GEO 1130: Meteorology

Course Catalog Description

Survey of atmospheric processes that create weather. Topics include solar radiation, temperature, moisture, pressure, wind, storm systems, weather forecasting, and air pollution. Problem solving skills and use of satellite imagery included. ***Prerequisites***: Enthusiasm! (and basic high school math)

General Information

Class Times	LL-124, 10:30-11:20 AM MWF
Required Texts	The Atmosphere 11th Ed. by Lutgens et al. (IBSN 0-321-58733-2), Dire Predictions (ISBN 978-0-1360-4435-2), and Course Materials Packet
Instructor	John Armstrong
Office Hours	SL 205, 10:30 AM - 12:30 PM, TTH, or by appointment
Email	jcarmstrong@weber.edu
Web	http://www.weber.edu/jcarmstrong
Phone	801.626.6215

Course Goals

GEO 1130 is an introductory survey of meteorology, the branch of geosciences that seeks to increase our understanding of Earth's atmosphere. We will examine fundamental atmospheric processes as a means of understanding the dynamic aspects of weather and climate. Since the interaction and impact of humans on Earth's climate system is a topic of daily discussion in the media, government, and industry, this course will focus on developing tools for understanding how the climate system is measured, analyzed, and understood using the scientific method.

Our course goals include:

- developing skills in using scientific inquiry in general and understanding the climate system in particular
- understanding the functions of Earth's atmosphere and how it interacts with other parts of Earth systems (hydrosphere, biosphere, and lithosphere)
- appreciating the importance of geoscience knowledge to human endeavors, with specific reference to meteorological hazards, air pollution, and climate change.

Assignments

Throughout the semester, you will receive homework assignments to be completed outside of class. These assignments will include a weather log, analysis of local and regional weather patterns, and other analysis problems. Homework assignments will be due at the beginning of class on the due date. Late assignments will be accepted, but the score will drop by 20% for each day late. For example, an assignment due on Monday would be worth 20% on the following Friday.

The In-Class Activities

We will also be conducting a number of in-class activities throughout the semester. All of these activities and materials are supplied in class. These will give you hands-on experience with difficult concepts, and, in general, are a lot of fun. Attendance is mandatory for credit.

Exams

There will be three, equally weighted exams during the course. These serve as a measure of your 'retained' knowledge and will help you (and me) keep tabs on your progress. If you must miss an exam, please make arrangements **in advance**. Makeup exams will not be given except under the most extreme circumstances. All exams will be held in the College of Science testing center.

Grading Policy

The course grading philosophy assumes that you will learn the most in the class from actually doing astronomy, either through homework assignments or in-class assignments. Therefore, the course grade is weighted towards the assignment rather than the exam end of things. 55% of your course grade comes from the assignments and activities. The other 45% comes from the exams.

Assignments	35%
In-Class Activities	20%
Exams (3 at 15% each)	45%

Attendance Policy

I will not be taking attendance in class, but much of your grade relies on regular attendance. I highly recommend you attend class all the time! We plan on having a lot of fun, so you really wouldn't want to be anywhere else, would you?

Expectations and Responsibilities

I want to stress upfront that this is a quantitative science course. With that in mind, we will be doing some math. Some of your assignments will require you to employ some mathematical skills, which I will help you refresh/acquire in this course. I expect you to give yourself adequate time to complete the assignments and to put a good faith effort into all of your collaborative work. You should expect me to provide you with as much support as humanly possible, including technical/psychological math support and general sympathy. That said, starting the assignment on the day it is due is an excellent way to dissolve the sympathy part! If you give me enough lead time to help, I will make sure you get it. My office hours are posted, and I can be available at other times if necessary. I am here to make sure you get as much out of this course as you possibly can.

Academic Integrity

Regarding academic integrity, I will enforce policies as laid down in Section IV:D of the Student Responsibilities outlined in the Student Code. Specifically, no cheating or other forms of academic dishonesty will be tolerated. The first instance of cheating will result in a zero on that assignment. The second instance will result in failing the class. You will be working in groups occasionally, however, so you will be required to distinguish the difference between collaboration and cheating. When in doubt, make sure to give credit where credit is due.

Special Accommodations

Any students requiring accommodations or services due to a disability must contact Services for Students with Disabilities (SSD) in room 181 of the Student Service Center. SSD can also arrange to provide course materials (including this syllabus) in alternative formats if necessary.

GEO 1130: Meteorology

Schedule (Subject to Change)

	Week of...	Weekly Topic	Reading	Notes
	3-Jan	Introduction to the Atmosphere	Ch 1	
Heat	10-Jan	Heating of the Earth and Atmosphere	Ch 2	
	17-Jan	Temperature	Ch 3	Martin Luther King Day January 17
	24-Jan	Moisture and Stability of the Atmosphere	Ch 4	
	31-Jan	Condensation/Precipitation	Ch 5	Exam 1 (Friday, no class)
Motion	7-Feb	Air Pressure and Wind	Ch 6	
	14-Feb	Atmospheric Circulation	Ch 7	
	21-Feb	Air Masses	Ch 8	Martin Luther King Day February 21
	28-Feb	Weather Patterns	Ch 9	
Weather	7-Mar	Tornados and Thunderstorms/Hurricanes	Ch 10 and 11	Exam 2 (Friday, no class)
	14-Mar	Spring Break		
	21-Mar	Weather Analysis and Forecasting	Ch 12	
	28-Mar	Air Polution /Climate Change	Ch 13, 14	
Impact	4-Apr	Climate Change	Ch 14	
	11-Apr	World Climates	Ch 15	
	18-Apr	Exam Review (Monday)	Finals Week Begins (Tuesday)	

