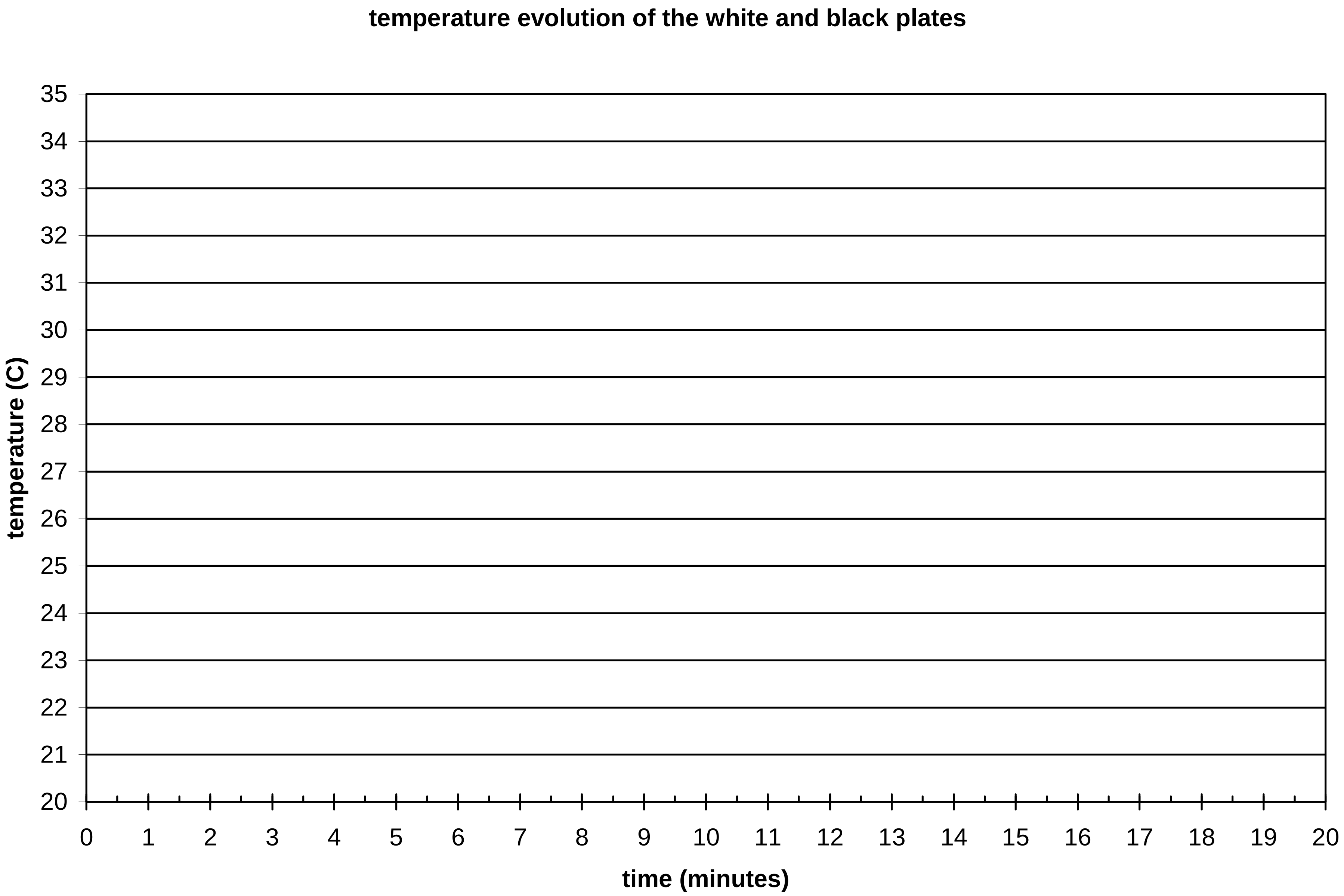
4b. How does the net rate of energy input change with time? Why does it change in this manner?

4c. What would happen to the initial rate of temperature change if the light bulb were replaced with a higher wattage bulb?

4d. How did the rate of temperature change differ between the two experiments (high albedo and low albedo cases)?

4e. What is the fundamental reason why the rates of temperature change of the two plates differed?

5. How would you change the experimental set-up to simulate the seasonal changes in radiation experienced by the Earth?


temperature evolution of the white and black plates
temperature (C)
35
34
33
32
31
30
29
28
27
26
25
24
23
22
21
20
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
time (minutes)

Lab III Section: Mon. / Thurs. **Name:**

Post-Lab Assignment

Satellites can be used to monitor radiation fluxes to and from the Earth/atmosphere system. For these exercises you will look at some examples of satellite images that make use of these fundamental ideas.

You will need to log on to a computer that has an Internet browser. Go again to http://weather.uwyo.edu.

Click on **Observations and Images,** to access the satellite images page. Satellite images are classified as either visible (produced from *reflected* visible radiation) or infrared (IR, produced from *emitted* longwave radiation). Of course, the planetary surface can only be viewed as a visible image when it is illuminated by a light source (the sun), so that visible images are available only during daytime. On the other hand, IR satellite images are a measure of the amount of radiation being *emitted (not reflected)* from objects in the satellite's field of view. Since all objects emit radiation both night and day, IR images are available both during the day and at night.

For visible satellite images, areas represented by light tones are areas where a large amount of the incoming visible light is being reflected back to space (high albedo). Areas with a high albedo are typically either cloud covered or snow covered.

The IR satellite images show the amount of radiation being emitted in the infrared part of the electromagnetic spectrum. Since the amount of radiation emitted increases with increasing temperature, areas emitting large amounts of radiation have high temperatures, whereas areas emitting smaller amounts of radiation have low temperatures. The image is coded such that *dark* areas represent regions of large IR emission (high temperature) while *light* areas (or color-coded areas) represent regions of small IR emission (cold temperature). Sometimes a scale on the bottom of the image is shown to indicate the range of brightness temperatures displayed.

1. View the visible satellite image from 18Z, by selecting
Conterminous US
Visible Sat
Date: pick the date of yesterday
Hour: 18 Z

1a. Describe the areas of the US covered by clouds or snow.

1b. How can areas covered by clouds and/or snow be distinguished from other parts of the image?

1c. Identify a large land area that is not covered by either clouds or snow. List that area here.

2a. Now return to the satellite image menu. Click on **Infrared Sat**. How do the temperatures of the cloud-covered areas differ from the non-cloud-covered region you identified in question 1c in the image?

2b. How does your answer to question 2a fit within the context of our knowledge that temperature generally decreases with height in the troposphere?

3a. Return to the satellite image menu and view the IR satellite images for 12Z and 20Z. How does the temperature of the cloud free area, identified in question 1c, change between 12Z and 20Z?

3b. Explain why this temperature change is observed. *Hint: Remember that local times in the USA lag behind UTC time.*

Note: *There is a take-home lab next week. Review the instructions for handing in the completed lab well in advance!*

ATSC 2000 Lab IV Section: Mon. / Thurs. (Circle) **Name:**

4. The Greenhouse Effect

*This is a 'Take-Home Lab' and can be completed in your own time. Attendance at lab during the regularly scheduled lab period is **not** required. However, your TA will be in attendance and you can receive guidance at the beginning of the lab session if you so desire.*
Hand in your completed lab to your TA no later than the first lecture meeting after your Lab normally meets. For instance, if your lab session is on Tuesday, and your lectures are on TTH, then the Lab Assignment is due two days later, on Thursday. Take home assignments handed in late will be subject to a penalty, if accepted at all.

Note that to complete the lab you must have access to the internet.

Before the Lab: Review all pages of Chapter 2; read all pages of Chapter 15 in *Meteorology - Understanding the Atmosphere* by S. A. Ackerman and J. A. Knox of the textbook and this lab assignment. You may also want to read the sections pertaining to Global Warming in the text (pp. 453 - 455).

I. Introduction

Global warming, caused by greenhouse gases and particulates that absorb sunlight, is a topic frequently discussed in the mass media. Predictions of warming of several degrees Celsius are often reported. In this lab we will explore the causes of the greenhouse effect using a simple model of the Earth/atmosphere system.

Scientists, including meteorologists, often construct simple mathematical models of complex systems in order to study their behavior. A model is just a simplified mathematical description of a real system, such as the atmosphere of the Earth. To produce a model, simplifying assumptions are made concerning the physical processes that occur within the system to be modeled. For today's lab we will use a model of the radiative transfers that occur between the Earth, the atmosphere, and space. Using this model we can "experiment" with different configurations of the system, such as increased greenhouse gas concentrations. Whenever a model is used it is important to realize that because the model is a simplification of the real system, the results of the model experiments may not be completely accurate.

Lab Goals:

1. Understand what causes the 'greenhouse effect'.
2. Realize that physical phenomena can often be described by mathematical models that simulate their behavior under both existing and changing environmental conditions.
3. Explore the nature of solar energy entering Earth's atmosphere, and how it affects both surface and atmospheric temperatures.

II. Review of the Greenhouse Effect

Recall from Chapters 2 and 3 that solar energy is the dominant source of energy for the Earth/atmosphere system, excluding a small contribution from radioactive decay in the Earth's crust. Approximately 30% of the solar energy that enters the top of the atmosphere is reflected back to space by the atmosphere and the surface of the Earth. This reflected radiant energy therefore plays no part in the energy budget of the Earth/atmosphere system. The fraction of the incoming solar energy reflected by the Earth/atmosphere system is referred to as the planetary albedo. Most of the non-reflected solar radiation passes through the atmosphere and is absorbed at the surface of the Earth.

Since the average temperature of the Earth remains relatively constant from year to year, we know that the amount of energy received at the surface must be balanced by an equal amount of energy that is lost. This loss of energy is in the form of longwave radiation as well as sensible and latent heat fluxes. Longwave radiation is strongly absorbed in the atmosphere by greenhouse gases, such as water vapor and CO_2. In addition, because the temperature of the atmosphere is not changing very much from year to year, the energy gained by the atmosphere from longwave radiation from the Earth and by sensible and latent heat fluxes from the surface must be balanced by equal energy losses. These losses occur as longwave radiation that is directed both out to space and back to the surface of the

Earth. The emission of longwave radiation from the atmosphere back to the surface of the Earth results in the greenhouse effect. The greenhouse effect keeps the surface of the Earth substantially warmer than it would be if the atmosphere contained no gases that absorbed longwave radiation. In this lab we will calculate the temperature of a planet identical to Earth, except that its atmosphere contains no greenhouse gases.

If the amounts of atmospheric greenhouse gases were to increase, it would be expected that the amount of longwave radiation trapped by the atmosphere would increase, and that the temperature of the Earth/atmosphere system would warm. Again, we will conduct a number of experiments in the lab to test this theory, using our simple model of the Earth/atmosphere system.

III. The Model

As stated above, a model is a simplified description of a real system, written in the language of mathematics. We are interested in modeling the transfer of radiation to, from, and within the Earth/atmosphere system. To do this we will make the following assumptions:

(a) No atmospheric motion occurs. Since sensible and latent heat fluxes require atmospheric motion, these fluxes will be equal to zero in our model.

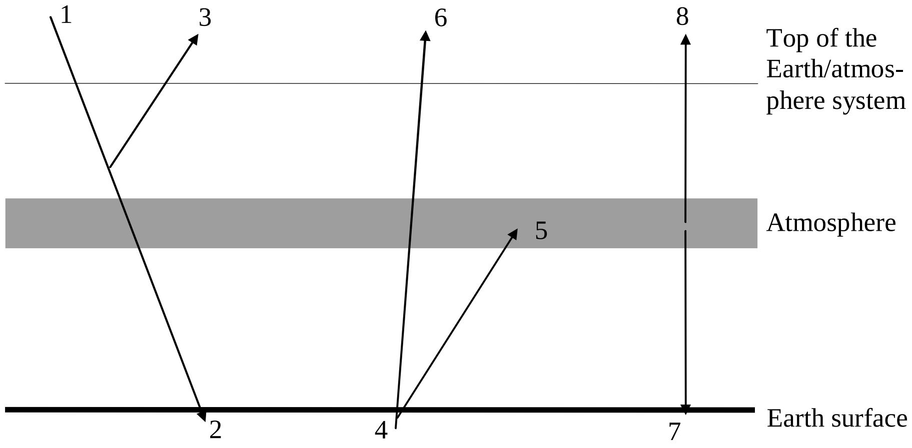
(b) The atmosphere is entirely transparent to shortwave radiation so that it does not *absorb* any solar radiation. It can, however, contribute to shortwave *reflection*.

(c) The amount of longwave radiation absorbed by the atmosphere increases as the concentration of greenhouse gases increases.

(d) The atmosphere is treated as a single layer, with one average temperature and constant radiative properties (i.e. no absorption of shortwave radiation and a fixed value of absorption for longwave radiation). More complex models could be constructed that treat the atmosphere as multiple layers.

The model then is just a set of mathematical equations that describe the physical processes of the simplified system. All models require input, or values that describe some initial condition of the system. The required inputs for the model used in this lab are the incoming solar radiation, the planetary albedo, and a value for the extent of longwave absorption by the atmosphere. We will vary these input values to determine their impact on the final state of the system.

Below is a diagram that represents the radiative fluxes in our model for the assumptions listed above.



The numbers in the diagram refer to the following radiative fluxes:

1. Incoming solar radiation
2. Solar radiation absorbed at the surface
3. Reflected solar radiation
4. Emitted longwave radiation from the surface
5. Longwave radiation absorbed by the atmosphere
6. Longwave radiation emitted from the surface to space
7. Longwave radiation emitted from the atmosphere to the surface
8. Longwave radiation emitted from the atmosphere to space

A list of equations that are used to calculate these radiative fluxes is given in the last page of this lab. You do not need to be able to understand these equations to complete this lab successfully. They are included for students interested in understanding the model used.

IV. Exercises

Before starting the lab, answer the following questions after you have read the relevant sections of the textbook and the above introductory material.

1. What would happen to the temperature at the surface of the Earth if no greenhouse gases were present in the atmosphere?

2. Describe in a few words what is meant by the term ‘model’, as used in this lab assignment?

3. What assumptions are made for the model of radiative transfer used in this lab?

The equations which describe our model have been programmed into an interactive spreadsheet that you can access at http://www.atmos.uwyo.edu/~geerts/atsc2000/lab/.

For this assignment the incoming solar radiation will be 341.8 Wm^{-2}, and will not be varied for our experiments. Use the following input pairs of values for the Albedo and the Longwave Absorptivity for the five indicated experiments. (Just enter these values in the appropriate boxes (rows #2 and #3) on the spreadsheet).

Experiment	**Planetary Albedo**	**Longwave Absorptivity**
1. Atmosphere with No Greenhouse Gas	0.30	0.00
2. Current values	0.30	0.77
3. Doubled CO_2	0.30	0.82
4. Doubled CO_2 with cloud feedback	0.40	0.82
5. Doubled CO_2 with ice cap feedback	0.25	0.82

4. Input the values from the table above, and use the model output in the Results column of the spreadsheet to complete the following tables:

Solar Radiation Fluxes (W m^{-2})

Experiment	**incoming solar radiation**	**solar radiation absorbed at the surface**	**reflected solar radiation**
1	341.8		
2	341.8		
3	341.8		
4	341.8		
5	341.8		

Longwave (LW) Radiation Fluxes (W m^{-2})

Experiment	LW radiation emitted from the surface	LW radiation from surface absorbed by the atmosphere	LW radiation emitted from the surface to space	LW radiation emitted from the atmosphere to surface	LW radiation emitted from the atmosphere to space
1					
2					
3					
4					
5					

Temperature

Experiment	**Surface Temperature**		**Atmospheric Temperature**	
	K	**°F**	**K**	**°F**
1				
2				
3				
4				
5				

5. For each of the experiments, draw a simple diagram of the fluxes. It should be similar to the one on page 3. Include just the *non-zero* radiative fluxes computed for each experiment. In other words, if there is no flux, do not draw that arrow. Label each arrow with its corresponding flux value.

Experiment 1: Atmosphere with No Greenhouse Gases

Experiment 2: Current Values

Experiment 3: Doubled CO_2

Experiment 4: Doubled CO_2 with Feedback Resulting from Increased Cloud Cover

Experiment 5: Doubled CO_2 with Feedback Resulting from Decreased Ice Cap Area

6a. How does the surface temperature change when the current concentrations of gases that absorb longwave radiation are added to the atmosphere? (Compare experiments 1 and 2).

6b. What name is given by meteorologists to this effect where the atmosphere can modify surface temperatures?

6c. Name *five* important trace atmospheric gases that can promote this effect. (See pp. 5 – 10, if necessary).

7a. What happens to the atmospheric temperature as the amount of absorption of longwave radiation in the atmosphere is increased in the experiments?

7b. Explain, with physical reasoning, why this change is observed.

7c. What happens to the surface temperature as the amount of absorption of longwave radiation in the atmosphere is increased in the experiments?

7d. Explain, with physical reasoning, why this change is observed.

8a. Experiment 4 simulates the effect of increased cloud cover. How is this achieved?

8b. Why does the planetary albedo increase when the cloud cover increases?

8c. How does the change in planetary albedo affect the surface temperature?

8d. Is the change in cloud cover, caused by global warming, a positive or negative feedback to the initial warming? In other words, does an increase in cloud cover caused by global warming, lead to enhanced or reduced warming, and the formation of even more or fewer clouds? Why?

8e. Why might cloud cover increase if global warming were to occur?

9a. Experiment 5 simulates the effect of a reduction in the area covered by the polar ice caps on a globally warmed planet. How does the planetary albedo change?

9b. Why does the planetary albedo change in this way?

9c. How does this change in planetary albedo affect the surface temperature?

9d. Is the change in the polar ice caps, caused by global warming, a positive or negative feedback to the initial warming? Why?

9e. What reason is there to expect that the area covered by ice caps would decrease if global warming were to occur?

V. Albedo Values for Other Planets

In this lab we have explored how the global average surface temperature of the Earth changes as we vary both the albedo and longwave absorptivity of the atmosphere. We would expect that changing these parameters would affect the surface temperatures of the other planets similarly. Of course, the surface temperatures of the outer planets would be expected to be lower than that of Earth because they are further from the Sun, whereas those of the inner planets, Venus and Mercury, would be higher. A graph of average temperature of planets, against their distance from the Sun, can be found at

http://profhorn.meteor.wisc.edu/wxwise/radiation/te.html

The temperature plotted here, on the y-axis, is the *radiative equilibrium temperature* (T_e). It applies to any planet, in the absence of an atmosphere (in other words, longwave absorptivity is ignored, set to 0). As expected, the average temperatures decrease rapidly as the distance from the Sun, plotted on the x-axis, increases. When plotted on a linear scale, the points for the innermost planets fall very close together making them hard to compare. You can appreciate the differences between the surface temperatures more clearly by switching the form of the x-axis to a log scale.

10. The albedo and distance from the Sun of the hypothetical planet Y, shown in magenta, can be varied using the sliders in the top right corner of the graph. Adjust the 'Distance' to be equal to 1.5, corresponding to 150,000,000 km, the average distance of the Earth from the Sun. Notice how the plotted position of planet Y moves as you adjust the slider. Now adjust the albedo to that of the Earth (0.30). Planet Y is now identical to Earth. How does T_{sfc} compare to that computed in Experiment 1 (Earth without greenhouse atmosphere) in the lab?

Please use Kelvin temperature values for this and subsequent questions.