GEO 1130: Meteorology

Course Materials

Instructor: John Armstrong
jcarmstrong@weber.edu

GEO 1130: Meteorology

Assignments

Instructor: John Armstrong
jcarmstrong@weber.edu

Assignment 1: Your Weather Journal

The single most important way to understand weather and climate is to document it. Throughout the semester, we will all be keeping a daily weather journal to record the weather conditions and forecast the weather.

What you'll need

- A journal or notebook. It should be sturdy since it will get daily use and it might even get wet!
- Pencil or pen
- Some weather

What to do

At least once each day, you will record the weather conditions. This should only take a few moments to record some information about the weather and your thoughts and observations. Eventually, you'll record data from your own weather station (see Assignment 2) but for starters, you should include:

- The time of day
- The temperature
- Rain and snow conditions, cloud cover, and wind conditions
- Environmental observations (flowers in bloom, leaves turning color, snow on the mountains, and the like)
- Your prediction for tomorrows weather
- Your thoughts and feelings

An example

24 August, 2009 – My Weather Log

Time: 10:00 AM MDT
Temperature: 74 degrees F
Rain/Snow: None
Cloud cover: Clear
Wind Conditions: Light
Environmental Conditions: The garden is doing well requiring less water in the unseasonably cool weather

Prediction: Tomorrow will be pretty much like today, since I can't see any storm systems coming and the weather has been pretty stable over the last couple of days.

Thoughts: The cool weather is surprising for this time of year. I recall last year it got pretty hot the week school started (in the 90s) and stayed warm for a while. I actually rode my bike 15 miles yesterday in the afternoon is was so pleasant. Hopefully more of the same tomorrow!

Assignment 1: Regional and National Weather Monitoring with the New York Times

We will be discussing regional and national weather trends throughout the semester using the New York Times weather section. Your task is to read the New York Times for weather-related stories for discussion in class as well as monitor various locations using data from the weather page. The New York Times is available for free from one of several racks on campus (there is one located in the Union Building and the Science Lab Building, as well as other locations).

What you'll need

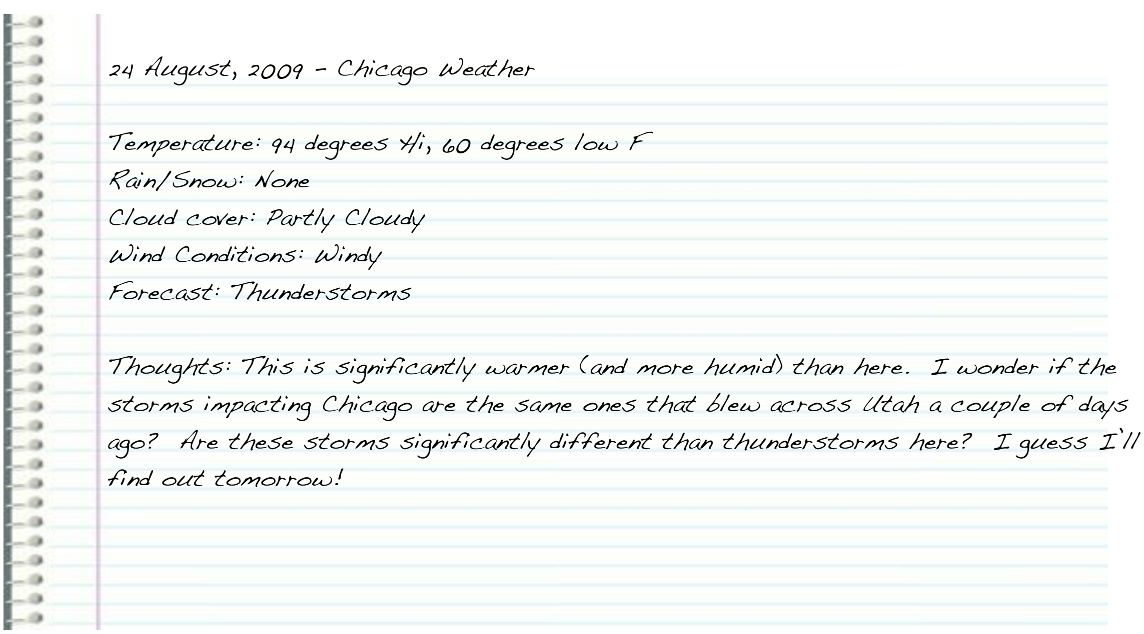
- Your weather journal
- Pencil or pen
- The New York Times
- Some weather

What to do

On Monday, Wednesday, and Friday pick up a New York Times and bring it with you to class. Spend a few minutes reviewing the news for weather-related stories (for class discussion!) and then turn to the New York Times weather section. We will be monitoring weather patterns and forecasts as they happen. In addition, select one city you will be keeping track of throughout the term and record this in your weather journal. Things to record:

- The high and low temperatures for that day
- Rain and snow conditions, cloud cover, and wind conditions
- Deviations from "normal" conditions (we will discuss how to determine what is "normal")
- How this compares to your local weather and some thoughts about the similarities and differences.

An example



Weather Journal Evaluation **Name:**

Item	Score	Comments
Daily Record (30 points)		
NY Times Daily (30 points)		
Data Analysis September (10 points)		
Data Analysis October (10 points)		
Data Analysis November (10 points)		
Weather Forecast Analysis (30 points		
Total		

Assignment 2: Building your own weather station[1]

Now that you are keeping a weather journal, you need some data to record. We are bombarded by weather forecasts and data from the radio, TV, and the internet, but very few of us have access to actual data from our local surroundings. In Utah in particular weather can change from moment to moment and place to place so getting accurate, local data is important.

In this assignment, you'll build your very own weather station that can measure temperature, pressure, humidity, rain fall, wind direction, and wind velocity. Note: If you already have a weather station, you are still required to build your own. You can compare the accuracy to your store-bought station in your weather journal.

What to hand in:

- You will be recording data from your weather station for the rest of the term, but I would love to see photographic documentation of your cool weather station. By the due date, email me (or print out and bring in) a photo of your personal weather station!

Part I: Building the Box and Measuring Temperature

What you'll need

- A weather-proof plastic box
- An inexpensive thermometer (you can buy these at Walmart for a dollar)

What to do

1. Since weather happens outside, you'll need to construct your weather station inside of a weatherproof box. Find a sturdy plastic or wooden box that can be placed on its side. Before you take the box outside, attach a thermometer to the inside of the bottom of the box. Once you turn the box on its side, the thermometer will be in the back of the box, protected from direct weather conditions.
2. Take your box outside and find a safe, sturdy location on the north side of the building where it's shadiest. Position the box securely beside the building, perhaps on a brick foundation.

Part 2: Building the Barometer (to measure changes in pressure)

Since barometers are very sensitive to minor changes in weather conditions, you'll want to keep the barometer indoors to get more accurate readings.

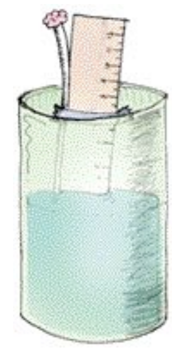
What you'll need

- A glass or beaker with straight sides
- a 12-inch ruler
- tape
- one foot of clear plastic tubing
- a stick of chewing gum
- water

[1] Modified from instructions provided by the Franklin Institute Resources for Science Learning

What to do

3. Begin by standing the ruler in the glass and holding it against the side. Tape the ruler to the inside of the glass. Make sure that the numbers on the ruler are visible.



4. Stand the plastic tube against the ruler in the glass. Make sure that the tube is not touching the bottom of the glass by positioning the tube up a half inch on the ruler. Secure the tube by taping it to the ruler.
5. Chew the stick of gum so that it is soft. While you're chewing, fill the glass about half way with water. Use the plastic tube like a straw and draw some water half way up the tube. Use your tongue to trap the water in the tube. Quickly move the gum onto the top of the tube to seal it.
6. Make a mark on the ruler to record where the water level is in the tube. Each time you notice a change in the water level, make another mark. You'll notice, over time, that the water level rises and falls. Pay attention to the change in weather as the water level changes.
7. The water in the tube rises and falls because of air pressure exerted on the water in the glass. As the air presses down (increased atmospheric pressure) on the water in the glass, more water is pushed into the tube, causing the water level to rise. When the air pressure decreases on the water in the glass, some of the water will move down out of the tube, causing the water level to fall. The change in barometric pressure will help you to forecast the weather. Decreasing air pressure often indicates the approach of a low pressure area, which often brings clouds and precipitation. Increasing air pressure often means that a high pressure area is approaching, bringing with it clearing or fair weather.

Part 3: Building the Hygrometer (to measure changes in humidity)

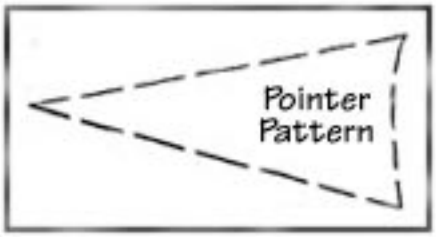
Place your hygrometer outdoors, inside your weatherproof weather station box. The hygrometer will measure the amount of moisture in the air, or humidity.