11. How does T_e change as the Earth's albedo varies from 0.0 (completely non-reflecting) to 0.8 (highly reflecting)? What would be the T_e value (in Kelvin) if it were possible for the albedo to increase to a limiting value of 1.0?

12. Reset the albedo to 0.30. The Solar Constant slider allows us to explore the effect on T_e if the Sun were to be dimmer or brighter. The range of values (1100 – 1500 W/m^2) corresponds to a Sun that is 80% - 110% as bright as it is now. How do changes in the Sun's brightness affect T_e? Give the predicted T_e values.

13. In fact, the Sun's brightness varies by only about 0.1% over the 11 year solar cycle, with variations up to 0.6% over several centuries. For more information, check out the NASA web site:

http://science.nasa.gov/headlines/y2003/17jan_solcon.htm?list59237

What do you conclude about the influence of solar variability on the Earth's surface temperature?

14. Now let's take a look at Mars. Adjust the 'Distance' slider to 2.3 (230,000,000 km), leaving the albedo = 0.30, and the solar constant to the current value (1367 W/m^2). What is the predicted T_e for Mars? Is this higher or lower than the T_e value plotted in black? Why is there a difference? Vary the albedo value to give the best agreement with the plotted T_e value. What albedo value do you predict for Mars?

15. Set the 'Distance' slider to 1.1 so that we can look at Venus. What albedo value do we need to select to optimize the calculated T_e value with that plotted?

16. Now take a look at Mercury, a lifeless planet with no atmosphere. What's the optimum albedo value?

17. List the four innermost planets of the solar system in order of *increasing* albedo. What plausible explanation could explain the albedo sequence that you have determined? Note that the albedo values you have determined may differ somewhat from the true ones (Mercury: 0.06; Venus: 0.78; Earth: 0.3; Mars: 0.17). These differences arise from the fact that we have presumed no atmosphere (zero longwave absorptivity value) for all four planets. In fact the longwave absorptivities of Mercury and Mars are less than that of Earth, whereas that of Venus is greater.

Appendix. Equations used in the model

Below is a list of the equations used in the model of radiative transfer for this lab.

$$\mathrm{SW_{in}} = \mathrm{S}/4$$

$$\mathrm{SW_{refl}} = \mathrm{SW_{in}} \cdot \mathrm{A}$$

$$\mathrm{SW_{abs\_sfc}} = (1 - \mathrm{A}) \cdot \mathrm{SW_{in}}$$

$$\mathrm{LW_{up\_sfc}} = \frac{\mathrm{SW_{abs\_sfc}}}{1 - \frac{\mathrm{a}}{2}}$$

$$\mathrm{LW_{abs\_atmos}} = \mathrm{a} \cdot \mathrm{LW_{up\_sfc}}$$

$$\mathrm{LW_{sfc\_to\_space}} = (1 - \mathrm{a}) \cdot \mathrm{LW_{up\_sfc}}$$

$$\mathrm{LW_{atmos\_to\_sfc}} = \frac{\mathrm{LW_{abs\_atmos}}}{2}$$

$$\mathrm{LW_{atmos\_to\_space}} = \frac{\mathrm{LW_{abs\_atmos}}}{2}$$

$$\mathrm{T_{sfc}} = \left(\frac{\mathrm{LW_{up\_sfc}}}{\sigma} \right)^{0.25}$$

$$\mathrm{T_{atmos}} = \left(\frac{\mathrm{LW_{abs\_atmos}}}{\sigma} \right)^{0.25}$$

Definition of Variables

$\mathrm{SW_{in}}$: incoming solar radiation (averaged over surface of Earth)

S : solar constant (1367 W $\mathrm{m^{-2}}$)

$\mathrm{SW_{refl}}$: reflected solar radiation

A : planetary albedo

$\mathrm{SW_{abs\_sfc}}$: solar radiation absorbed at the surface

$\mathrm{LW_{up\_sfc}}$: longwave radiation emitted from the surface

a : longwave absorptivity

$\mathrm{LW_{abs\_atmos}}$: longwave radiation absorbed by the atmosphere

$\mathrm{LW_{sfc\_to\_space}}$: longwave radiation emitted from the surface to space

$\mathrm{LW_{atmos\_to\_sfc}}$: longwave radiation emitted from the atmosphere to the surface

$\mathrm{LW_{atmos\_to\_space}}$: longwave radiation emitted from the atmosphere to space

$\mathrm{T_{sfc}}$: temperature of the surface

σ : Stefan-Boltzman constant

$\mathrm{T_{atmos}}$: temperature of the atmosphere

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5. Humidity Variables

Pre-lab Assignment

Before the Lab: Read all pages of Chapter 4 in *Meteorology - Understanding the Atmosphere* by S. A. Ackerman and J. A. Knox of the textbook and this lab assignment. Answer the ***pre-lab questions*** below.

Answer the questions and *turn in this page at the* ***beginning*** *of the lab session.*

1. List the five humidity variables that are discussed in this lab.

2. What happens to a saturated air parcel if it (a) warms, (b) cools?

3. Define the dewpoint?

4. What is the name of the instrument that will be used in this lab to measure the wet-bulb temperature?

ATSC 2000 Lab V Section: Mon. / Thurs. (Circle) Name ……………………….

Humidity Variables
Main Lab Assignment

I. Introduction

Humidity is a measure of the amount of water vapor present in the atmosphere, at a given time and location. Meteorologists use a number of different variables to represent the amount of moisture in a given sample of air. The use of so many different variables to represent the same basic measurement may seem strange, but each of the humidity variables that will be presented in this lab has their own advantages and disadvantages.

The humidity variables used in this lab include:
- Vapor pressure
- Saturation vapor pressure
- Relative humidity
- Dewpoint
- Wet-bulb temperature

Lab Goals:
1. Learn about humidity variables and their inter-relationships
2. Determine relative humidity both indoors and out, using a psychrometric chart to interpret measurements made with a sling psychrometer

II. Review of Terms

Saturation: A given sample of air (an air parcel) is said to be saturated when the rate of evaporation from a flat surface of water into the parcel is exactly equal to the rate of water vapor condensation onto the water surface, from the air parcel. In the atmosphere any addition of water vapor to a sample of air that is already saturated will result in condensation and the formation of clouds or fog. Therefore, when an air parcel is referred to as "saturated," the air contains the maximum amount of water vapor possible at the prevailing temperature, without condensation occurring.

Vapor pressure (e): The vapor pressure is the pressure exerted by the water vapor molecules in a sample of air. The water vapor pressure contributes to the overall pressure similarly to the pressure contributions from the other gases present (nitrogen, oxygen, argon, etc.)

Saturation vapor pressure (e_s): The saturated vapor pressure is the contribution to the total pressure from the water vapor molecules in a sample of air that is saturated. A given air parcel will have separate values for the vapor pressure and the saturation vapor pressure associated with it. The vapor pressure is a measure of the amount of water vapor *actually* in the air parcel, while the saturation vapor pressure is a measure of the *maximum* amount of water vapor the air parcel could hold at its current temperature. (Remember that the saturation vapor pressure increases as the temperature of the air parcel increases. When the air parcel is saturated the vapor pressure will equal the saturation vapor pressure.

Relative humidity (RH): The relative humidity is a measure of how close the air is to being saturated and is the ratio of the actual vapor pressure to the saturation vapor pressure. (Relative humidity is also given by the ratio of the mixing ratio to the saturation mixing ratio). Because the relative humidity is calculated based on the actual amount of water vapor in an air parcel and the maximum amount of water vapor an air parcel could hold (which depends on the temperature of the air parcel) *the relative humidity will change if either the amount of water vapor present changes or the temperature changes*. This is an important idea to understand. It means that the relative humidity cannot be used when comparing the actual amount of water vapor present at two different locations or times (since the temperature may not have been the same when the two relative humidity measurements were made). If you are interested in comparing the actual amount of water vapor present at two different locations, other humidity variables such as the vapor pressure, dewpoint, or wet-bulb temperature must be used.

Dewpoint (T_d): The dewpoint (or dewpoint temperature) is the temperature to which a sample of air must be cooled at constant pressure in order to become just saturated. By cooling an air sample, the saturation vapor pressure will decrease. If the air is cooled enough, the actual vapor pressure will become equal to the saturation vapor pressure and the air sample will be saturated.

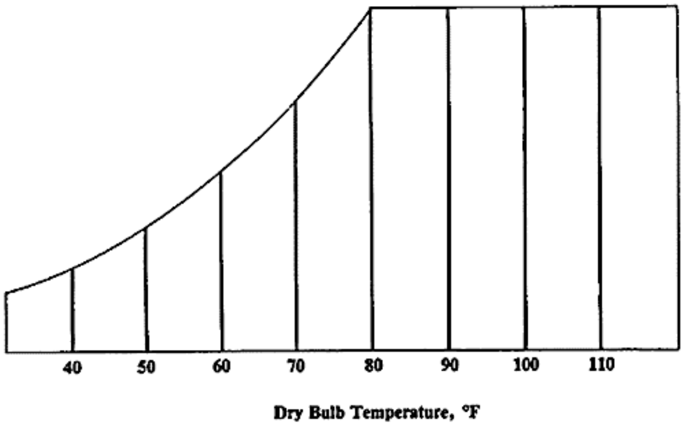
Wet-bulb temperature (T_w): The wet-bulb temperature is the temperature a wetted thermometer bulb measures when exposed to a steady stream of air. The wet-bulb temperature will be measured in this lab with a *sling psychrometer*.

III. Determination of Humidity Variables

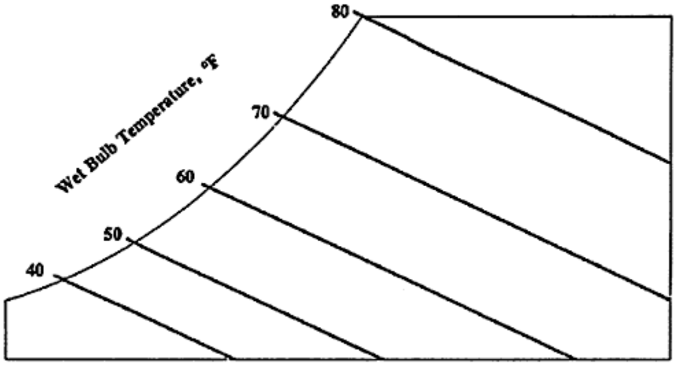
The humidity variables used in this lab can be determined using a simplified **psychrometric chart**, which graphically illustrates the relationships between air temperature and relative humidity. A guide to the psychrometric chart can also be found at http://www.ianr.unl.edu/pubs/generalag/g626.htm

The psychrometric chart has lines for *dry bulb temperature*, *wet bulb temperature*, *dewpoint*, *water vapor pressure* and *relative humidity.*

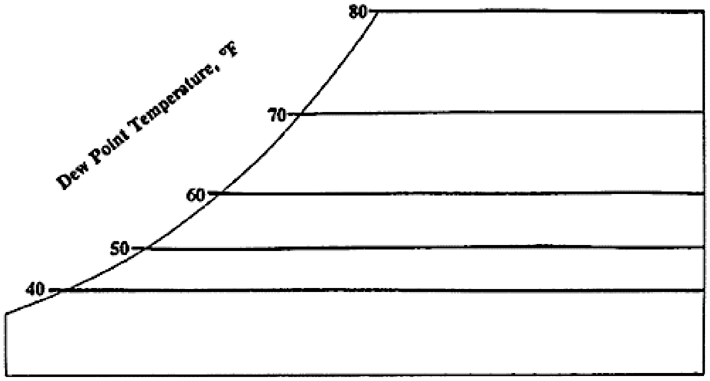
The *dry bulb temperature* (T), measured by an ordinary thermometer, is plotted along the horizontal bottom chart axis. Vertical lines are lines of constant dry bulb temperature.



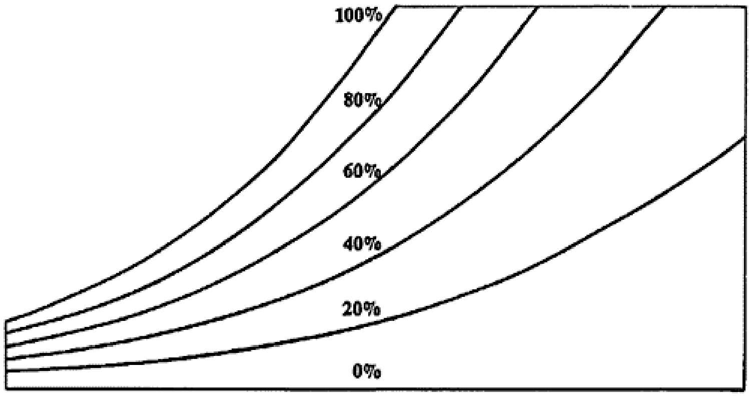
Wet bulb temperature (T_w) is plotted along the curved upper left boundary of the chart. The lines sloping down from 'top left' to 'bottom right' are lines of constant wet bulb temperature.



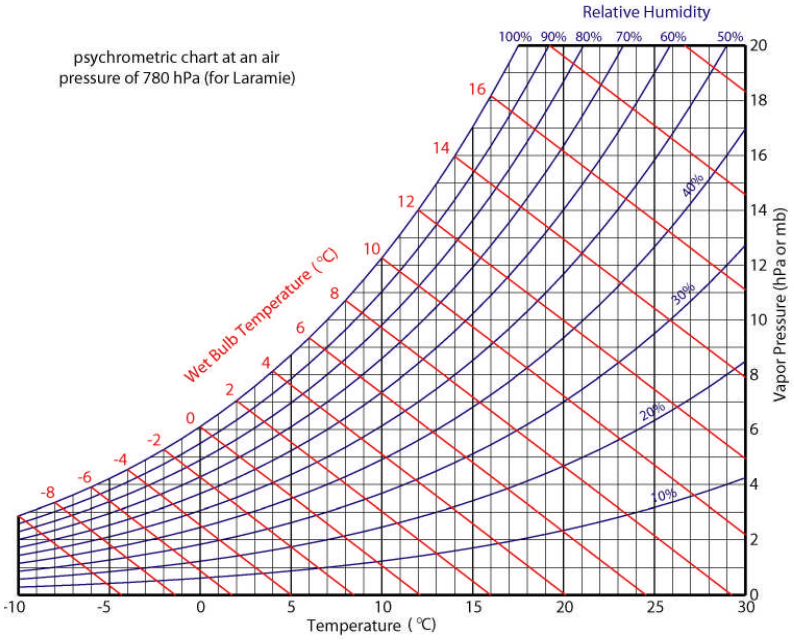
Dewpoint (T_d) uses the same numerical scale as wet bulb temperature; the horizontal lines represent constant dewpoint.



Lines of constant *<u>relative humidity</u>* (RH) curve upwards from the lower left to the upper right of the chart.



<u>Vapor pressure</u> (e) (or on some charts, water vapor mixing ratio) is plotted on the vertical right hand axis and is represented by horizontal lines. Therefore any given horizontal line specifies a saturation (dew point) temperature and the corresponding saturation vapor pressure at that temperature.



Knowing the values of any two of the above five parameters fixes the intersection point of the lines for those two parameters on the chart, and allows the values of the other three parameters, whose lines pass through that point, to be determined. For example, if T = 23°C and T_d = 4.5°C, then T_w must be 12°C, RH must be 30%, and the actual vapor pressure 8.4 hPa (equal to the saturation vapor pressure at the dewpoint).

A simplified **psychrometric chart** appropriate for use at Laramie's average atmospheric pressure of 780 hPa is appended at the end of this lab. (Note that a slightly different chart would be needed at sea level because the dew point and wet bulb temperatures are slight functions of pressure).

IV. Exercises

In this section of the lab you will make measurements of the air temperature and wet-bulb temperature inside and outside of the Engineering Building, using a sling psychrometer. Your TA will show you the proper way to operate this instrument. ***Please take care when using the sling psychrometer that it does not hit against some other object, so that it breaks!*** From these measurements you will use the psychrometric chart to determine other humidity variables. We will also attempt to estimate the dewpoint inside the Engineering Building using a cooled container of water. Your TA will explain the method we will use.

1. Complete the tables below with your measurements and determinations of the humidity variables inside and outside of the Engineering Building. In the first blank column of the table (titled Individual Measurement) fill in the boxes for the temperature and wet-bulb temperature. Average values of the temperature and wet-bulb temperature for all the measurements taken by everyone in the class will be used to complete the last column of the table (titled Average Measurement). Use the temperature and wet-bulb temperature values and the average values of these temperatures in the last column, to determine the remaining humidity variables, using the psychrometric chart.

Inside the Engineering Building

Humidity Variable	**Individual Measurement**	**Average Measurement of Group**
T (°C) (measured)		
T_w (°C) (measured)		
T_d (°C)		
Vapor Pressure: e (mb)		
Dew-point Depression (°C)		
Relative Humidity (%)		

Outside the Engineering Building

Humidity Variable	**Individual Measurement**	**Average Measurement of Group**
T (°C) (measured)		
T_w (°C) (measured)		
T_d (°C)		
Vapor Pressure: e (mb)		
Dew-point Depression (°C)		
Relative Humidity (%)		

Answer questions 2a – 2f by considering the parameter values in the last (right-hand) column of each of the above tables.

2a. Which location has the greater relative humidity?

2b. Which location has the smaller dew point depression?

2c. How do your answers to questions 2a and 2b relate to the conclusions that you drew in lab I concerning the relationship of dew point depression and relative humidity?

2d. Which location has the most water vapor present? In other words, where is the vapor pressure highest? (Remember that relative humidity measurements cannot be used when comparing the actual amount of water vapor present at two locations).

2e. What variable(s) did you compare when answering question 2d?

2f. How would the values of e, T_d, and RH change if you were to repeat your measurements outside the Engineering Building at sunrise, when the temperature is colder? (Assume that the actual amount of water vapor in the air was unchanged).

3. We can also estimate the dewpoint inside the Engineering building by observing the temperature at which condensation occurs on the sides of a cooling beaker of water. (Your TA will demonstrate the experimental procedure).

3a. Was the experiment successful? **Yes**! No (Please circle)

If the experiment was unsuccessful, answer question 3b, then skip questions 3c – 3f, and go on to question 4a. If it was successful, skip question 3b, and go on to question 3c.

3b. Why do you think the experiment failed to work?

3c. At what temperature did you notice dew form on the outside of the ice/water container?

3d. Why does this temperature correspond to the dewpoint?

3e. How does this measurement of the dewpoint compare with the calculated value in the table above?

3f. Why do you think the two measurements may differ?

4a. How can the relative humidity change throughout the day, even when the dewpoint remains constant?

4b. When, therefore, would you conclude would be the most likely time for dew and/or fog formation? Why?

5. During the winter the dewpoint outside is much lower than the dewpoint during the summer, but the relative humidity is higher during the winter than the summer. Explain how this apparent contradiction is possible.

6. Based on the information given in problem 5, and the fact that the temperature inside a house is kept approximately constant throughout the year, at what time of year would you expect to find the lowest relative humidity inside? (Assume that the air inside the house has the same amount of water vapor as the air outside the house). Why?

7a. You are cooking a big pot of spaghetti on your stove (during the winter), and notice dew forming on the inside of your kitchen window. Explain why dew condenses on your windows.

7b. How does the **dewpoint** of the air in your **kitchen** compare to the **air temperature outside**?

8a. Given an air temperature of 15°C and a dewpoint of 5°C, determine the vapor pressure, saturation vapor pressure, and relative humidity.