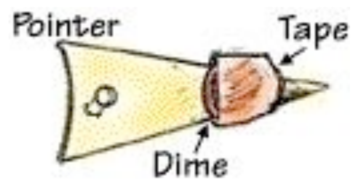
What you'll need

- a scrap of wood or flat styrofoam (about 9 inches by 4 inches)
- a flat piece of plastic, 3 inches by 3 inches thin enough that you can cut
- 2 small nails
- 3 long strands of human hair (8 inches long)
- a dime
- glue
- tape
- hammer
- scissors strong enough to cut plastic

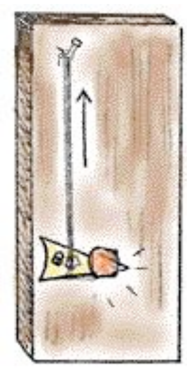
What to do

1. First, cut the piece of plastic into a triangular shape (refer to pictures). Then, tape the dime onto the plastic, near the point. Poke one of the nails through the plastic pointer, near the base of the triangle. Wiggle the nail until the pointer moves freely and loosely around the nail. On the plastic pointer, between the dime and the nail hole, glue the hair strands to the plastic.





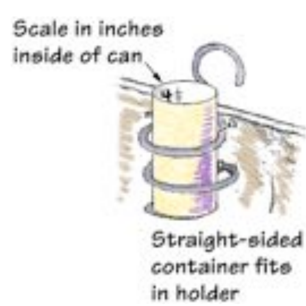
2. Position the pointer on the wood or styrofoam base about three quarters of the way down the side. (Refer to picture.) Attach the nail to the base. The pointer must be able to turn easily around the nail. Attach the other nail to the base about one inch from the top of the base, in line with the pointer. Pull the hair strands straight and tight so that the pointer points parallel to the ground. That is, make sure the point of the pointer is perpendicular to the hair. The hair should hang perfectly vertical and the pointer should point perfectly horizontal. Glue the ends of the hair to the nail. If the hair is too long, trim the ends.



3. The human hair cells will indicate the level of moisture in the air by expanding and contracting. When their air is moist, the hair will expand and lengthen, making the pointer point down. When the air is dry, the hair will contract and shorten, making the pointer point up. When you make your hygrometer observations each day, you should make a mark to indicate where the pointer points. Over time, you'll be able to see the humidity patterns that will help you forecast the weather.

Part 4: Building the Rain Gauge (to measure rainfall)

Your rain gauge needs to be kept outdoors, but not inside the weatherproof box. If it's possible, though, you may want to keep them near each other to make it easier to record your data.



What you'll need

- a glass beaker, or straight-sided container that can be marked with a measuring scale

- a metal coat hanger (bent to make a holding rack)
- hammer and nails (to secure that rack)

What to do

1. Basically, any measuring glass left outside can serve as a rain gauge. However, since most rain showers are usually quite windy, you'll want to fasten your rain gauge somewhere so that it doesn't blow over. Locate a good place for your gauge. There should be nothing overhead, like trees, electric wires, or the edge of a roof. These obstructions can direct rainwater into or away from your gauge, creating a false reading. The edge of a fence, away from the building, is often a good place for your gauge.

2. Once you have found the spot, attach the holding rack (refer to picture). Then, slip your measuring glass into position. Wait for rain, then record your measurement, and empty the glass.

Part 5: Building the Weather Vane (to measure wind direction)

A weather vane is also know as a wind direction indicator. The vane points in the direction from which the wind blows.

What you'll need

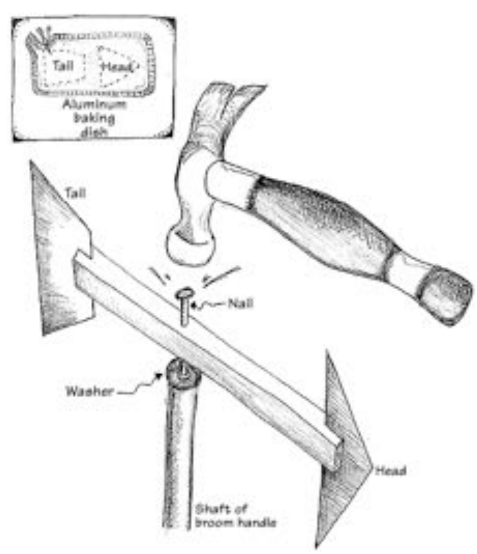
- A long wooden dowel (about the size of a broom-stick)
- an aluminum pie plate
- a 12-inch long piece of wood (like a sturdy ruler)
- nails
- a metal washer
- hammer
- glue
- small saw or serrated knife
- wire (for mounting)
- scissors (strong enough to cut the pie plate)

What to do

1. Begin with the 12 inch piece of wood. Use the small saw (or serrated knife) to cut a vertical slit at each end of the stick. The slit should be about one half inch deep. At the midpoint (exactly halfway) of the top of the stick, hammer one nail all the way through the stick. Then turn the wood around the nail several times until the stick turns easily around the nail.

2. Refer to the pattern picture and cut the head and tail from the aluminum plate. Glue the head into the slot at one end of the wooden stick. Glue the tail into the other end. Allow time for the glue to dry before you take the vane outside.

3. Attach the weather vane to the long wooden dowel by placing the metal washer on the end of the dowel and then hammering the nail through the wooden stick and into the wooden dowel. (Refer to the pic-



ture.) Make sure that the vane moves freely and easily around the nail.

4. Now you are ready to mount your weather vane outside. If you mounted your rain gauge on a fence, you may want to mount your weather vane near it. Position the wooden dowel beside the fence and secure it with wire. Try to get the vane as high above the fence as you can while still keeping the dowel steady and secure.

5. The head of the pointer will always point to the direction from which the wind is blowing. For example, if the head points to the Northeast, then the wind is blowing from the Northeast. It's as simple as that. (A common mistake is to think that the wind is blowing toward the North-East.) Record your wind direction readings in your weather journal.

Part 5: Building the Anemometer (the wind-o-meter, to measure velocity)

An anemometer helps you determine wind speed. Use it with your weather vane to measure the wind.

What you'll need

- Five 3 ounce paper dixie cups
- Two straight plastic soda straws
- a pin
- scissors
- paper punch
- small stapler
- sharp pencil with an eraser

What to do

1. Take four of the Dixie cups. Using the paper punch, punch one hole in each, about a half inch below the rim.

2. Take the fifth cup. Punch four equally spaced holes about a quarter inch below the rim. Then punch a hole in the center of the bottom of the cup.

3. Take one of the four cups and push a soda straw through the hole. Fold the end of the straw, and staple it to the side of the cup across from the hole. Repeat this procedure for another one-hole cup and the second straw.

4. Now slide one cup and straw assembly through two opposite holes in the cup with four holes. Push another one-hole cup onto the end of the straw just pushed through the four-hole cup. Bend the straw and staple it to the one-hole cup, making certain that the cup faces in the opposite direction from the first cup. Repeat this procedure using the other cup and straw assembly and the remaining one-hole cup.

5. Align the four cups so that their open ends face in the same direction (clockwise or counterclockwise) around the center cup. Push the straight pin through the two straws where they intersect. Push the eraser end of the pencil through the bottom hole in the center cup. Push the pin into the end of the pencil eraser as far as it will go. Your anemometer is ready to use.

6. Your anemometer is useful because it rotates with the wind. To calculate the velocity at which your anemometer spins, determine the number of revolutions per minute (RPM). Next calcu-

late the circumference (in feet) of the circle made by the rotating paper cups. Multiply your RPM value by the circumference of the circle, and you will have an approximation of the velocity of at which your anemometer spins (in feet per minute). (Note: Other forces, including drag and friction, influence the calculation but are being ignored for this elementary illustration. The velocity at which your anemometer spins is not the same as wind speed.)

7. The anemometer is an example of a vertical-axis wind collector. It need not be pointed into the wind to spin. (Note: This paper cup anemometer will produce a reasonable approximation of circumferential velocity, but should not be used for any purpose other than elementary illustration.)

Part 6: Building the compass (for measuring direction)

To record your weather data, you'll need a compass. You can make your own using only a stick, a few stones, and the sun.

What you'll need

- A flat area where the sun shines directly (no shade)
- A straight stick or dowel, about 18 inches long
- Four heavy rocks (about the size of golf balls)
- A few smaller stones for marking

What to do

1. Locate a flat sunny space near your weather station. Begin by digging a hole about six inches deep. Bury the base of the stick. The stick should now be standing up to a height of twelve inches.

2. The first thing you'll need to do is locate "North." In the morning, place a small marking stone at the end of the shadow cast by the stick. Later in the afternoon, the shadow should be about the same length as it was in the morning, but in a different direction. Place a marking stone at the end of the afternoon shadow. Position your right foot on the morning stone and your left foot on the afternoon stone. Your body now faces south. Another way to think of this is that the two shadows meet at the stick to form an "arrow" pointing south.

3. Once you have located "south," place one of the four heavy stones on the ground, about twelve inches in front of the stick. Position a second stone in the "north" position by tracing a straight line opposite away from south. Position "east" and "west" carefully opposite from each other. Be sure that they are equally distant from "north" and "south." You can use your compass to find wind direction and other weather data.

Assignment 3: Temperature

Temperature is a fundamental concept that we interact with every day. In fact, it is one of the few environmental measurements nearly everyone on the planet consults before making critical decisions (what clothes to wear, what to drive, and what to do). However, critical though it may be, measuring and monitoring temperature is quite difficult. In this exercise, you'll monitor daily temperature changes in two locations and compare the results. This is a pretty intense, day-long activity that requires a little bit of work but a lot of coordinated data taking.

What you'll need

- Your weather journal
- Pencil or pen
- Your weather station
- Access to the Internet
- Some weather

What to do

1. Record the temperature from your weather station thermometer at regular intervals for as much of the day as possible. The more data you can take, the better. **At a minimum**, record temperatures at:
    a. 6 AM (or as close to as possible)
    b. 10 AM
    c. Noon
    d. 3 PM
    e. 6 PM
    f. 10 PM (or as close to as possible)
2. Log on to the weather station at http://apps.weber.edu/Weather/ and record the temperatures at those same times.
3. Graph the results. You can do this by hand on graph paper or with a computer spreadsheet program like Excel, but neatness counts. You need to make sure you
    a. Draw legibly (with a ruler!) or use a computer program
    b. Include a title and subtitle
    c. Label the axes with units (time on the x-axis, temperature on the y-axis)
    d. Include a legend
    e. Plot points, not lines, since these represent your actual data
    f. Draw the plots so they can be easily compared (that is, use the same ranges for the axes for both graphs)
4. On your graph, note the minimum, maximum, and average temperatures.