8b. If the dewpoint is the same as in problem 8a, but the temperature increases 10°C find the vapor pressure, saturation vapor pressure, and relative humidity. Recall that the relative humidity and the actual (e) and saturation vapor (e_s) pressures are related by the following formula:

$$RH = \frac{e}{e_s} \cdot 100\%$$

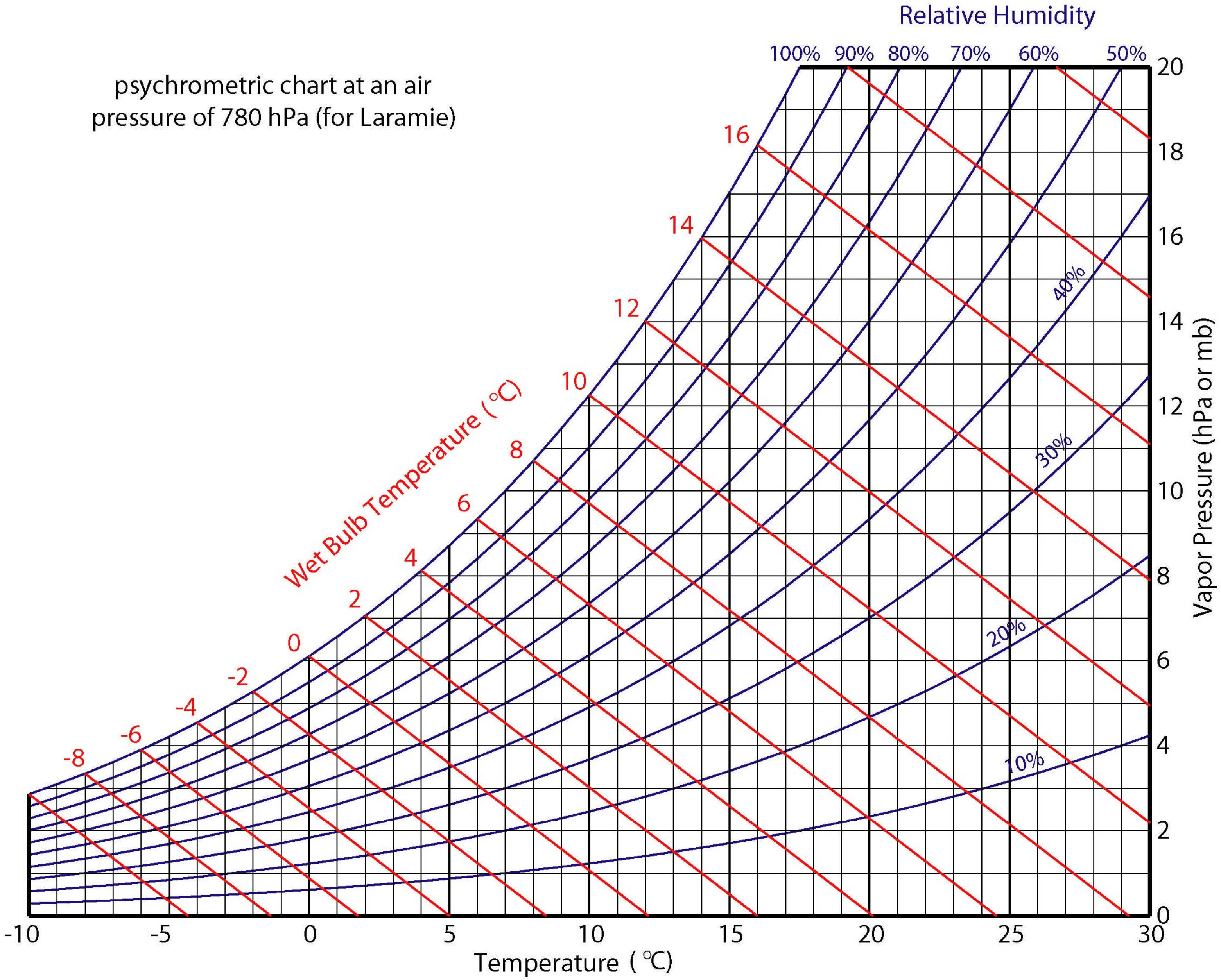
9a. Look back at the tables on page 4. For both the measurements inside and those outside the Engineering building, what is the difference in the relative humidity values determined from your own temperature observations and those averaged from the group as a whole?

<u>Inside:</u> *<u>Outside:</u>*

($RH_{individual} - RH_{group}$) = ; ($RH_{individual} - RH_{group}$) =

9b. The percentage difference (*PDiff*) in the RH value determination is given by $PDiff = 100 \frac{RH_{individual} - RH_{group}}{RH_{group}}$

What is the percentage difference of your relative humidity measurement inside and outside the building? (The value you obtain reflects the level of uncertainty involved in individual measurements of the RH. You should be aware that there is a measurement uncertainty associated with *every* scientific measurement).


psychrometric chart at an air pressure of 780 hPa (for Laramie)
Relative Humidity
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
Wet Bulb Temperature (°C)
-8
-6
-4
-2
0
2
4
6
8
10
12
14
16
Vapor Pressure (hPa or mb)
0
2
4
6
8
10
12
14
16
18
20
Temperature (°C)
-10
-5
0
5
10
15
20
25
30

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6. Thermodynamic Diagrams

Pre-lab Assignment

Before the Lab: Read this lab assignment; read pages 70 – 72 of Chapter 3 and pages 99 – 101 of Chapter 5 in *Meteorology - Understanding the Atmosphere* by S. A. Ackerman and J. A. Knox of the textbook. Answer the ***pre-lab questions*** below.

Answer these questions based on the information given in the text of this lab assignment. *This page must be turned in at the beginning of the lab period.*

1. Name the five lines displayed on a thermodynamic diagram.

2. What does the term *adiabatic* mean?

3. What is the numerical value of the dry adiabatic lapse rate?

4. Why is the rate of temperature decrease for moist adiabatic ascent less than for dry adiabatic ascent.

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Thermodynamic Diagrams
Main Lab Assignment

I. Introduction

The thermodynamic diagram is an important tool for meteorologists. It can be used to determine the static stability of the atmosphere, and thereby help to determine whether or not clouds will develop and what form those clouds subsequently take, as well as allowing other processes involving the vertical movement of air to be visualized.

The diagrams graphically represent physical processes that can also be described by a series of equations. However, it is easier to visualize these processes graphically, rather than relying on tedious calculations. In this lab you will learn to use thermodynamic diagrams to describe a number of processes in the atmosphere, and to determine the stability of the atmosphere. In the following lab we will again use thermodynamic diagrams to investigate cloud formation processes.

Lab Goals:

(1) Become familiar with the Stuve thermodynamic diagram.
(2) Know how to represent the state of the atmosphere on a thermodynamic diagram and how to use the diagram to predict how the temperature and humidity changes within rising and sinking air parcels.
(3) Be able to determine the condensation level (CL) that defines cloud base for a rising air parcel.
(4) Understand both dry and moist adiabatic lapse rates.

II. The Thermodynamic Diagram

The use of thermodynamic diagrams will be described by your lab instructor. A thermodynamic diagram is included with this lab (at the back of the lab packet) for your calculations.

Thermodynamic diagrams are used to describe the state of the atmosphere. The state of an air parcel can be characterized by values of temperature and pressure, and a moisture variable. The horizontal and vertical lines on the thermodynamic diagram are used to describe an air parcel's pressure and temperature, respectively. The vertical lines on the diagram (isotherms) are labeled in degrees Celsius and are plotted at 10°C intervals. The horizontal lines are lines of constant pressure (isobars). The pressure values plotted adjacent to these lines decrease as you move up the graph, the same way that pressure decreases as you move upwards in the atmosphere. For practice, make sure that you can find the following points on the diagram: T = 0°C and p = 700 mb (located near the center of the diagram); T = 30°C and p = 1000 mb (located near the lower right side of the diagram).

The final variable required to describe the state of an air parcel is a moisture content variable. Lines of constant mixing ratio are plotted as blue dashed lines which slope upwards and to the left on the diagram included with this lab. The mixing ratio of an air parcel is the mass of water vapor contained in the parcel for each kilogram of dry air in the air parcel.

The mixing ratio lines are actually used to describe two characteristics of the air parcel. The mixing ratio line which passes through the point defined by the parcel temperature and pressure describes the *saturation* mixing ratio, r_s, of the air parcel. The saturation mixing ratio is analogous to the saturation vapor pressure discussed in the humidity lab, in that it is a measure of the maximum amount of water vapor that can be held in the air parcel at a given temperature and pressure. The mixing ratio line that passes through the intersection point of the parcel pressure and *dewpoint* is that of the *actual* mixing ratio, r, a measure of the actual amount of water vapor contained in the air parcel. Therefore an unsaturated air parcel at a given pressure level is characterized by *two* points on the thermodynamic diagram, one given by the parcel temperature and pressure, and the other by the parcel dewpoint and pressure. If the air parcel is saturated then the temperature and dewpoint are equal, and only *one* point is required to describe the state of the air parcel on the diagram.

From the saturation mixing ratio and the actual mixing ratio, the relative humidity, RH, can be determined using the formula:

$$RH = \frac{r}{r_s} \cdot 100\%$$

This formula is analogous to that involving vapor pressure values used in last week's humidity lab. Often the state of an air parcel will not be located exactly at the intersection of the temperature, pressure, or mixing ratio lines printed on the diagram, and therefore you will need to interpolate between the plotted lines. Don't worry about being over precise. You should be able to estimate the temperature to better than one degree Celsius, the pressure to within 10 mb, and the mixing ratio to within 0.1 to 1 g/kg depending on your location on the graph (the spacing between mixing ratio lines is not constant).

III. Exercises (Part I)

In this section of the lab you will become familiar with the use of the thermodynamic diagram by carrying out some simple exercises.

For each of the problems, plot the required points on the thermodynamic diagram included at the back of the lab manual and label the point with the problem number. It is advisable to use a pencil, so that you can easily erase errors. *(Use only **one** of the thermodynamic diagrams supplied with your lab manual! The other will be needed for a later lab).*

1a. Locate the points which describe the following air parcel state (mark these points on your thermodynamic diagram):

$T = -15°C$, $T_d = -25°C$, and $p = 600$ mb

1b. What is the mixing ratio of this air parcel?

1c. What is the saturation mixing ratio of this air parcel?

1d. Use the formula on the previous page to calculate the relative humidity of the air parcel.

2a. Locate the points which describe the following air parcel state (mark these points on your thermodynamic diagram):

$T = 30°C$, $T_d = 13°C$, and $p = 1000$ mb

2b. What is the mixing ratio of this air parcel?

2c. What is the saturation mixing ratio of this air parcel?

2d. What is the relative humidity of the air parcel?

3a. Locate the points which describe the following air parcel state (mark these points on your thermodynamic diagram):

$T = 0°C$, $T_d = -15°C$, and $p = 780$ mb

3b. What is the mixing ratio of this air parcel?

3c. What is the saturation mixing ratio of this air parcel?

3d. What is the relative humidity of the air parcel?

IV. Dry Adiabatic Processes

Now that you are able to determine the state of an air parcel using a thermodynamic diagram, you can start to use it to describe physical processes, specifically dry adiabatic processes and moist adiabatic processes.

Adiabatic processes are those in which an air parcel does *not* exchange heat energy with its surroundings. The temperature of a parcel undergoing an adiabatic process can nevertheless change, if its pressure changes. In the atmosphere, parcel pressure changes usually result from rising or sinking motions of the parcel. Thus, parcels that sink are warmed by adiabatic compression, while those that rise undergo decompressional adiabatic cooling.

As an air parcel rises in the atmosphere it moves upward into regions of lower pressure (since pressure always decreases as you move to higher elevations). As the pressure decreases, the air parcel expands, because initially the pressure inside the air parcel is slightly greater than the pressure outside the air parcel. This is similar to how a bag of chips that you've bought at lower elevation expands when you bring it up unopened to Laramie, where the atmospheric pressure is lower. In order for the parcel, or the bag of chips, to expand, energy must be used. Where does this energy come from? Since no energy is exchanged between the parcel and the environment in an adiabatic process, the energy must come from the thermal energy contained by the air molecules within the parcel. Therefore if energy is used to allow the parcel to expand, the thermal energy, and hence the temperature, of the parcel decreases. In summary, the temperature of a rising air parcel decreases, even though there is no exchange of heat energy between the parcel and the environment, because the air molecules have to give up some of their energy to allow the parcel to expand. The air parcel continues to expand until the pressure inside is exactly equal to the pressure of the surrounding air. (When an air parcel sinks in the atmosphere, the pressure of the surroundings increases, the parcel is compressed, and the temperature inside the parcel increases).

The *dry* adiabatic process is an adiabatic process in which no change of phase of water vapor occurs. The fact that it is termed 'dry' does not mean that the parcel does not contain any water vapor, only that the water vapor in the air parcel does not experience any change of phase. For a dry adiabatic process the temperature of a rising air parcel always decreases at a constant rate of 9.76°C/km. This rate of temperature change is known as the **dry adiabatic lapse rate** (a lapse rate is just the rate of temperature change with change in altitude). For a sinking air parcel, the temperature will increase at the same dry adiabatic lapse rate. These changes of temperature with changes in height (and pressure) are represented on the thermodynamic diagram by solid green lines, which slope upwards and to the left. These lines are referred to as **dry adiabats**.

The use of dry adiabats to describe dry adiabatic processes is straightforward. First locate the point on the diagram (given by the temperature and pressure) that represents the initial state of the air parcel. For rising motion, follow the dry adiabat that intersects the initial temperature and pressure intersection point, upwards and to the left, until you arrive at the new pressure of the air parcel. Now read the new temperature corresponding to the intersection point of the dry adiabat and the final pressure. Note that if the initial state of the air parcel does not lie exactly on a dry adiabat, a path that is parallel to the nearest dry adiabat is followed to describe the process. Sinking motions can be described in the same way, except that the dry adiabat is followed down and to the right on the diagram.

What about the moisture contained in the air parcel during a dry adiabatic process? As mentioned above, the amount of water vapor in the air parcel will not change during a dry adiabatic process, since no phase changes occur, so the mixing ratio of the air parcel (obtained knowing the initial dewpoint) remains constant during the process. However, the dewpoint decreases slightly with decreasing pressure at higher altitudes. Following the mixing ratio line upwards that passes through the initial dewpoint allows the decreasing value of the dewpoint (for rising motion) to be tracked.

How does the saturation mixing ratio of the air parcel change during dry adiabatic ascent? The saturation mixing ratio is determined by the air parcel’s temperature and pressure. Since the temperature of the air parcel decreases for rising motion, the corresponding saturation mixing ratio will also decrease (because as the air temperature decreases the amount of moisture needed to saturate the air decreases).

As an air parcel rises in a dry adiabatic process, notice that the temperature of the air parcel decreases more rapidly than the rate at which the dewpoint decreases. Therefore, if an air parcel is lifted sufficiently, the temperature and the dewpoint will become equal, and the air parcel will become saturated. Also note that while the saturation mixing ratio of the air parcel decreases during ascent, the actual mixing ratio remains constant. Obviously if the air parcel is lifted sufficiently, the actual mixing ratio and saturation mixing ratio will become equal, and the air parcel will become saturated.

Further lifting of the air parcel above the level of saturation would result in a supersaturated condition if condensation did not occur, since the temperature would be less than the dewpoint, and the actual mixing ratio would become greater than the saturation mixing ratio. We know that significantly supersaturated conditions are not common in the atmosphere, so continued lifting beyond the height at which saturation occurs must be accompanied by condensation (a change of phase of water vapor). The height at which the air parcel just reaches saturation is known as the condensation level (CL) (sometimes referred to as the Lifting (or Lifted) Condensation Level (LCL)). For continued lifting beyond the CL we can no longer describe the change of state of the air parcel by the dry adiabatic process, but instead must turn to the moist adiabatic process, which describes the change of state of the air parcel as condensation of water vapor occurs.

V. Moist Adiabatic Processes

The moist adiabatic process describes changes of temperature, dewpoint, mixing ratio, and saturation mixing ratio for a saturated air parcel that is rising. For this process the temperature and dewpoint are equal, as are the mixing ratio and saturation mixing ratio. Cooling associated with the ascending motion results in condensation. Moist adiabatic processes are represented on the thermodynamic diagram by the red saturated adiabats, which curve up to the left.

The rate of temperature decrease for a moist adiabatic process is less than that for a dry adiabatic lapse rate, because as water vapor condenses it releases latent heat. The latent heat that is released provides some of the energy needed for the expansion of the air parcel, so that not as much of the thermal energy of the air parcel is required to cause the parcel to expand. The temperature of the parcel therefore decreases at a slower rate than in a dry adiabatic process.

Remember that for moist adiabatic processes the state of the air parcel is described by only one point, since the temperature and dewpoint are equal at saturation. As the saturated air parcel rises, the temperature decreases, but so does the mixing ratio. The mixing ratio decreases because in parallel with the temperature decrease, water vapor condenses to form liquid water (or ice), so that the parcel’s water vapor content goes down.

VI. Exercises (Part II)

In this section of the lab you will explore both dry and moist adiabatic processes using your thermodynamic diagram.

2e. Start with the air parcel described in problem 2 of Section III. Lift this air parcel from its initial pressure of 1000 mb to a pressure of 900 mb. Mark the new temperature, dewpoint, and pressure as well as the lines used to get to these points on your thermodynamic diagram. Label these points 2e.

2f. What is the new temperature and dewpoint at a pressure of 900 mb?

2g. What is the mixing ratio at 900 mb?

2h. Has the mixing ratio changed from its value at 1000 mb (listed in problem 2b)? Why or why not?

2i. What is the saturation mixing ratio at 900 mb?

2j. Has the saturation mixing ratio changed from its value at 1000 mb (listed in problem 2c)? Why or why not?

2k. Calculate the relative humidity of the air parcel at 900 mb.

2l. How has the relative humidity of the air parcel changed from the value at 1000 mb (calculated in problem 2d)?

2m. Now continue lifting the air parcel until it reaches its CL. Mark the point representing the condensation level on the diagram as 2m.

2n. What is the pressure of the air parcel at the CL?

2o. What is the temperature of the air parcel at the CL?

2p. What is the dewpoint of the air parcel at the CL?

2q. What is the mixing ratio of the air parcel at the CL?

2r. What is the relative humidity of the air parcel at the CL?

2s. Finally, lift the air parcel from the CL to a pressure of 500 mb. Mark this point on the diagram as 2s.

2t. What is the temperature of the air parcel at 500 mb?

2u. What is the mixing ratio of the air parcel at 500 mb?

2v. How is the mixing ratio of the air parcel at 500 mb different from the mixing ratio of the air parcel at the CL? What has happened to this water vapor between the CL and 500 mb?

3e. Start with the air parcel described in problem 3 of Section III. Lift this air parcel from its initial pressure of 780 mb to its CL. Mark this point on your thermodynamic diagram as 3e.

3f. What is the pressure of the air parcel at the CL?

3g. What is the temperature of the air parcel at the CL?

3h. What is the dewpoint of the air parcel at the CL?

3i. What is the mixing ratio of the air parcel at the CL?

3j. Finally, lift the air parcel from the CL to a pressure of 500 mb. Mark this point on the diagram as 3j.

3k. What is the temperature of the air parcel at 500 mb?

3l. What is the mixing ratio of the air parcel at 500 mb?

3m. How is the mixing ratio of the air parcel at 500 mb different from the mixing ratio of the air parcel at the CL? What has happened to this water vapor between the CL and 500 mb?