Based on your data, answer the following questions

Your Name	
Date Data Taken	
Your Latitude	
Your Longitude	

1) Compare the results from your location and the location of the Weber State Weather Station. What are the main similarities and differences? What might account for these?

2) Imagine the Weber State Weather Station was located on the top of Mount Ogden instead of the stadium. How would the data be different? Sketch a graph of what such data might look like.

3) Imagine the Weber State Weather Station was located on Antelope Island instead of the stadium. How would the data be different? Sketch a graph of what such data might look like.

4) What would the graph of your data look like if you were located in Montana instead of Ogden, UT? Sketch an example.

5) What would the graph of your data look like if you were located in Florida instead of Ogden, UT? Sketch an example.

6) Just for fun, compute the heating degree-days (or cooling degree-days) for both of your graphs. Also, compute the growing degree-days for sweet corn. Comment on how these values could be used to determine your ability to heat/cool your home and grow your own food.

Assignment 4: Moisture and Stability

NAME________________________

The hallmark of weather on Earth is the changing state of water (known as *phase changes).* Sometimes it is a vapor, sometimes a liquid, and sometimes a solid. In this exercise, you'll examine some situations where phase changes result in a familiar weather phenomena: Clouds.

What you'll need

- Your weather journal
- Pencil or pen
- Your weather station
- Access to the Internet
- Your textbook
- Some weather

What to do

1. Using Table 4-1 and Figure 4-9 in your textbook, answer the following questions:
    a. If a parcel of air at 15 C contains 5 g/kg of water vapor, what is the relative humidity?

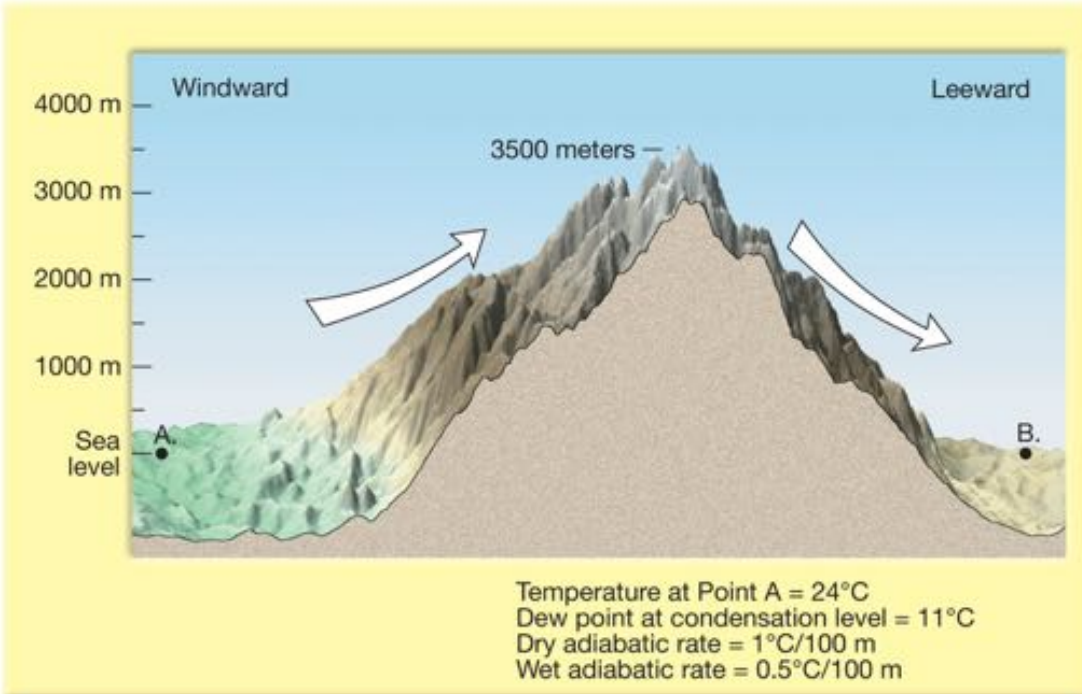
    b. If the temperature of this same parcel of air dropped to 5 C, how would the relative humidity change?

2. Using your hygrometer (reconstructing it after the storm if required) measure the humidity and record the temperature in the morning (sometime between 6 AM and 8 AM) and in the afternoon (between 4 PM and 6PM). **NOTE:** You can only measure the *change* in humidity with your weather station. How will you record a measure of humidity at two different times?

Time	Humidity	Temperature

3. What is your *change* in relative humidity?

4. What has happened to change the humidity?



Based on the figure above, answer the following questions:

1) What is the elevation of the cloud base?

2) What is the temperature of the ascending air when it reaches the top of the mountain?

3) What is the dew point temperature of the rising air at the top of the mountain, assuming 100% humidity?

4) Estimate the amount of water vapor that must have condensed (in g/kg) as the air moved from the cloud base to the top of the mountain.

5) What will the temperature of the air be if it descends to point B? (Assume that the moisture that condensed fell as precipitation on the windward side of the mountain)

Lab 8

Atmospheric Motion

Materials Needed

- ruler

Introduction

What causes the wind to blow? This lab considers how pressure gradient, Coriolis, and frictional forces act to influence wind speed and direction. We examine how surface winds differ from upper-air winds and consider how horizontal winds lead to vertical motion.

Pressure Gradient Force

Horizontal winds are driven by horizontal differences in pressure between two locations. This pressure difference is referred to as a horizontal pressure gradient. The greater its value, the stronger the wind. Consider stations A and B, separated by 250 km.* The pressure is 1016 mb at station A and 1020 mb at station B—a 4-mb pressure difference over 250 km. We can express this pressure gradient as:

$$\frac{\Delta p}{d} = \frac{4 \text{ mb}}{250{,}000 \text{ m}}$$

The direction of pressure gradient force is from higher to lower pressure.

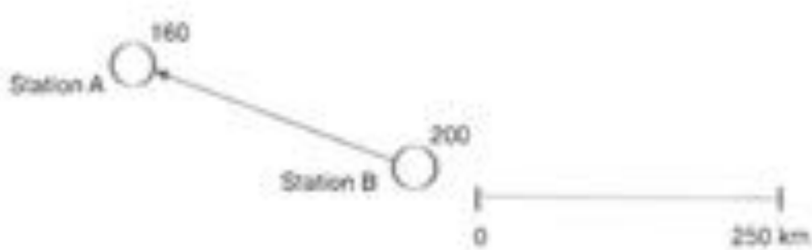


Figure 8-1

*Note how pressure is depicted on surface weather maps. To decode the values shown, first move the decimal one place to the left (e.g., station A with a value of 160 becomes 16.0). Then preface the number with a "9" or a "10". Since sea level pressure on earth is generally between 950 and 1050 mb, we can safely assume a pressure of 1016.0 mb at station A and 1020.0 mb at station B.

Surface weather maps include isobars—lines of constant pressure—that help us see horizontal pressure gradients. The U.S. map below shows isobars drawn at 4-mb intervals.

1. *Using Figure 8-2:*
   a. Circle the area with the greatest pressure gradient.
   b. Use arrows to show the direction of pressure gradient force at a few locations. (These are typically drawn perpendicular to isobars.)
   c. Label a region where you would expect the lightest winds.