4a. Locate the points that describe the following air parcel state. Mark these points on your thermodynamic diagram as 4a.

$T = 30°C$, $T_d = 21°C$, $p = 800$ mb

4b. Find the mixing ratio, saturation mixing ratio, and relative humidity for the points given in problem 4a.

4c. Lift the air parcel described in problem 4a from 800 mb to 750 mb. Mark the new temperature and dewpoint as 4c.

4d. What is the temperature and dewpoint at 750 mb?

4e. Lift the air parcel from problem 4c to the CL. Label this point as 4e.

4f. What is the pressure, temperature and dewpoint at the CL?

4g. What is the mixing ratio, saturation mixing ratio, and relative humidity at the CL?

4h. Continue lifting this air parcel to a pressure of 600 mb. Label this point 4h.

4i. What are the temperature, dewpoint, and relative humidity at 600 mb?

ATSC 2000 Lab VII Section: Mon. / Thurs. (Circle) **Name:**

7. Static Stability and Clouds

Pre-lab Assignment

Before the Lab: Read pages 99 – 125 of Chapter 4 in *Meteorology - Understanding the Atmosphere* by S. A. Ackerman and J. A. Knox of the textbook, and this lab assignment. Also, answer the ***pre-lab questions*** below.

Answer these questions based on the information given in the text of this lab assignment. *This page must be turned in at the* ***beginning*** *of the lab period*.

1. What three characteristics of clouds are used in the cloud classification scheme described in this lab?

2. List the ten basic cloud types.

3. What is the basic *general* definition of stability, applicable to any context? (**Not** the *specific meteorological* definition).

4. List the lifting mechanism(s) and whether an air parcel is warmer or colder than the environment for the following static stability classifications. Remember that some classifications require more than one lifting mechanism.

Conditionally unstable:

Absolutely unstable:

Absolutely stable:

ATSC 2000 Lab VII Section: Mon. / Thurs. (Circle) Name ……………………….

Static Stability and Clouds
Main Lab Assignment

I. Introduction

Clouds come in a variety of shapes and sizes, as you know from your own day-to-day observations. Also, we know that clouds form on some days and not on others. In this lab we will briefly explore some of the reasons for the wide variety of clouds that are observed. First, we will look at photographs of a number of cloud types, and do a short cloud identification quiz. After the quiz, we will explore the concept of static stability, using the thermodynamic diagram as our tool, to study cloud formation processes.

Lab Goals:

(1) Become proficient in cloud identification.
(2) By using the thermodynamic diagram, be able to determine whether the atmosphere is stable or unstable. Understand stability/instability criteria.
(3) Investigate the formation of surface radiation fog at night.

II. Cloud Identification

Meteorologists classify clouds based on the cloud shape, height of cloud base above ground, and the presence of precipitation. Classification systems are used in order to facilitate communications between people. It is much easier to tell a friend that cumulus clouds were present on a summer afternoon than to go through the process of describing all of the features of the observed clouds. The classification system, once learned, allows a specific mental image of a cloud to form from just one or two words. The system most commonly used contains ten cloud types. The table below lists nine of the ten cloud types, as well as fog, and the characteristics that are associated with each cloud type.

High Bases (6-12 km)	Cirrus	Cirrostratus	Cirrocumulus
Middle Bases (2-7 km)		Altostratus Nimbostratus	Altocumulus
Low Bases (0-2 km)		Stratus Nimbostratus Fog	Stratocumulus
	Wispy	**Flat layer**	**Cellular or wavy layer**

Besides the nine cloud types listed in the table above, there is an additional cloud type that describes clouds that typically have low cloud bases (0-2 km) but that are vertically developed. This cloud type (cumiliform) includes cumulus and cumulonimbus clouds. Cumulus clouds are the white, puffy clouds often observed on summer afternoons. Cumulonimbus clouds are the clouds associated with thunderstorms. Other cloud types, such as lenticular clouds, mammatus, and contrails do not fit into this classification scheme. Many photos of clouds have been posted on the world-wide-web, for example:

http://www.wolkenatlas.de/wbilder.htm
http://www.atmos.washington.edu/gcg/Atlas/
http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/cld/cldtyp/home.rxml
http://vortex.plymouth.edu/clouds.html
http://www.cloudman.com/

III. Exercises (Part I)

1. For this part of the lab, your teaching assistant will show you a group of cloud slides, and discuss how you can identify each cloud type. At the end of the slide show, your TA will show you an additional eight slides. Fill in the table below by identifying the clouds present in each of these slides.

Slide Number	Cloud Type
1	
2	
3	
4	
5	
6	
7	
8	

2. What cloud type(s) is/are present in the sky today? How would you describe the cloud cover (SCT, BKN, OVC, etc.)?

IV. Stability

Stability refers to the way a system responds to a disturbance. If the system spontaneously attempts to restore itself to the condition prior to the disturbance then the system is *stable*. If the system continues to move away from its initial condition after being disturbed then the system is called *unstable*.

When meteorologists refer to static stability they are interested in the way the atmosphere will respond to a disturbance that causes an air parcel to be displaced upwards or downwards. An air parcel can be lifted by a number of methods. One example is air that is forced to rise over a mountain barrier. If the air parcel continues to rise spontaneously after passing up and over the mountain, then the atmosphere is unstable (the air parcel continues to move away from its initial position after the disturbance is removed). If the air parcel returns spontaneously to its original elevation after passing over the mountain, then the atmosphere is stable. The response of an air parcel to a perturbation depends on the air parcel temperature and the environmental temperature (the temperature of the air surrounding the air parcel). If an air parcel is warmer than its surroundings, then it will be buoyant and will rise (since warmer air is less dense than cooler air). If the air parcel has the same temperature as its environment then the parcel will not move up or down. Finally, if the air parcel is colder then its environment, it will sink (since colder air is more dense than warmer air).

Meteorologists classify the atmosphere into four stability classes, according to the behavior of air parcels. These classes are **absolutely unstable**, **conditionally unstable**, **neutral**, and **absolutely stable**. The first two classes refer to situations where the air parcels that are lifted become warmer than their environment, and thus continue to rise. Recall from the thermodynamic diagram lab that an air parcel can be lifted via a dry adiabatic process or a moist adiabatic process. Also, remember that the temperature of the air parcel changes at a different rate for each of these processes. An air parcel lifted by a dry adiabatic process, cools at a faster rate than an air parcel lifted by a moist adiabatic process. Therefore, it is more likely for an air parcel that is lifted by a moist adiabatic process to remain warmer than the environment (since the air parcel cools off at a slower rate during this process). If an air parcel that is lifted by a dry adiabatic process is warmer than its environment, then the stability classification is **absolutely unstable**. If an air parcel is colder than its environment when lifted by a dry adiabatic process, but is warmer than its environment when lifted by a moist adiabatic process, then the stability classification is **conditionally unstable**. The *conditional* part of this classification arises because the instability is conditional on the air parcel being saturated and lifted by a moist adiabatic process. If an air parcel is lifted and has the same temperature as the environment then the stability classification is **neutral**. Finally, if an air parcel is lifted by either a moist or dry adiabatic process and is colder than its environment then the stability classification is **absolutely stable**. The following table summarizes the descriptions of stability classes in this section.

Stability Classification	Lifting Mechanism	Parcel Temperature compared to Environmental Temperature	Result
Absolutely Unstable	Dry Adiabatic Process	Warmer	Continues to rise
Conditionally Unstable	Dry Adiabatic	Colder	Sink
	Moist Adiabatic	Warmer	Continues to rise
Neutral	Dry Adiabatic Moist Adiabatic	Equal	Does not move
Absolutely Stable	Dry Adiabatic Moist Adiabatic	Colder	Sink

V. Exercises (Part II)

3. Starting at the point on your thermodynamic diagram that has a pressure of 1000 mb and a temperature of 20°C, draw and label an environmental temperature profile up to 900 mb for each of the following conditions:

3a. An absolutely unstable condition
3b. A conditionally unstable condition
3c. An absolutely stable condition

4a. Plot the following data, collected by a radiosonde, on the thermodynamic diagram included at the back of this lab manual. The data represents the temperature structure of the atmosphere just before sunrise. Use the plotted data to answer questions 4b – 6e.

Pressure (mb)	Temperature (°C)
1000	0
950	4
900	0
850	-5
750	0

4b. Lift an air parcel dry adiabatically from 1000 mb, assuming that the air parcel initially has the same temperature as the environment, to a pressure of 900 mb. What is the temperature of the air parcel at 900 mb?

4c. Is the air parcel warmer or colder than the environment?

4d. What stability class would you use to describe the air parcel at 900 mb?

5a. Now, using the same sounding from problem 4, assume that the surface air has warmed to a temperature of 10°C by mid-afternoon, while the environmental temperatures at all other heights have remained the same. Lift an air parcel dry adiabatically from a pressure of 1000 mb with a temperature of 10°C, to a pressure of 900 mb. What is the temperature of this air parcel at 900 mb?

5b. Is the air parcel warmer or colder than the environment?

5c. What stability class would you use to describe the air parcel at 900 mb?

6a. Assume the afternoon temperature at the surface is still 10°C and the dewpoint is 3°C. What is the pressure at which clouds will begin to form if an air parcel with this combination of temperature and dewpoint is lifted dry adiabatically? As explained on page 5 of lab VI, clouds will form at the CL, where the temperature and dewpoints are the same.

6b. Is the air parcel at cloud base warmer or colder than the environment?

6c. Will this air parcel continue to rise spontaneously from cloud base?

6d. Continue to lift the air parcel from cloud base, following a moist adiabat. At what pressure will the cloud top occur?

6e. How does the parcel temperature compare to the environmental temperature at cloud top? Why is this significant?

6f. Explain why you are more likely to see convective clouds form in the afternoon rather than in the morning.

7a. Plot the pressure, temperature, and dewpoint from the following table on the thermodynamic diagram included at the back of this lab manual. Use a solid line for sunset temperatures and a dashed line for sunrise temperatures. The data represents the temperature structure of the atmosphere at sunset and sunrise. The temperature change column is not plotted, but is there for a reference. You will use the temperature change data for question 7b and 7c

Pressure (mb)	Sunset Temp (°C)	Sunset Dew Point Temp (°C)	Temperature Change (°C)	Sunrise Temp (°C)	Sunrise Dew Point Temp (°C)
850	20	13	-12	8	8
800	15	11	-3	12	11
750	9	5	-2	7	5
700	5	0	-1	4	0
650	2	-7	0	2	-7
600	0	-15	0	0	-15

7b. During the night, the temperature cools by the amount listed in the fourth column of the table in question 7a. Usually, the atmosphere cools most near the surface at night and much less aloft, as indicated in the table. Plot the new morning temperatures on your diagram based on the temperature changes listed. If the air temperature cools to a value lower than the sunset dewpoint, we assume that water vapor condenses during the night as the air cools, at a rate that allows the dewpoint to decrease and remain exactly equal to the air temperature.

7c. Based on the new temperature and dewpoint profile mark the layer which becomes foggy overnight. Realize that fog forms at all heights where the dew point and ambient temperatures are equal. What is the pressure at the top of the fog layer?

7d. Explain why fog usually forms overnight and not during the daytime.

7e. It is often observed that fog initially forms close to the surface and that during the night the depth of the fog increases. Why is this? (If you run out of space for your answer, continue on the back of this sheet).

ATSC 2000 Lab VIII Section: Mon. / Thurs. (Circle) **Name:**

8. Freezing of Water - Ice Nucleation

Pre-lab Assignment

Before the Lab: Read pages 82 – 97 of Chapter 4 in *Meteorology - Understanding the Atmosphere* by S. A. Ackerman and J. A. Knox of the textbook and this lab assignment. Also, answer the ***pre-lab questions*** below.

Answer these questions based on the information given in the text of this lab assignment. *This page must be turned in at the* ***beginning*** *of the lab period.*

1. At what temperature will pure water freeze?

2. What needs to be present in water for it to freeze at a temperature warmer than the answer given to question 1?

3. What determines the actual temperature at which a water sample will freeze?

4. Which single quantity reflects the range of measured values of a repeatedly measured parameter?

ATSC 2000 Lab VIII Section: Mon. / Thurs. (Circle) Name ……………………….

Freezing of Water - Ice Nucleation
Main Lab Assignment

I. Introduction

The temperature of 0°C (32°F) is well known as the melting point of ice, but liquid water does not always freeze at this temperature. More precisely, 0°C is the temperature at which water and ice can co-exist in equilibrium. The formation of ice in water at 0°C or at slightly lower temperatures requires the presence of an **ice nucleus**. This is similar to the condensation of water in air on *condensation nuclei*. All by itself, ice forms in ultra-pure water only near -40°C. However, impurities suspended in the water may serve as nuclei, called *ice nuclei*, or more precisely, *freezing nuclei*.

Freezing nuclei are much less abundant than condensation nuclei. Also, different types of freezing nuclei initiate ice formation at different temperatures. The temperature at which a water sample freezes depends on the type and number of freezing nuclei suspended in the water.

To investigate the action of freezing nuclei, we will observe the temperatures at which water droplets of uniform size freeze. Different water samples will be used, some of which will be pure and others of which will contain impurities that can promote freezing. The drops will be cooled from room temperature to well below 0°C, until all of them have been observed to freeze, as evidenced by a change in their appearance from clear to slightly milky, and a slight distortion of their roughly spherical shape.

If the experiment goes well, we will be able to demonstrate (1) that water can supercool and remain liquid at temperatures well below 0°C, and (2) that the nucleation (freezing) temperature depends on suspended impurities.

Lab Goals:

(1) Successfully carry out an experiment to investigate the freezing temperatures of both pure and contaminated water droplets. Appreciate the behavior of freezing nuclei.
(2) Assess uncertainties in our experimental measurements and know how they may be quantitatively expressed.

II. Method

Sample drops will be placed on a clean surface prepared on top of a copper plate that is cooled by placing it on a pedestal whose base is surrounded by dry ice. The freezing of the drops will be detected by their change in appearance from clear to milky (opaque), and by a slight distortion of their roughly spherical shape. The freezing temperatures of the drops for each of the different water samples will be recorded and compared.

1. Make a sketch of the apparatus. Label the primary components and describe their functions.

III. Procedure

The surface of the copper plate will be prepared by the lab instructor to assure consistently clean conditions. Dirt on the surface can contain ice nuclei and compromise the integrity of the experiment. Water samples to be tested will be **(a) distilled water, (b) dilute soil suspension, and (c) silver iodide (AgI) suspension**. Equal size water drops are placed on the block using a hypodermic syringe. The tip of the syringe needle is held close to, but not touching, the surface. It is important that we try and generate small drops of uniform size, otherwise any conclusions that we may draw from comparisons of the freezing temperatures will be suspect. Record the observations on the table below, and work out the average freezing temperature of the drops for each water sample.

Each test has distilled water drops, and drops from the two other samples. Twenty drops are placed on the plate, and a temperature sensor attached. The plate is then placed on the cooling pedestal. Each group of drops can be observed by one or more students. When a drop freezes, the temperature shown on the digital display is recorded for that drop. In order to obtain good experimental statistics, the experiment is repeated three times. The following table shows the number of drops of each kind of water in each experiment.

Experiment Number	Distilled Water	Soil Suspension	Silver Iodide
1	10	5	5
2	5	10	5
3	5	5	10

DROP NUMBER	DISTILLED WATER		DROP NUMBER	SOIL SUSPENSION		DROP NUMBER	SILVER IODIDE
1			1			1	
2			2			2	
3			3			3	
4			4			4	
5			5			5	
6							
7							
8							
9							
10							
			6			6	
			7			7	
			8			8	
			9			9	
			10			10	
11			11				
12			12				
13			13				
14			14				
15			15				

						11	
						12	
						13	
						14	
						15	
16			16			16	
17			17			17	
18			18			18	
19			19			19	
20			20			20	
Average			Average			Average	

IV. Analysis of Observations

1. Did you notice any difference in the appearance of the water drops when they were above 0°C and when they were supercooled? If so, describe the observed difference.

2. List the samples in order of decreasing *average freezing temperatures*:

Sample	**Average Freezing Temperature (°C)**

3. List the lowest and highest freezing temperatures and the range of freezing temperatures for each sample.

Sample	**Lowest (°C)**	**Highest (°C)**	**Range (°C)**

4. Which samples had the smallest and largest range of freezing temperatures?

5. Explain why drops taken from the same sample froze at different temperatures.

6. Which sample had the most active freezing nuclei? Which sample had the most active freezing nucleus?

7. If all 20 of the drops of each sample had been put together in one large drop, at what temperature would that large drop have frozen: List answers using the chart on the following page.

Sample	**Freezing Temperature (°C)**

V. Statistical Uncertainty Analysis of the Data

For each water sample, we observed that the droplets froze over a range of temperatures, and we calculated the average (mean) freezing temperatures from these values. When reporting experimental data of any kind where we have multiple determinations of the same quantity, it is useful to give the *median value* and the *standard deviation of the mean*. The *median value* is the central value of the range of values after they have been arranged in ascending (or descending) order. Thus there are as many values that are greater as are smaller than the median. For example, if you have 19 values, the median is that ranked 10th. For an even number of values, say 20, the median will be the average of the two near-middle values, value #10 and value #11 in our example.

The *standard deviation of the mean* (σ) provides information about the magnitude of the *range* of values that have been determined. It tells us whether all the measured values cluster closely about the mean (a small σ value), or whether they are more spread out (a large σ value). For a so-called 'normal distribution' of values, for which the mean and median values are identical, 68.3% of the data will be within one standard deviation of the mean, i.e., in the range ($X_{avg} \pm \sigma$), where X_{avg} is the mean (average) value of the data points, and 95% of the data points will be within two standard deviations of the mean.

How do you work out the *standard deviation of the mean* for each of your data sets, for which you have N freezing temperatures? (If the experiment went well, N will be equal to 20). Follow this calculation procedure:

a) subtract the average value from each of the N values (some differences will be positive and some negative)
b) square each one of these N differences, and then add them all together
c) divide the sum of the squared differences by (N-1) where N is the number of data points. The number you've just calculated is called the *variance*.
d) take the square root of the *variance* to get the *standard deviation of the mean*

Instead of doing this calculation 'by hand' you can use one of several web sites to do the calculation for you. Obviously to do this, you will need to find a computer with an internet browser. Other than the computer in the lab accessible to your TA, the nearest ones are in the first floor Engineering Labs, used in the first lab. Go to http://www.physics.csbsju.edu/stats/descriptive2.html where you will find a more extensive discussion of 'descriptive statistics' and click on the link that says "Click here to calculate mean, standard deviation, etc". Follow the simple instructions to compute σ. Alternatively, with your TA's help, enter your freezing temperature values into a Microsoft Excel spreadsheet and use it to compute both the mean and standard deviation values.

Enter the values of lowest and highest observed freezing temperature in rows 2 and 3 of the following table, for each water sample. Also enter the calculated median droplet freezing temperature, the mean (average) droplet freezing temperature (from the last line of the table of data in section III), and the standard deviation of the mean in the following table, for each of the three water samples.

	Distilled Water	Soil Suspension	Silver Iodide
Lowest Freezing Temperature			
Highest Freezing Temperature			
Median Freezing Temperature			
Mean Freezing Temperature			
Standard Deviation of the Mean			
1 σ Freezing Temperature Range			
% of Drops freezing outside the 1 σ range			

8. For which sample is the difference between the median and mean temperatures the greatest?

9. For which sample do the data points cluster most tightly around the mean freezing temperature?

Adding and subtracting the standard deviation of the mean from the mean freezing temperature gives ‘the 1 standard deviation range of values’ ($X_{avg} \pm \sigma$). Write in these ranges in data row 6 of the table, and in data row 7 (the last row) write in calculated values of the percentage of the number of data points that fall outside the 1 σ range specified in row 6.

10. Are the ranges of temperature values in data row 6 greater or smaller than the corresponding ranges of freezing temperatures specified by data rows 1 and 2 of the table?

11. Do the percentages listed in row 7 confirm the statistical prediction that 68.3% of the freezing temperatures lie within the 1 σ freezing temperature range and that 31.7% lie outside the range? If the agreement with the statistical prediction is poor, suggest why.

The bottom line!

12. Can you say for which sample the class did the best job at measuring the freezing temperatures? Why or why not?

Note: *There is a take-home lab next week. Review the instructions for handing in the completed lab well in advance!*

ATSC 2000 Lab IX Section: Mon. / Thurs. (Circle) **Name:**

9. Interpreting Weather-Satellite Images

Read this note carefully! *This is a* ***'Take-Home Lab'*** *and can be completed in your own time. Attendance at lab during the regularly scheduled lab period is* **not** *required. However, you can visit with your TA if you so desire and receive guidance at the beginning of the lab session, or during office hours.*
You must turn in this lab ***to your TA*** *by the first class day following the day that your lab section normally meets. Lab Assignments handed in late will be subject to a penalty, if accepted at all.*

Before the Lab: Read pages 138 – 148 of Chapter 5 in *Meteorology - Understanding the Atmosphere* by S. A. Ackerman and J. A. Knox of the textbook, about satellite observations of weather. Then go online and access http://www.atmos.uwyo.edu/~geerts/atsc2000/lab/, click on "Lab 9: Interpreting Weather-Satellite Images", and then on "Weather-satellite images" in the Background Reading section (see **Introduction** below). The primer you will access, was authored by Dr. David Dempsey at San Francisco State University, and is used here with his permission. Also visit the web site http://profhorn.meteor.wisc.edu/wxwise/satir/IRCloud.html to explore how the appearance of an object in the infrared varies with temperature.

Lab Goals:

(1) Appreciate the different types of satellite images that are routinely acquired.
(2) Learn to distinguish the appearances of various surfaces and clouds when viewed in both the visible and infra-red by satellite instruments.
(3) Understand how an object's temperature affects its appearance in the infra-red.

I. Introduction

Having accessed the web site, click on "Start" and read through Part I (Introduction), to review satellite imagery briefly. Go back to "Weather Satellite Images" if necessary, and then go on to review the material found in the link "Some Mostly Common-Sense Properties of Features Distinguishable on Weather-Satellite Images". Now answer questions 1 – 7 below.

Answer these questions based on the information given in the reading assignments of this lab. The questions and answers can be found as the Part II 'Background Questions' at http://www.atmos.uwyo.edu/~geerts/atsc2000/lab/. Short answers are sufficient, but make sure you understand the answers because you will be tested on these in the Lab.

1a. Suppose two patches of ground are identical, except that one has a high albedo and the other a low albedo. The sun shines on each equally. Which one, if either, looks brighter? Which one, if either, will become warmer? Why?

1b. According to the basic laws of radiation, what determines the intensity with which an object **emits** radiative energy?

2a. From the point of view of a satellite orbiting the Earth, would you expect any **visible** light reaching you from the Earth to be emitted from the Earth or reflected by the Earth? Why?

2b. What about longwave **infrared** radiation from the Earth — is it reflected or emitted? Why?

3a. Which <u>two</u> factors determine the intensity of **visible** light coming from features of the Earth as viewed from a satellite?

3b. What <u>one</u> factor determines the intensity of **infrared** radiation coming from features of the Earth as viewed from a satellite?

4a. What creates contrast (that is, differences in shades of gray) on **visible** satellite images?

4b. What creates contrast (that is, differences in shades of gray or differences in color) on **infrared** satellite images?

5a. On a **visible** satellite image, what would a relatively dark shade of gray represent? What about a relatively light shade?

5b. On a conventional black and white **infrared** satellite image, what would a relatively dark shade of gray represent? What about a relatively light shade?

6a. Which of the four features typically distinguishable on **visible** images (land surfaces, ocean surfaces, cloud tops, and snow/ice surfaces) tend to appear relatively dark? Which tend to appear relatively light? Which one generally appears the darkest?

6b. On an **infrared** image, which features (land surfaces, ocean surfaces, cloud tops, or snow/ice surfaces) tend to appear relatively dark and which relatively light, and under what conditions? (Consider time of year, time of day, latitude, and altitude.)

7. How is the time record that appears on each satellite image (in Universal Time Coordinates, or UTC-- also known as Greenwich Mean Time, or GMT) converted to local time in **Wyoming**?

The above web-based exercises (http://www.atmos.uwyo.edu/~geerts/atsc2000/lab/) and the reading in Ahrens should have familiarized you with the two types of satellite orbits, and with the most commonly used types of images. If you would like to test your knowledge, review your answers to questions 1 – 7 again, before proceeding further.

8a. What are the two types of satellite orbits?

8b. Which one of these two gives continuous imagery over the same region, e.g. the USA?

8c. Which one of these is closer to Earth and therefore able to take more detailed pictures?

II. Exercises

*Part III of the web module (*http://www.atmos.uwyo.edu/~geerts/atsc2000/lab/*) (Image Interpretation Excercises) lists the exercises. They are reproduced in the same order and with the same number sequence below (prefixed by II-) for your answers.*

II-1. The two visible images provided in Q1 show the West Coast of North America. The clouds off the coast are brighter in Image #2 than they are in Image #1. Why?

II-2a. What difference do you see in the brightness of clouds between lower and higher latitudes along the specified lines of longitude (75°W, 105°W, and 135°W)?

II-2b. In terms of the factors responsible for differences in brightness of features on visible images, what accounts for the differences?

II-3a. Based on the pair of visible images shown in Q3, which *generally* seems to have the higher albedo: (a) snow-free land surfaces, or (b) ocean surfaces? How can you tell?

II-3b. Are there some cases where snow-free land and ocean surfaces seem to have similar albedos? If so, where, and what does the land surface most likely consist of in such cases?

II-4. Based on the pair of IR images shown in Q4, what generally appears darker on IR images, land surfaces or ocean surfaces? Or can you say, in general? (If not, explain why).

II-5a. The pair of IR images in Q5 were recorded 8 hours apart. Note (a) the brightness of the land surfaces in each image and (b) the brightness of the ocean surfaces in each image. What difference do you see in the brightness of land surfaces between the two images? What accounts for the difference?

II-5b. What difference do you see in the brightness of ocean surfaces between the two images? Why is this behavior different from the behavior of the land surfaces that you observed?

II-6. Q6 makes reference to five different areas depicted on a map of the West Coast of the U.S.A. (see web page for Q6).

II-6a. On the IR image recorded at 14Z, which of the five areas identified on the map appear brightest? Which appear darkest? Which appear roughly the same as each other?

II-6b. Over the 6 hours from 14Z to 20Z, which of the five areas have changed brightness significantly, and in what sense (brighter or darker)?

II-6c. On the visible image recorded at 20Z, which of the five areas have relatively high albedo? Which have relatively low albedo? In each of the five areas, what feature (land surface, ocean surface, cloud top, or snow/ice surface) are we probably looking at?

II-6d. Explain why the foothills around the Central Valley became significantly darker (that is, warmer) between 14Z and 23Z, whereas most parts, if not all parts, of the other four areas did not.

II-7a. Based on the images shown in Q7, what type of image (visible or IR) is generally best for distinguishing high clouds from low clouds? Why?

II-7b. Which kind of image would generally best allow you to distinguish any cloud (low or high) from surrounding ocean or land surfaces? Why?

II-8a. What are at least two general rules that you can think of to help you identify a single image, recorded during the daytime, as IR or visible?

1.

2.

II-8b. What additional clue might you be able to use to identify a pair of images (of the same type) as IR or visible if they were recorded at different times of day?

ATSC 2000 Lab X Section: Mon. / Thurs. (Circle) **Name:**

10. Force Balances and Atmospheric Motion

Pre-lab Assignment

Before the Lab: Read all pages of Chapter 6 in *Meteorology - Understanding the Atmosphere* by S. A. Ackerman and J. A. Knox of the textbook, and this lab assignment. Also, answer the ***pre-lab questions*** below.

Answer these questions based on the information given in the text of this lab assignment. *This page must be turned in at the* ***beginning*** *of the lab period.*

1. What are the four basic forces that act on air parcels in the atmosphere?

2. Explain how these forces can be divided into two categories.

3. What two characteristics of an object's motion can be altered when a force acts on the object?

4. What would cause a pressure gradient force to be present in the atmosphere?

5. How does the strength of the Coriolis force vary for a fixed wind speed as one moves from the North Pole towards the equator?

6. What forces are in balance for geostrophic flow?

7. Describe the circulation around a circular low pressure center in the Northern hemisphere for a geostrophically balanced flow and for a flow that is influenced by friction.

ATSC 2000 Lab X Section: Mon. / Thurs. (Circle) Name ……………………….

Force Balances and Atmospheric Motion
Main Lab Assignment

I. Introduction

In this lab you will explore the forces which act on air parcels in the atmosphere. These forces are responsible for driving the observed winds and creating weather systems. Although the mathematics used to describe atmospheric motions can become very complex, the basic principles that govern these motions can be easily understood.

Once an understanding of the forces that act on the atmosphere is achieved you will be able to explain features of the atmosphere which you have likely observed in your daily activities. An example of this is the fact that low pressure systems are often accompanied by cloudy, stormy weather.

Lab Goals:

(1) Understand the factors that influence the magnitude and direction of the four forces (gravitational, pressure gradient, Coriolis, and frictional) acting on air parcels.
(2) Understand how the forces interact, leading to parcel motion, characterized by a resultant wind velocity.
(3) Understand how wind and pressure fields on weather maps are related.

II. Basic Forces in the Atmosphere

There are **four** basic forces that act on air parcels in the atmosphere. These forces can be subdivided into those that act on air parcels that are both at rest (not moving) or in motion, and those that act only on air parcels which are moving. The forces that act on an air parcel, regardless of whether or not it is moving, are the **force of gravity** and the **pressure gradient force**. Forces that act on an air parcel only when the parcel is in motion include the **Coriolis force** and the **frictional force**. These latter two forces increase in strength as the velocity of the air parcel increases.

When a force acts on any object it creates an acceleration. An acceleration can be in the form of a change in speed and/or a change in direction of the object's motion. If two forces act on an object in opposite directions and with equal strength, then the object experiences no acceleration, since the two forces exactly balance each other. Only when the sum of all of the forces acting on an object is non-zero will the object accelerate. When the sum of forces acting on an object is zero then the object either remains at rest (if it was initially at rest) or continues to move in a straight line at a constant speed, if it was initially in motion.

Of the four forces that act on parcels in the atmosphere, only the force of gravity does not directly influence horizontal atmospheric motions. The **force of gravity** pulls the atmosphere down towards the center of the Earth and prevents the air molecules from escaping to space, as may well have happened on less massive solar system objects like Mercury and the Moon.

The **pressure gradient force** (PGF) arises when there are *horizontal* differences in air pressure. This force acts in such a way that it accelerates air from regions of higher pressure towards regions of lower pressure. This is the primary force that initiates atmospheric motions. If the atmosphere is assumed to be initially at rest, and a constant pressure gradient force exists throughout the atmosphere, then the air will start to move from regions of higher pressure towards regions of lower pressure. Initially no other horizontal forces will act on the air because there is no motion. (Recall that the Coriolis and friction forces require motion before they can act).

The pressure gradient force is stronger when the pressure changes by a large amount over a small distance and is weaker when the pressure varies only slightly over large distances. The strength of the pressure gradient force can be estimated by looking at weather maps. On certain weather maps lines of constant pressure, called ***isobars***, are drawn to illustrate the pressure distribution at a given height in the atmosphere, so that regions of high and low pressure are discernible. Where these lines are packed closely together the pressure gradient force is large. Where the lines are widely spaced the pressure gradient force is small. In both cases the pressure gradient force is perpendicular to the isobars and points towards lower pressure. When scientists graphically display forces on a diagram, they draw an arrow pointing in the direction that the force is acting (for the pressure gradient force the arrow would point from higher pressure towards lower pressure). The length of the arrow is used to represent the strength, or magnitude, of the force. In the example above, the arrow used to represent the pressure gradient force would be longer in the region of closely spaced isobars and shorter in the region where the isobars are spaced further apart.

The **Coriolis force** is an apparent force that is caused by the rotation of the Earth. The laws which govern all motions assume that the frame of reference used to describe the motion is “fixed” and not moving. For the wind, we describe the motion relative to the surface of the Earth, so that when a meteorologist reports that the wind speed is 25 kts, it means that the wind is moving at a speed of 25 kts *relative* to the surface of the Earth. As the Earth is rotating, the frame of reference used to describe atmospheric motions is *not* fixed, and additional forces must be used to describe the motion. The additional force required to describe atmospheric motions is the **Coriolis force**. This force always acts perpendicular to the direction in which the air is moving, and is directed to the right of this direction in the Northern hemisphere and to the left in the Southern hemisphere. For example, if a southerly wind is observed (the wind is blowing out of the south towards the north) the Coriolis force acts towards the east in the Northern hemisphere, and towards the west in the Southern hemisphere. We are interested not only in the direction of the Coriolis force, but also in its magnitude. The magnitude of the Coriolis force increases as the wind speed increases. In addition, for the same wind speed, the magnitude of the Coriolis force becomes larger as you move polewards, and decreases as you move towards the equator. At the equator the magnitude of the Coriolis force is zero.

The final force that acts on the atmosphere is that of **friction**. As you know from everyday experiences, friction acts to slow down a moving object. The same is true in the atmosphere. A force that slows down an object must act in a direction opposite to the motion. For the example above, the southerly wind will have a friction force that is directed form the north towards the south (opposite to the air’s motion from south to north). The magnitude of the friction force increases as the wind speed increases and as the roughness of the surface increases. A mountainous region will have a greater roughness compared to a flat field of wheat, which will in turn have a greater roughness than a smooth surface of water. For these three types of surfaces and for a fixed wind speed, the friction force will be largest over the mountainous terrain and smallest over the smooth water.

III. Geostrophic Balance

Geostrophic flow occurs in the troposphere when the only forces acting on the atmosphere are the pressure gradient and the Coriolis forces, and they are in balance. This happens frequently at altitudes more than a kilometer or so above the surface, where frictional forces are essentially non-existent. Lower down, close to the surface in the so-called *planetary boundary layer*, the force of friction must be considered.

Initially, it may be puzzling to understand how atmospheric motion is possible if the pressure gradient and Coriolis forces are exactly balanced. To understand this phenomenon, let’s assume that the atmosphere is initially at rest and that there is a constant pressure gradient force acting throughout the atmosphere. An air parcel initially at rest will begin to accelerate due to this pressure gradient force. The pressure gradient force accelerates the air from regions of higher pressure towards regions of lower pressure. Remember that the Coriolis force only acts on air that is already in motion, and so it is zero when the air is at rest. Once the pressure gradient force begins to accelerate the air, the Coriolis force will start to influence the motion. Initially the wind speed will be small and thus so will the Coriolis force. This small Coriolis force will still start to deflect the wind towards the right of its initial motion, in the Northern hemisphere. As the wind continues to accelerate, the Coriolis force will become larger, even though the pressure gradient force remains constant. Eventually the wind speed will be sufficiently large for the Coriolis force to have deflected the air parcel through 90° to the right. The magnitude of the Coriolis force will then be exactly equal to that of the pressure gradient force. See page 172 of text. The two forces will be directed in opposite directions, so there will be no net acceleration on the air and it will continue to move in a straight line. In order for these two forces to be directed in opposite directions the wind must be blowing such that lower pressure is to its left and higher pressure to its right (looking downwind). This is because the Coriolis force always acts to the right of the wind direction in the Northern hemisphere and that the pressure gradient force is always directed towards lower pressure. Thus, lower pressure must be to the left of the wind.

For a circular pattern of isobars, the geostrophic flow will be directed counterclockwise around a low pressure center and clockwise around a high pressure center, in the Northern hemisphere, as shown in Figure 6.15 of the text. The opposite directions apply in the Southern hemisphere.

For certain applications meteorologists will produce maps on a constant pressure surface rather than at a constant height. Recall that constant height maps are marked with lines of equal pressure (isobars). Constant pressure maps are instead labeled with lines of constant height. The height of a pressure surface in the atmosphere will vary with location. As an example, the height of the 500 mb surface is lower towards the poles than it is towards the equator. The lines on a constant pressure map can be interpreted in the same way that lines on a topographic map are interpreted. An important feature of these two map types is that they have the same pattern if drawn for similar locations in the atmosphere and thus lines of constant height can be interpreted in the same way as isobars. The pressure gradient force will be directed towards lower heights and will have a larger magnitude when the height contours are more tightly packed. A geostrophic wind drawn on a constant pressure map will be directed such that lower heights are to the left of the wind direction, in the Northern hemisphere and the geostrophic wind speed will increase as the height contours become more closely spaced.

IV. Flows influenced by friction

Now consider a flow that is in geostrophic balance that begins to be affected by friction. The friction force will decrease the wind speed from the value it would be if no friction were present, so the wind speed will become less than the geostrophic value. As the wind speed decreases, the Coriolis force must also consequently decrease. The pressure gradient force remains unchanged however, and will therefore now have a larger magnitude than the Coriolis force, so that the wind will be disproportionately influenced by the pressure gradient force, and turn towards lower pressure. Whenever friction acts on the atmosphere the wind will be directed at least partially towards regions of lower pressure and away from regions of higher pressure. See Figure 6.19. As the roughness of the surface increases, the friction force for a given wind speed also increases, and the wind has a larger component across the isobars (height contours) towards lower pressure (heights). You can explore force interactions at http://profhorn.meteor.wisc.edu/wxwise/kinematics/testwind.html

As noted previously, geostrophic flow circulates counterclockwise around a low pressure center in the Northern hemisphere, paralleling the isobars. When friction starts to influence this flow, the winds are still directed in a counterclockwise sense, but now spiral in towards the center of low pressure. Similarly, winds affected by friction spiral outwards from a center of high pressure in a clockwise fashion.

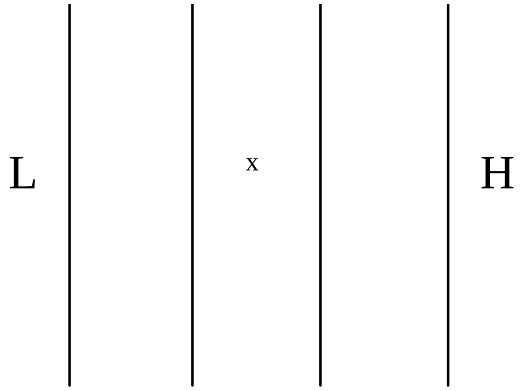
The flow of low level air inward toward low pressure centers and outward from high pressure centers causes vertical motion. As air spirals into a low pressure center, the air that accumulates in the center of the low must be displaced. Since this *convergence* into low pressure centers only occurs near the surface of the Earth, the air cannot be displaced down into the surface, and so it must rise. The opposite occurs with a high pressure center. Air *diverges* away from the high pressure center, and since this air cannot come from the surface, it enters the circulation from aloft by descending down into the high pressure center. Therefore, low pressure centers are characterized by rising motion and high pressure centers are characterized by sinking motion. See Fig. 6.24 in the text.

From previous lab assignments you have realized that when air is forced to rise it cools, resulting in an increase in relative humidity. If the air is forced to rise sufficiently, the relative humidity will reach 100%, condensation will occur, clouds will form, and precipitation may occur. Since low pressure centers are characterized by rising motion, they are therefore often associated with clouds and precipitation. In regions around high pressure centers the air is sinking. Air that is forced to sink becomes warm and its relative humidity decreases. Therefore regions of high pressure are characterized by clear skies and fair weather.

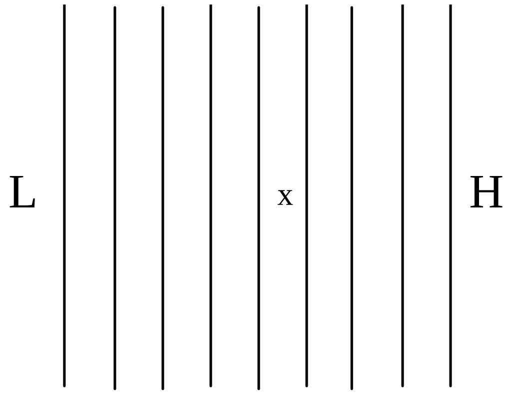
V. Exercises

1. Draw arrows which represent the pressure gradient force at the marked locations (“x”) on the maps below. *Remember, the pressure gradient force always acts at right angles to the isobars*. The contours (lines) represent isobars on a constant height map. Indicate the direction of the pressure gradient force with an arrow and represent the *magnitude* of the force by the *length* of the arrow. <u>Make sure that the magnitude of your forces (i.e., the length of your arrows) for each part of this problem are consistent with each other part of the problem, given on the next page.</u>

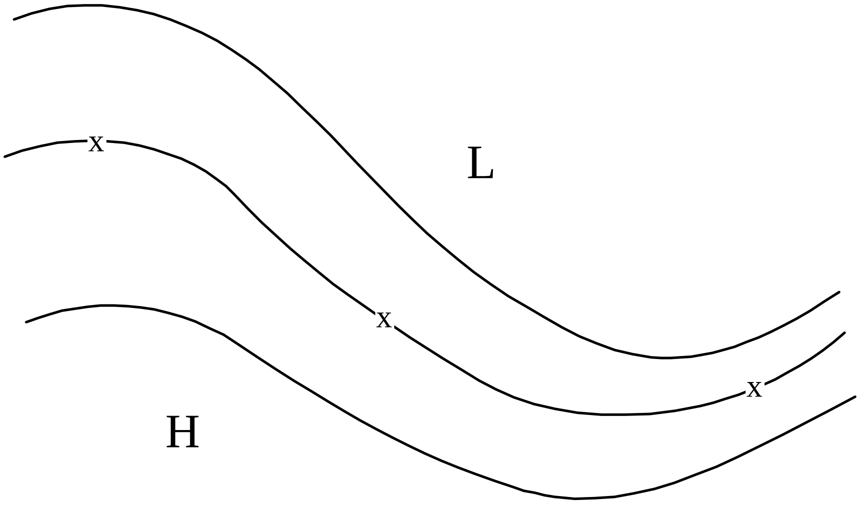
1a.



1b.



1c.



2a. Assume that the wind speed is 20 m s^{-1} at both 60°N and 25°N. At which of these two latitudes is the Coriolis force that acts on the wind largest?

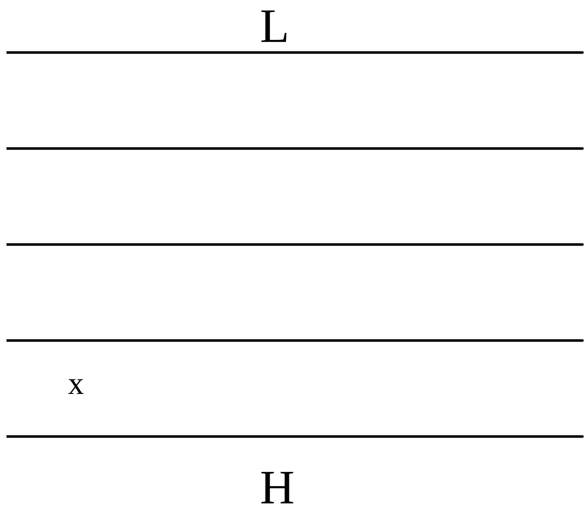
2b. Why?

2c. What is the direction of the Coriolis force on the wind at the two latitudes from problem 2a if the wind is blowing from the west at both locations?

2d. What would your answer to problem 2c be if the latitudes were in the Southern hemisphere?

2e. If there is a 20 m s^{-1} wind blowing at the equator, what is the magnitude of the Coriolis force? Why?

3. Starting at the marked location on the map below, illustrate how the atmosphere, initially at rest, will arrive at geostrophic balance for the given pattern of isobars. Assume that the map represents conditions in the Northern hemisphere. Draw the path that the air parcel will follow as it comes into geostrophic balance, and mark the *direction* and *magnitude* of the pressure gradient and Coriolis forces on this path at the starting position, at an intermediate location, and at the final position.



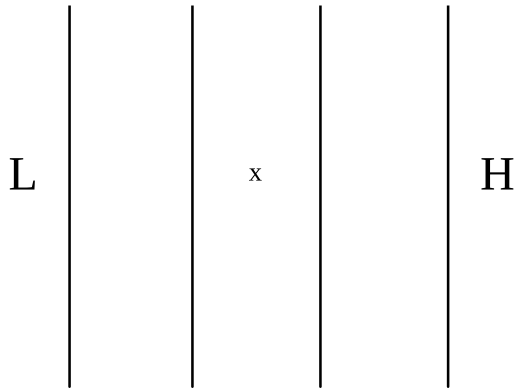
4. For each problem below, draw a picture which illustrates the direction of the pressure gradient and Coriolis forces, and the location of the low and high pressure centers for the given geostrophic wind directions. Assume that north is at the top of the page.

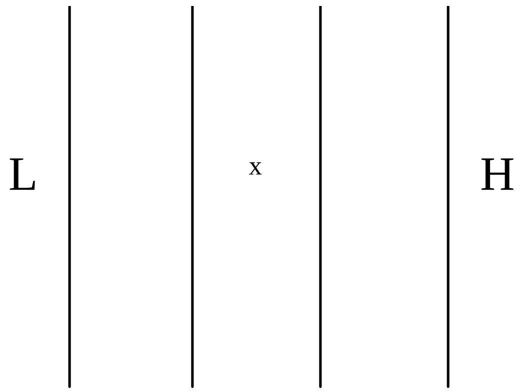
4a. West wind, Northern hemisphere

4b. West wind, Southern hemisphere

4c. Southwest wind, Northern hemisphere

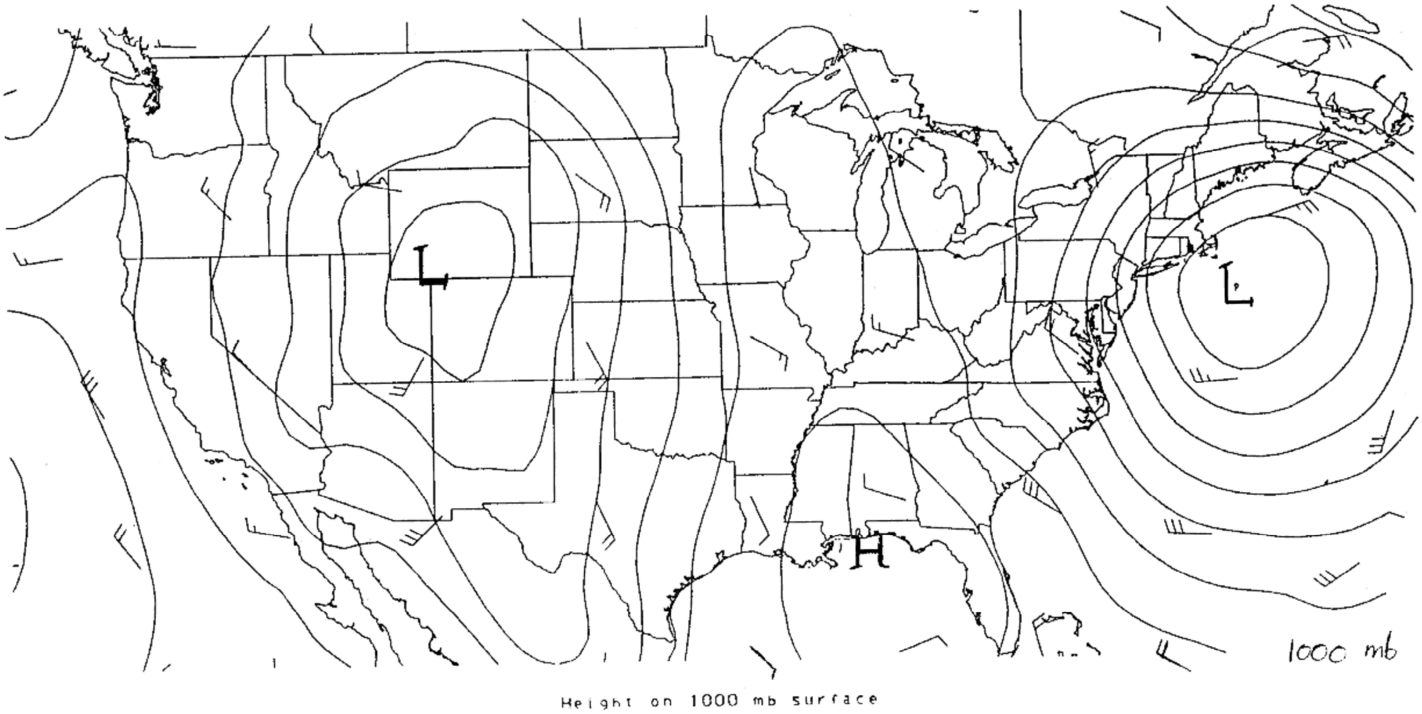
5a. For the figures below, draw the geostrophic wind that would be expected for the given pattern of isobars in the top figure, and the wind that would be expected if the pressure gradient, Coriolis, and friction forces were balanced in the bottom figure. Include arrows that represent the forces acting on the wind in each diagram. Label all arrows in your figures. (Assume that the given pressure distributions are located in the Northern Hemisphere).





5b. Explain why the two wind vectors drawn for problem 5a are different.

6. Use the map of the 1000 mb height contours and wind vectors below to answer the following questions.

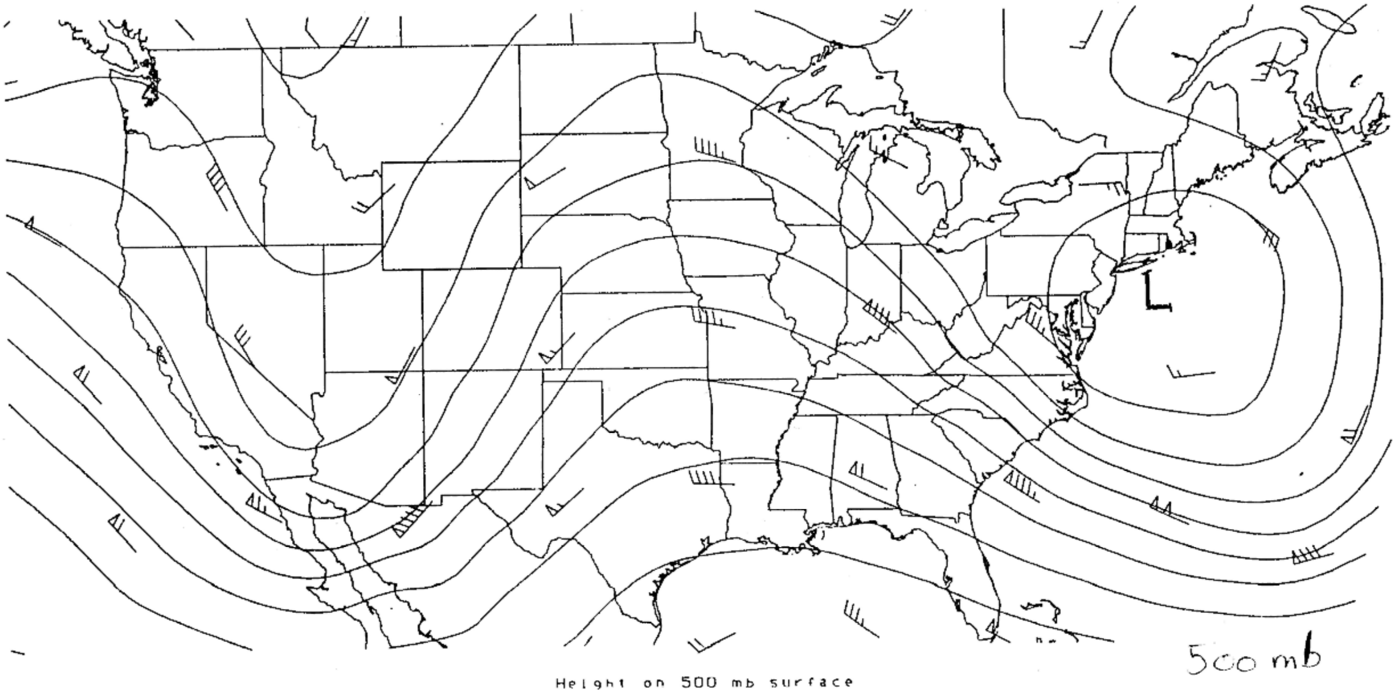


6a. Are the plotted winds on this map geostrophic? How can you tell?

6b. Explain why the wind vector plotted in southeastern Utah is directed nearly perpendicular to the height contours in that region, while the wind vector plotted south of the low pressure center in the Atlantic Ocean is nearly parallel to the height contours.

6c. Why are the wind vectors plotted in South Dakota and Kansas turned in an intermediate direction relative to the height contours compared to the wind vectors discussed in problem 6b? Explain your answer completely.

7. Use the map of the 500 mb height contours and wind vectors below to answer the following questions.



7a. Do the winds on this map appear to be in geostrophic balance? How can you tell?

7b. Where are the strongest and weakest winds located on this map?

7c. Explain why the strongest winds are found at the location given in problem 7b.

7d. Explain why the weakest winds are found at the location given in problem 7b.

8. Given that the 1000 mb pressure surface is located nearly at the surface of the Earth while the 500 mb pressure surface is located approximately 5 km above the surface of the Earth, do your answers to problems 6a and 7a make sense? Explain.

9a. On the vertical cross-section of the atmosphere drawn below, indicate the horizontal wind direction expected near the surface of the Earth and the vertical motions expected above each pressure center, indicated by H and L. Then, complete the circulation. Remember that the tropopause acts as an 'upper lid' to the motion.

9b. Based on the air flows you have drawn in the figure in problem 9a, explain why cloudy skies are associated with low pressure centers near the surface of the Earth.

9c. Based on the air flows you have drawn in the figure in problem 9a, explain why clear skies are associated with high pressure centers near the surface of the Earth.

Note: Next week's pre-lab requires both time and effort to complete successfully!
Lab instructors: please spend some time in Lab 10 introducing the students to contour analysis. Please go to http://cimss.ssec.wisc.edu/wxwise/contour/contour1.html and try each of the lessons.

ATSC 2000 Lab XI Section: Mon. / Thurs. (Circle) **Name:**

11. Frontal Disturbances: Part I: Surface Charts

Pre-lab Assignment

Before the Lab: Read all pages of Chapter 9 in *Meteorology - Understanding the Atmosphere* by S. A. Ackerman and J. A. Knox of the textbook, and this lab assignment. Also, answer the ***pre-lab questions*** below. ***Do not underestimate the effort required to complete the pre-lab questions successfully!***

Answer these questions based on the information given in the text of this lab assignment. *This page must be turned in at the* ***beginning*** *of the lab period.*

1. List the four basic air mass types.

2. Define what is meant by the term front.

3. What are the four types of fronts?

4. Go to http://www.atmos.uwyo.edu/~geerts/atsc2000/lab/synlab/ and click on Pre-lab assignment. After viewing the images of satellite, radar, and surface weather conditions, analyze the weather chart, valid for 00 Z on 17 October 1996. This chart is at the back of this manual. Make sure you use the chart for October 17th!

Draw isobars (lines of constant pressure) with a contour interval of 4 mb, starting at the lowest pressure (i.e., 1000 mb, 1004 mb, 1008 mb, etc). Pressure is shown in the upper right corner of each station plot. Look back to Lab 1 if you need help decoding the station model. Remember that the pressure is located in the upper right and that it is coded into 3 digits. It is often helpful to write down the coded pressure that you would like to contour (i.e., 000, 040, 080, etc.) so you don't have to keep decoding it. Also, draw in the cold front (thick, blue line with triangles) and warm front (thick, red line with half-circles), if present. Here are some guidelines:

- Typically the isobars are smoothly-curved lines, but they do show a kink at the cold front.
- Isobars are aligned more or less with the wind, although the wind often crosses the isobars at a small angle, from high to low pressure.
- Try starting your contours at the edges of the map.

Analyzing a weather chart is more than a contouring exercise, it needs an understanding of the relationship between wind and isobars to do correctly. Even the best meteorologists can only do this with pencil and eraser – it is very much a trial and error procedure. Be ready to hand in your hand-analyzed chart as part of your pre-lab.

Note that the web-based pre-lab includes a module that teaches you how to contour (click on "try these exercises first" in paragraph four, and then each of the "Lessons").

ATSC 2000 Lab XI Section: Mon. / Thurs. (Circle) Name ……………………………….

Frontal Disturbances: Part I: Surface Charts
Main Lab Assignment

I. Introduction

The daily weather depends on what happens aloft, in the troposphere. The objective of this lab is to demonstrate typical patterns of surface weather in mid-latitudes, where day-to-day weather variations are dominated by fronts, especially in winter. This lab is tightly linked to the next lab, which will demonstrate that the changes experienced at the surface are connected to events in the upper troposphere, the realm of the jet stream. These two labs together should give you a good insight into the structure and evolution of mid-latitude cyclones and frontal disturbances.

Maps that depict weather conditions at the surface of the Earth are referred to as surface weather maps. On these maps meteorologists analyze the positions of low and high pressure centers as well as the location of fronts. In this lab you will locate the position of a cold front based on available surface weather station data, and record changes in the weather as the front passes specific individual weather stations.

Lab Goals:

1. Gain expertise in drawing contour lines on surface weather maps.
2. Learn to identify regions of high/low pressure and frontal boundaries on weather maps.
3. Use surface weather map information to track a developing weather system.

II. Fronts and Air Masses

An air mass is simply a large part of the atmosphere that has relatively uniform characteristics. Air masses form over regions that have fairly constant, uniform surface characteristics, such as large expanses of the ocean or the Arctic tundra. The characteristics of a given air mass depend on the type of surface over which it forms and the time of year that it forms. The forces that act on the atmosphere may cause an air mass to move from its formation region into other locations. The movement of different air masses over a given location, such as Laramie, gives us the variations in day-to-day weather with which we are all familiar.

Air masses are classified based on their temperature and moisture content. Cold air masses are referred to as polar (P), while warm air masses are referred to as tropical (T). Dry air masses have the designation continental (c) and moist air masses have the designation maritime (m). From these categories four combinations are possible, leading to **four** air mass types. These air mass types *(italicized)* are listed in the table below.

Origin	**Polar (P)**	**Tropical (T)**
Continental (c)	*cP*	*cT*
Maritime (m)	*mP*	*mT*

In reality there is a continuum from one airmass to another, of course. The atmosphere simply does not classify itself into distinct regimes as do species in the biosphere. Yet sometimes the transition from one airmass to another is surprisingly abrupt, something that is somewhat puzzling if you think of warm and cold airmasses as fluids like coffee and milk, which mix rather easily in a cup. These abrupt boundaries of airmasses are called *fronts,* a term borrowed from World War I, the period when weather fronts and their evolution were first described.

Fronts are identified based on the temperature of the air mass that moves into a given region once the front passes. Thus a **cold front** is a boundary that, once it passes your location, ushers in colder air. Similarly, a **warm front** is a boundary that brings warmer temperatures to a location as it passes by. If the boundary between two air masses is not moving, the front is a **stationary front**. In addition to these three frontal types, meteorologists also recognize **occluded fronts**, which have a more complex structure. More on those in the next lab.

In this lab assignment you will identify fronts based on available surface weather observations. What are the clues that meteorologists look for on a weather map when identifying the location of frontal boundaries? The first, and most obvious answer, is a large change in temperature over a short distance. A cold front marks the leading edge of a change from relatively uniform warm temperatures to colder temperatures. Sometimes the temperature pattern is not clear, and other clues must be used to locate the position of a front. Therefore, weather observations of humidity, wind, and pressure are also used.

A cold frontal passage at a given location is typically characterized by the following changes: a rapid decrease in temperature behind the front, drier air (lower dewpoint) behind the front, a veering of the wind, e.g. a shift in direction from a southerly direction ahead of the front to a westerly direction behind the front, and an increase in pressure. Not all of these "typical" characteristics are necessarily observed, however, with every cold frontal passage. When locating a cold front, start at the surface low pressure and work outwards away from it. Often the cold front will be most distinct close to the *low* (i.e., the low pressure center) and will become more diffuse as one moves further away, until eventually no front can be identified. Satellite and radar imagery can also be used to locate a front, because clouds and precipitation are often associated with fronts. In this lab you will be aided by this imagery. A cold front is often, but not always, at the leading edge of a comma-shaped cloud mass.

Remember that the location of a given front is not always obvious. If a group of meteorologists were asked to locate a front on exactly the same surface weather chart, each of them might pick slightly different locations for a given front, or they may disagree even on whether a front is actually present! Despite the different answers these meteorologists give, they will all have good *reasons* for locating the front in a given position. This is an important point to remember. Whenever locating a front make sure that you have good reasons for picking one location over another. This is the only way you can defend your choice to other meteorologists.

After the Lab: Don't forget to answer the **post-lab take-home questions** in section IV of this lab assignment.

III. Exercises

Compare your frontal analysis performed in the pre-lab with the "correct" one**,** to be handed out by your lab assistant, and discuss the differences with your colleagues and lab assistant.

1. What is the local time of the map you analyzed, in Laramie (assume MDT)?

2. Fill out the Table below with observations at Cheyenne WY (labeled CYS on the chart), and at Wichita KS (labeled ICT, in south-central Kansas). Make sure you enter the correct units for each variable. Remember also to decode coded weather observations (such as sea level pressure). Refer back to Lab I if you need to review how to do this.

Date/Time	961017/0000	
station ID	**CYS**	**ICT**
temperature (ºF)		
dewpoint (ºF)		
sea level pressure (mb)		
wind speed (kts)		
wind direction		
cloud cover		
pressure tendency (mb)		

3. Determine whether Cheyenne was in the prefrontal warm airmass or the postfrontal cold airmass at this time. Explain your choice in terms of temperature, dewpoint, wind direction, and pressure tendency.

- temperature high or low?
- dewpoint high or low?
- wind direction (draw an arrow):
- pressure tendency up or down?
- conclude: warm or cold airmass?

4. Determine whether Wichita was in the prefrontal warm airmass or the postfrontal cold airmass at 00 UTC on 10/17/96. Again explain your choice.

- temperature high or low?
- dewpoint high or low?
- wind direction (draw an arrow):
- pressure tendency up or down?
- conclude: warm or cold airmass?

5. Follow the directions in http://www.atmos.uwyo.edu/~geerts/atsc2000/lab/synlab/. On the left, click on “lab” for Lab XI. After viewing the imagery, **analyze the surface weather chart at 00 UTC on 18 October 1996**, i.e. 24 hours later than the chart you did in the Pre-Lab. This chart is in the back of this manual. Again, draw the contours of constant pressure (isobars), and the fronts. Invariably you will do better this time than the first time.

6. Fill out the following observations:

Station	**ICT (Wichita, KS)**	
Date/Time	961017/0000	961018/0000
temperature (ºF)		
dewpoint (ºF)		
sea level pressure (mb)		
wind speed (kts)		
wind direction		
cloud cover		
pressure tendency (mb)		

7. Note that the changes you see in Wichita cannot be explained by the changes from day to night: the two observations were made at the same time of the day. Now determine whether Wichita, at 00 UTC on 10/18/96, that is 24 hours later, was still in the prefrontal warm airmass, or not. Explain your choice, as you did before (next page).

* temperature high or low?

* dewpoint high or low?

* wind direction (draw an arrow):

* pressure tendency up or down?

* conclude: warm or cold airmass?

8. How did the cold front move from day 1 (00 UTC on 17 October) to day 2 (00 UTC on 18 October)? Give both direction, and estimated speed. To estimate speed, you need a map scale. You can use this scale: along its southern state-line, Kansas is 414 miles wide. (Make a note of your answer so that you will be able to answer Post-Lab question 5).

9. In what direction did the low move in the same 24-hour period?

10. Did the minimum sea level pressure of the low change, and if so, by how much?

Day 1 minimum pressure:

Day 2 minimum pressure:

Difference:

11. In what direction did the postfrontal high move in the same 24-hour period?

12. Did the maximum sea level pressure of the high change, and if so, by how much?

Day 1 maximum pressure:

Day 2 maximum pressure:

Difference:

Don’t forget to complete the **post-lab exercises** before next week’s lab.

Lab IV. Section: Mon. / Thurs. **Name:**

Frontal Disturbances: Part I: Surface Charts
Post-lab Assignment

Answer these questions based on what you have learned in this lab. *This page must be turned in at the* ***beginning*** *of the next lab period.*

Follow the directions in http://www.atmos.uwyo.edu/~geerts/atsc2000/lab/synlab/. On the left sidebar, click on “post-lab” for Lab XI. You will need to follow instructions on the web to be able to answer the questions below.

1. In what type of airmass is Indianapolis in the radar image shown?
2. In what type of airmass is Des Moines IA?
3. Does the frontal surface slope back to the west, or forward to the east?
4. Determine the depth (or height) of the cold airmass at 12 UTC on 18 Oct, in kilometers.
5. Estimate the speed of the cold front from the animated cross section, and compare to the speed you obtained in Q8 of the Lab.
6. At what time does the squall line first form? Express time in UTC and CST.
7. Why do you think it started at that time of the day?
8. Using the speed you calculated in Q5, predict the time at which the cold front will pass through Indianapolis.
9. Determine at what time (between which two hours) a cold front passed through Denver?

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12. Frontal Disturbances. Part II: The Jet Stream and Surface Weather

Pre-lab Assignment

Before the Lab: Read pages 192 – 203 of Chapter 7 and pages 282 – 291 of Chapter 13 in *Meteorology - Understanding the Atmosphere* by S. A. Ackerman and J. A. Knox of the textbook and this lab assignment. Answer the ***pre-lab questions*** in section IV of this lab assignment.

Pre-lab Questions **(***Turn in this page at the* ***beginning*** *of the lab session).*

Answer these questions based on the information given in the text of this lab assignment.

1. What is the jet stream, and how does it behave?

2. Why does the jet stream form in the upper troposphere of the mid-latitudes?

3. What happens to the jet stream when a cP airmass plunges down from the Canadian Plains towards the Gulf of Mexico?

Go to http://www.atmos.uwyo.edu/~geerts/atsc2000/lab/synlab/ and click on “Pre-lab” for Lab XII. First we are going to look at the current weather forecast. Please follow the instructions on the web, and then answer the following questions.

4. How many major streaks do you count in the jet stream around the northern mid-latitude belt? How many major trofs?

5. We return to our 16-18 October 1996 case study from last week’s Lab. Describe what happens to the jet streak in the jet stream as it moves from the west, over the Pacific Northwest and further eastward, between 12 UTC on 16 October and 18 UTC on 18 October.

6. At what *altitude* is the jet strongest? (Convert the pressure units, used in the image, to km)

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Frontal Disturbances. Part II: The Jet Stream and Surface Weather
Main Lab Assignment

I. Introduction

The purpose of this lab is to build on the knowledge about fronts and airmasses gained in last week's lab (Lab XI), and to gain some understanding about why *frontal disturbances* develop in the first place. Without these disturbances (or cyclones), the mid-latitude belt, which includes Laramie, would be much drier, and, moreover, would be colder in winter, especially over continents. After discussing the typical evolution of frontal disturbances, we will explore the *jet stream*, discuss why it is there, and gain some insight into the role it plays in the existence and evolution of frontal disturbances. To do this we need to look at *upper-level charts*, i.e. charts of temperature, pressure, and winds in the middle and upper troposphere.

Lab Goals:
(1) Understand how the jet stream helps the formation of mid-latitude cyclones.
(2) Follow the development of a mid-latitude cyclone both at the surface and aloft.

II.a Tropical and mid-latitude cyclogenesis

Hurricanes are intense, deep low-pressure centers (or *lows* or *cyclones* for short) that form over warm, tropical oceans. These storms are fueled by water vapor evaporated from warm ocean surfaces. As the water vapor condenses in the eyewall updraft, latent heat is released. The rate of evaporation increases with wind speed (clothes on a line dry faster when it is windy). More evaporation means more fuel for the storm. This implies a *positive* feedback cycle which explains the intensification of weak tropical depressions to full-blown hurricanes. There is also a negative feedback, friction. The more wind, the more friction, which tends to decelerate and dissipate the storm. A lot of fuel is therefore needed. Consequently, these *tropical cyclones* will only form when the sea surface is at least 80ºF. At lower temperatures the lower atmosphere cannot hold enough water vapor to fuel the storm. Remember that saturation vapor pressure increases rapidly with increasing temperature.

Once you realize how sensitive tropical cyclones are to sea surface temperature, you may be surprised to learn that cyclones also grow and evolve in the colder mid-latitude belt (30-60º N and S). In fact these *mid-latitude cyclones* tend to be more frequent and more intense in *winter*, when it is even colder. They can even develop over land (although they tend to grow more vigorously over oceans). These lows tend to form in areas where a large *temperature gradient* exists, unlike tropical cyclones, which form in a uniformly warm environment.

How is it that cyclones form away from the tropics, near a *frontal* zone separating warm from cold airmasses? What feeds mid-latitude cyclones? It is the *jet stream*. Its kinetic energy fuels the storms that keep places like Ireland and the coastal regions of the Pacific northwest wet. And, as we will see, the jet stream aloft exists because of the frontal zone below.

II.b The jet stream

The jet stream is a current of strong winds in the mid-latitude upper troposphere. It is surprisingly narrow, usually narrower than the state of Wyoming. It never follows a steady track. Instead, it meanders like a trickle of water running down a window. Sometimes it fans out, and sometimes it speeds up as it flows through a constriction, as do some rivers. The rapids (on a river) are called *streaks* in the jet stream. Both the meanders (*Rossby waves*) and the jet streaks are important in the fueling of mid-latitude cyclones.

The jet stream exists because of the frontal (*baroclinic*) zone, present in the lower troposphere in the mid-latitude belt. The jet stream blows *above and along frontal zones*, keeping the cold airmass to its lower left, in the northern hemisphere. This cold dense air polewards of the frontal zone leads to low pressure in the upper troposphere at high latitudes. In fact the whole polar region has low pressure aloft. This sets up a strong pressure gradient, which results in particularly vigorous geostrophic flow around the polar region. This is the flow that constitutes the jet stream. Contrast this large temperature gradient with the tropics where warm air prevails everywhere throughout the year. Furthermore, in winter the high latitudes cool off significantly, especially over the continents, resulting in an even larger temperature gradient and a stronger jet stream. And with a stronger jet comes more intense frontal disturbances.

The next question to be addressed is 'why does the jet meander and streak'? Mid-latitude cyclones that develop at the surface provide the answer. As the winds circulate around these intensifying lows they distort the baroclinic zone. Recall that in the northern hemisphere, the winds are blowing counterclockwise, so that on the western side of the low, northerly winds advect cold air southward, producing a cold front. As the cold airmass is swept southward, the jet stream too must move south, producing or amplifying a *trof* (dip) in the jet stream. And on the eastern side of the low, southerly winds advect warm air northward, producing a warm front. As the warm airmass sweeps northward, the jet stream too moves north, amplifying a *ridge* in the jet stream. This meander in the jet is known as a *Rossby wave*.

The Rossby waves and jet streaks, themselves dependent on the fronts and frontal disturbances in the lower troposphere, in turn fuel mid-latitude storms. When the jet stream is changing its orientation and/or speed it requires an acceleration or deceleration, which is only possible if air is pulled up from below in diverging regions of the jet, and pushed down on the other side of the jet in convergence regions. Where air is sucked up, clouds, precipitation, and *cyclogenesis* (i.e. the formation of a surface cyclone) occur. Where air is pushed down, the subsidence causes clearing, dry air, and a surface high. There is a lot of truth in the expression that "after rain follows sunshine".

This proposed explanation may sound like a circular argument! In fact, it's not so much a circular argument as yet another example of *positive feedback*. Thus the jet stream and mid-latitude cyclones are interdependent phenomena that exhibit synergistic behavior. For example, consider a cold continental airmass and a warm air mass that has been heated by relatively warm ocean waters, meeting over the US Gulf and mid-Atlantic coasts during winter. The resulting high low-level temperature gradient implies a strong jet stream (streak) aloft. Now consider that a tiny meander forms in this jet stream, one that is perhaps even too small for weather balloons and weather models to detect. This meander may be sufficient to trigger a feedback loop that ultimately produces, through the prevailing *baroclinic instability*, a massive cyclone at the surface. The cyclone in turn will eventually distort the jet stream so much that the jet can no longer fuel the storm, causing the cyclone to dissipate. This lab focuses on the life cycle of just such a cyclone, from its birth as a frontal disturbance until its death as it dissipates.

After the Lab: *Don't forget to answer the post-lab take-home questions in section V of this lab assignment.*

III. Exercises

We will perform the exercises as a class group, with the TA acting as our 'tour guide' through the sequence of maps to be examined. Go to http://www.atmos.uwyo.edu/~geerts/atsc2000/lab/synlab/ and click on "lab" for Lab XII. The case study we will review is the same as that used in last week's lab, i.e. the frontal disturbance that developed over the Great Plains on 16-17 October 1996. Our focus now will be on the vertical structure of the storm.

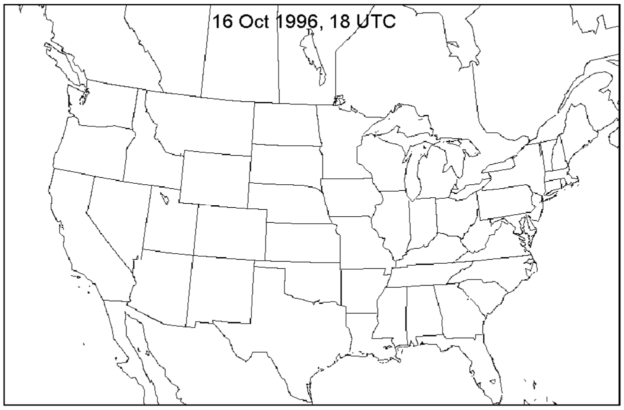
A. Vertical structure of lows and highs, trofs and ridges

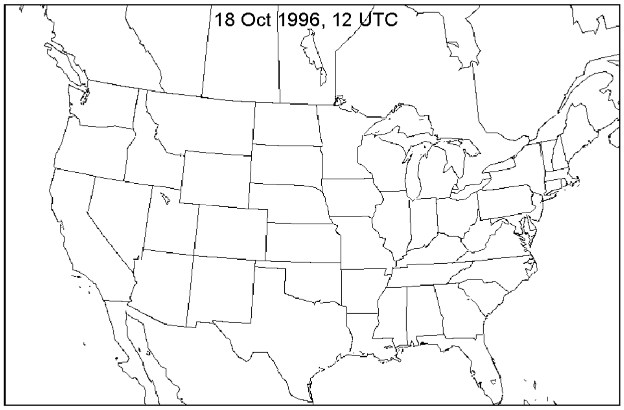
1. At what level is the atmospheric pressure topography steepest? (Hint: at what level are the contours most closely packed? Choose from 1000, 850,700, 500, and 250 mb)

2. At what level is the jet stream in the cross section you saw in the Pre-lab? Explain the relationship between the steepness of isobaric surfaces and the wind speed.

3. How does the surface low, centered near Duluth MN, change position and shape as you move up from the surface to the lower stratosphere?

4. On the outline of North America below, mark the positions of the low/trof at the two different times shown (place three asterisks, labeled 1000, 500, and 250)





5. Compare the trof's vertical tilt of the young disturbance on the left (18 Z on 10/16) to that of the mature disturbance on the right (12 Z on 10/18).

B. The surface low and the jet stream aloft: a synergy

1. How many surface lows do you count around the mid-latitude belt?

2. The two major lows are near Iceland and the Aleutian Islands. Ignore these two lows. Do the other lows move, and if so, in what direction?

3. Do these other lows maintain the same strength, do they weaken, or do they intensify?

4. Is there a relationship between the location of 500 mb trofs (or lows) and the surface lows?

5. In an open-wave cyclone, the upper trof is to the _________ of the surface low (fill out: *west* or *east*).

6. Clearing skies and rising pressure occur ____________ the cold front (fill out: *ahead of* or *behind*).

7. The upper trof is located above the ____________ airmass _____________ the cold front (fill out either *cold … behind* or *warm… ahead of*)

C. Lifecycle of a frontal disturbance

1. Indicate which stage each of the following snapshots of this evolving frontal disturbance is in. Choose from: initial stage (I), open wave cyclone stage (II), or occluding cyclone stage (III).

Date/time	Stage	Date/time	Stage
10/16 18 Z		10/18 00 Z	
10/17 00 Z		10/18 06 Z	
10/17 06 Z		10/18 12 Z	
10/17 12 Z		10/18 18 Z	
10/17 18 Z			

2. Explain your choice of stage for the 18 UTC 16 October case. <u>Circle the correct choice</u>:

   a) *where is the surface low relative to the upper-level trof?*

   to the east of the UL trof — almost right below the UL trof

   b) *where is the surface low?*

   in the cold airmass — in the warm airmass

   c) *is the upper trof shallow or deep?*

   shallow — deep (high amplitude wave)

   d) *has the upper trof become a cut-off low?*

   open wave — cut-off low

3. Explain your choice of stage for the 18 UTC 18 October case. <u>Circle the correct choice</u>:

   a) *where is the surface low relative to the upper-level trof?*

   to the east of the UL trof — almost right below the UL low

   b) *where is the surface low?*

   in the cold airmass — in the warm airmass

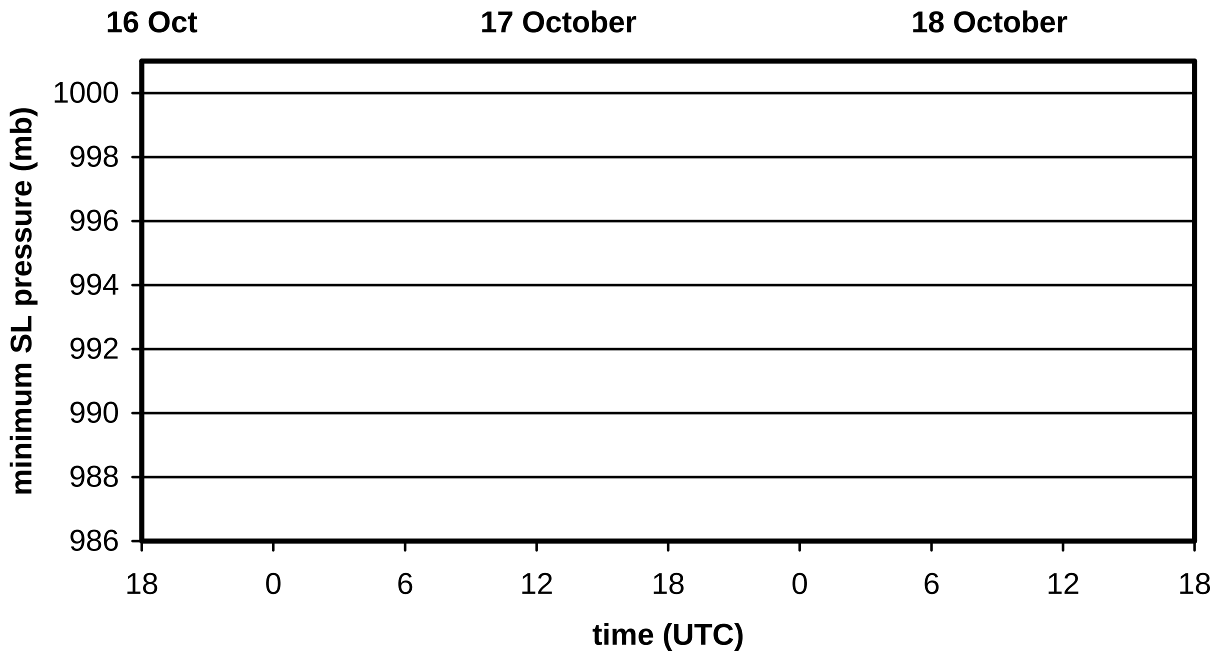
   c) *is the upper trof shallow or deep?*

   shallow — deep (high amplitude wave)

   d) *has the upper trof become a cut-off low?*

   open wave — cut-off low

4. Using the 9 charts you just examined, plot the minimum sea-level pressure vs. time, on the chart below. Indicate when the cyclone was most intense.



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Frontal Disturbances. Part II: The Jet Stream and Surface Weather
Post-lab Assignment

Answer these questions based on what you have learned in this lab. ***Even though there is a Take Home Lab next week, this lab assignment is still due to your TA by the start of lab.***

Follow the directions in http://www.atmos.uwyo.edu/~geerts/atsc2000/lab/synlab/. On the left, click on "post-lab" for Lab XII. You will need to follow instructions on the web to be able to answer the questions below.

10. Identify A-E on the surface chart of 00 UTC on 18 October 1996. You can choose from: *cold front, warm front, warm sector, low, post-frontal high*.

    a. :

    b. :

    c. :

    d. :

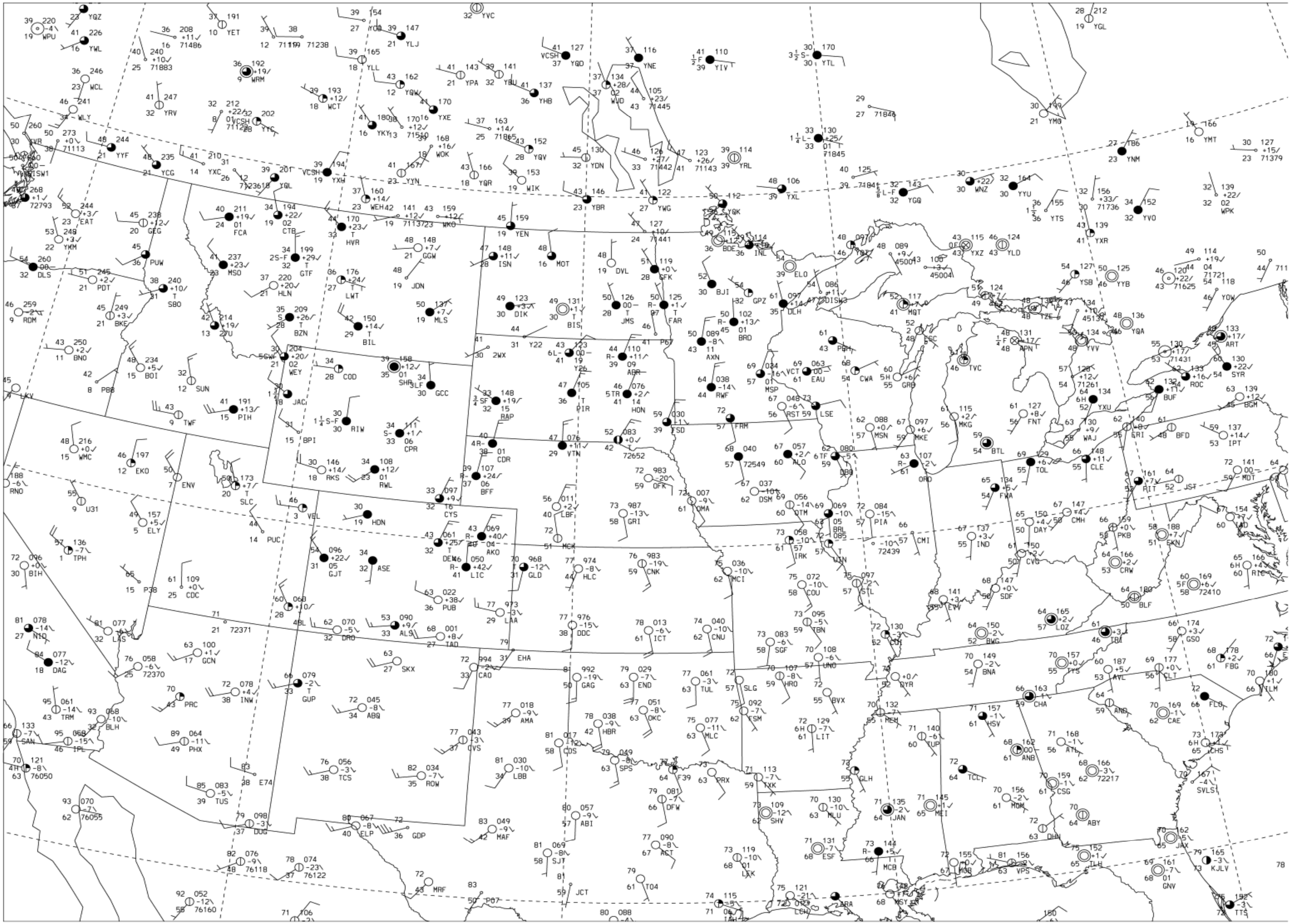
    e. :

11. Initially the surface low is in the .... air, while 24 hours later it is in the .... air (fill out: *cold* or *warm*).

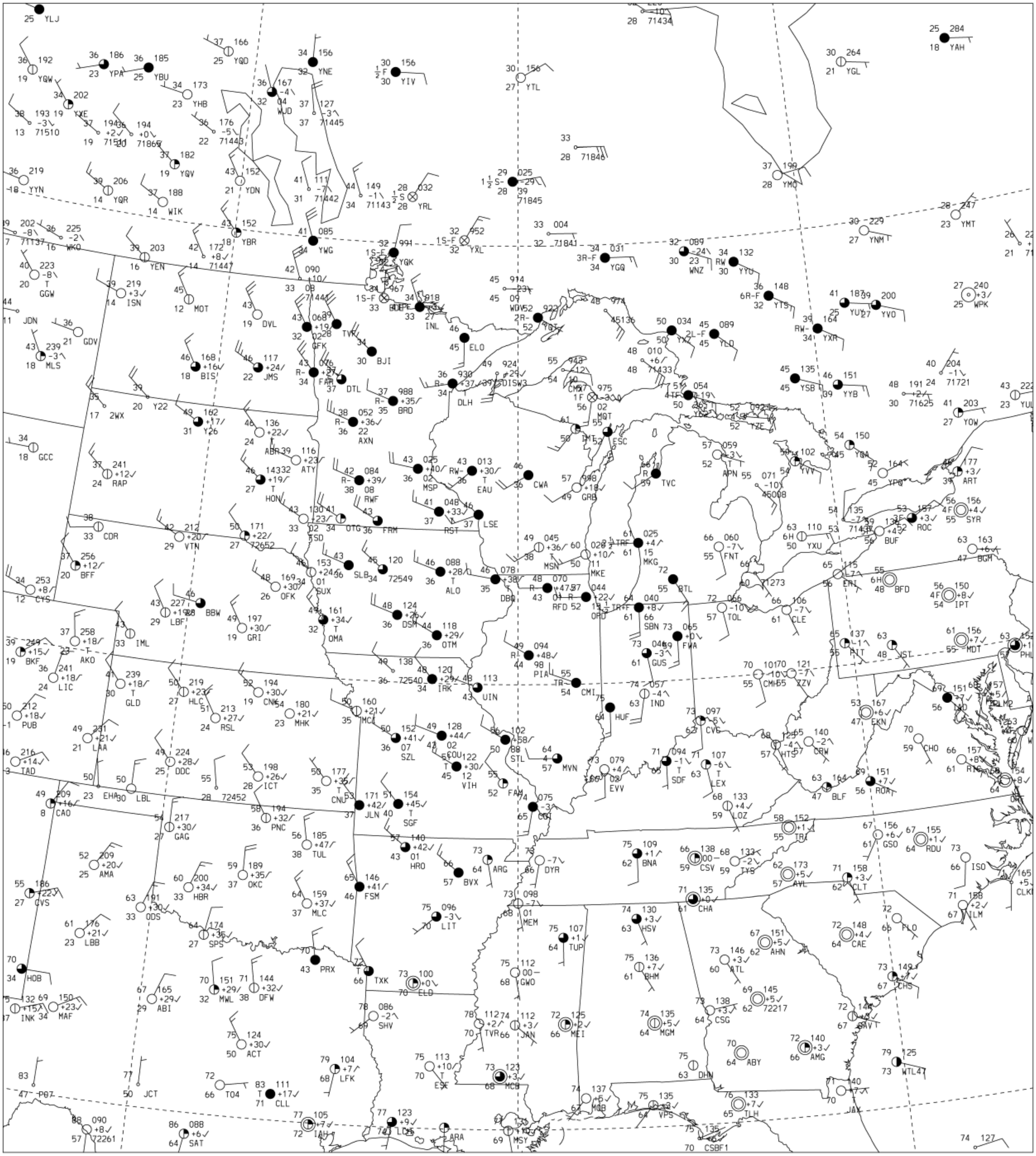
12. When the surface low moves into the cold airmass, the frontal disturbance is in the ………………. stage (fill out: initial, open-wave, occluding)

13. Why is there so little precipitation along the cold front initially (before 18 Z on 17 October), and why does heavy precipitation fall along the cold front when it moves further southeast (after 18 Z on 17 October)?

14. In what stage of development is the frontal disturbance at 06 UTC on 17 October?

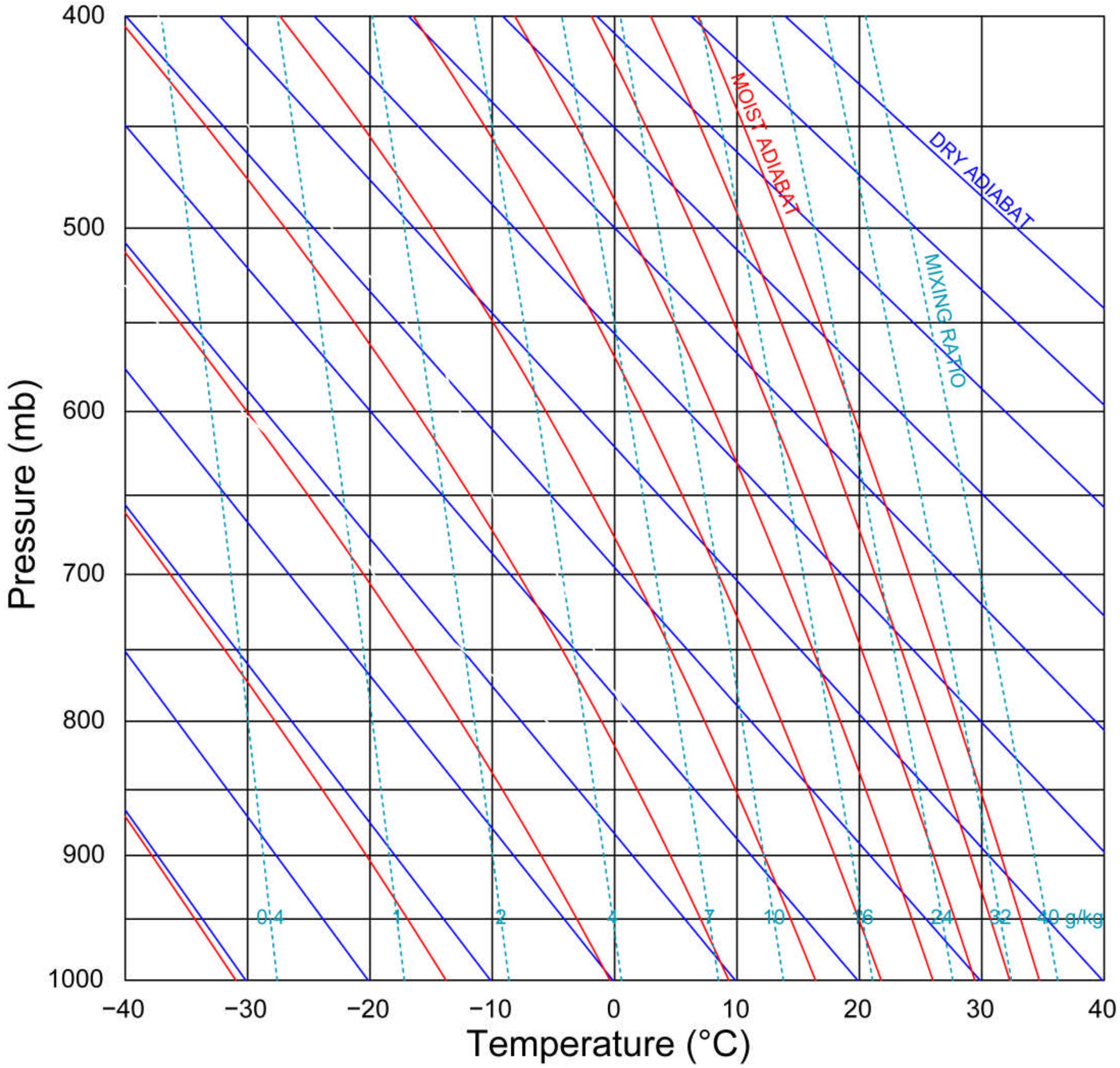


17 OCT 96 0000Z

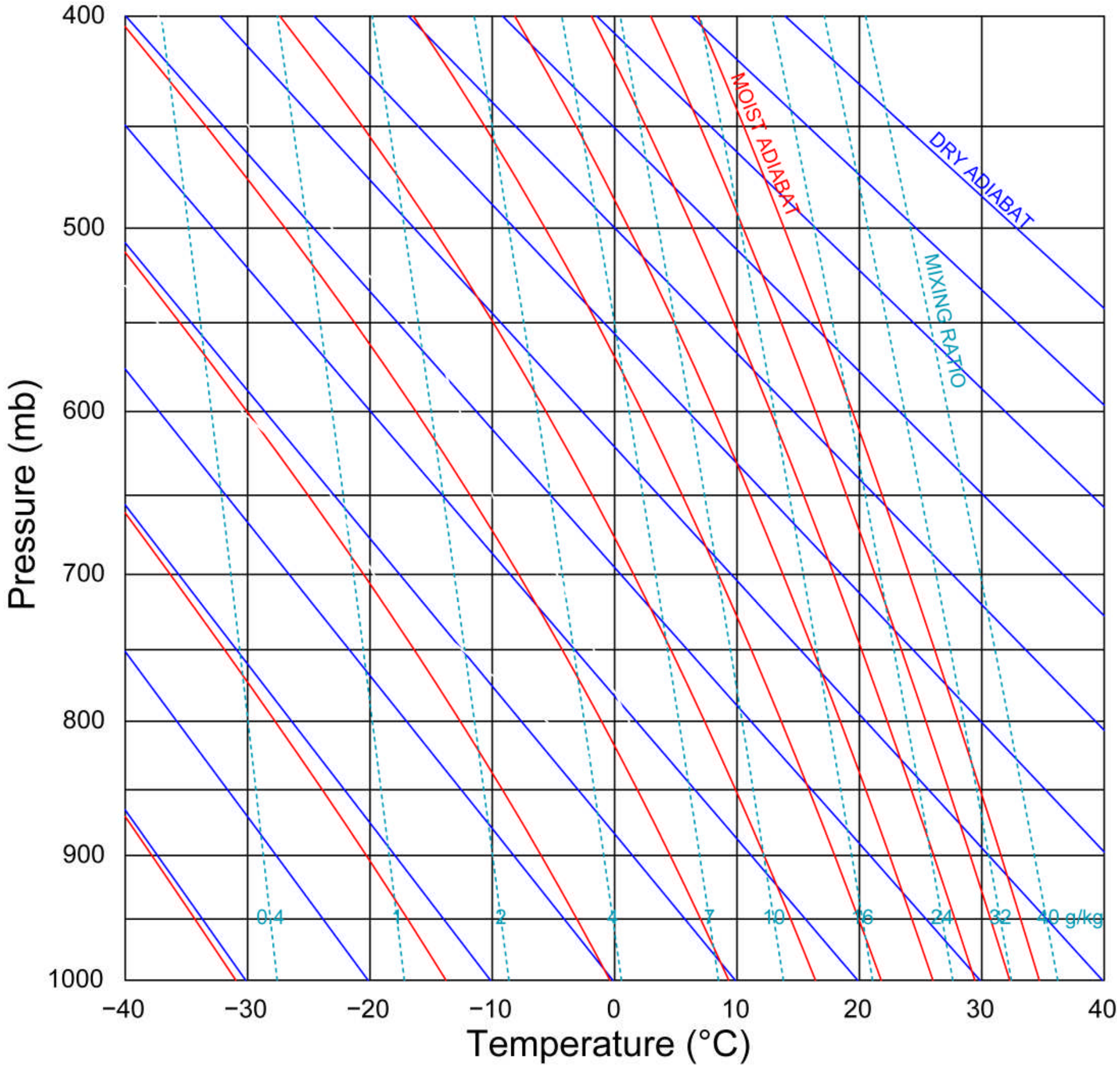


18 OCT 96 0000Z

STUVE THERMODYNAMIC DIAGRAM



STUVE THERMODYNAMIC DIAGRAM



STUVE THERMODYNAMIC DIAGRAM