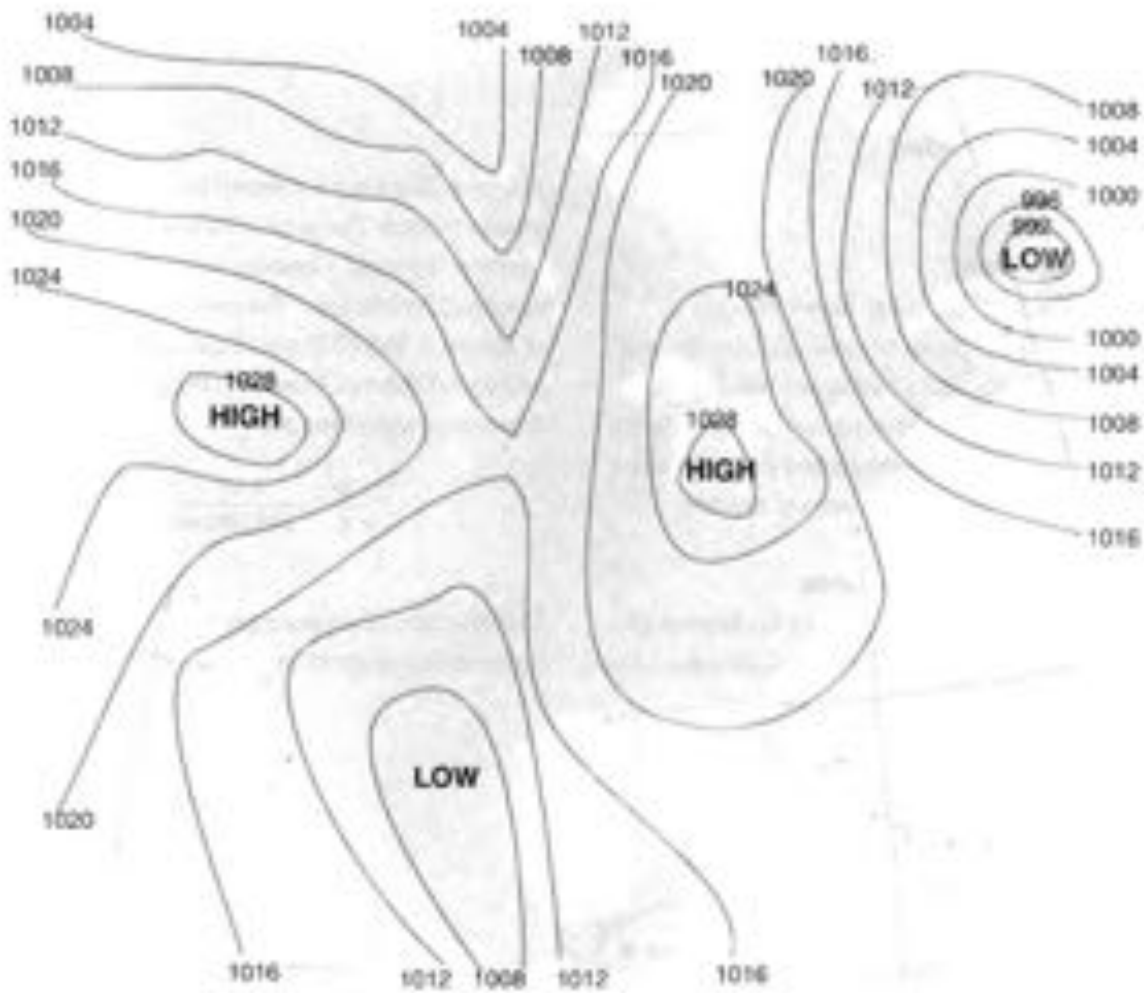


Figure 8-2

Optional Exercise: Mathematical Treatment of Pressure Gradient Force

The magnitude of the pressure gradient force is a function of the pressure difference between two points and air density. It can be expressed as:

$$\frac{F_{PG}}{m} = -\frac{1}{\rho} \cdot \frac{\Delta p}{d}$$

where F_{PG} = pressure gradient force
- m = unit mass (1 kg)
- ρ = density (kg m^{-3})
- Δp = pressure change (pascals or kg m^{-1} s^{-2})
- d = distance (m)

Let's consider an example where the pressure 5 km above Little Rock, Arkansas, is 540 mb and 5 km above St. Louis, Missouri, it is 530 mb. The distance between the two cities is 450 km, and the air density at 5 km is approximately 0.75 kg m^{-3}. In order to use the pressure gradient equation, we must use compatible units. We first convert pressure from millibars to pascals (Pa), another measure of pressure that has units of kilograms per meter per second squared. (Note that 1 mb = 100 Pa.) In our example the pressure difference above the two cities is 10 mb or 1000 Pa (1000 kg m^{-1} s^{-2}). Thus we have:

$$\frac{F_{PG}}{m} = -\frac{1}{0.75 \text{ kg m}^{-3}} \cdot \frac{1{,}000 \text{ kg m}^{-1} \text{s}^{-2}}{450{,}000 \text{ m}} = -0.00296 \text{ m s}^{-2}$$

Newton's second law states that force equals mass times acceleration ($F = m \cdot a$). In our example we have considered pressure gradient force per unit mass; therefore our result is an acceleration ($F \div m = a$). Because of the small units shown above, pressure gradient acceleration is often expressed as centimeters per second squared. In this example we have 0.296 cm sec^{-2}.

2. *Assuming a sea-level air density of 1.2 kg m^{-3}, calculate the magnitude of the pressure gradient force per unit mass in Figure 8-1.*

Coriolis Force

Most of our knowledge about the forces influencing wind is derived from Newton's laws of motion. These laws, however, are valid only when viewed from a fixed frame of reference. Since the earth rotates on its axis, our view of air movement is not from a fixed reference frame and we must compensate by considering the Coriolis force.

To understand why the Coriolis force causes a deflection from the path of motion we consider a simple drawing exercise.

3. *For the Northern Hemisphere:*
   a. Put an object at the top of your desk and align Figure 8-4 of your lab manual as in Figure 8-3, where x indicates the object.

   b. Draw a dashed line from the North Pole in Figure 8-4 directly toward the object at the top of the desk.

   c. Repeat step b, but this time draw a solid line toward the object at the top of the desk while you simultaneously rotate your lab book in the direction of the earth's rotation shown in Figure 8-4. (It is best to have someone turn the book while you draw the line.)

4. *For the Southern Hemisphere:*
   a. Put an object at the bottom of your desk and align page 73 of your lab manual as in Figure 8-3.

   b. Draw a dashed line from the South Pole in Figure 8-4 directly toward the object at the bottom of the desk.

   c. Repeat step b, but this time draw a solid line toward the object at the bottom of the desk while you simultaneously rotate your lab book in the direction of the earth's rotation shown in Figure 8-4.

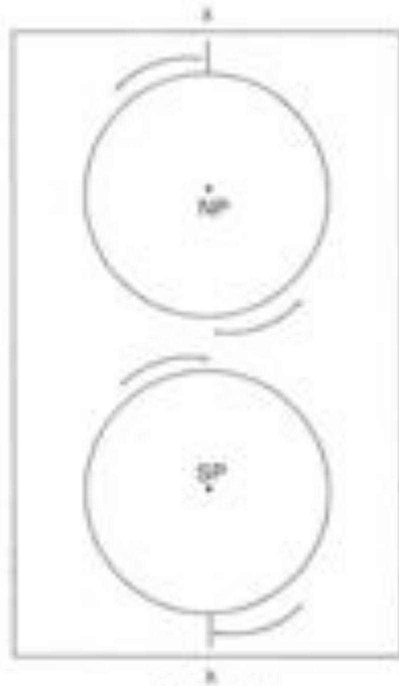


Figure 8-3

5. *How did the path of the solid line differ from the dashed line in the Northern Hemisphere example? What does this say about deflection relative to air motion in the Northern Hemisphere?*

6. *Describe the deflection relative to the path of motion in the Southern Hemisphere.*

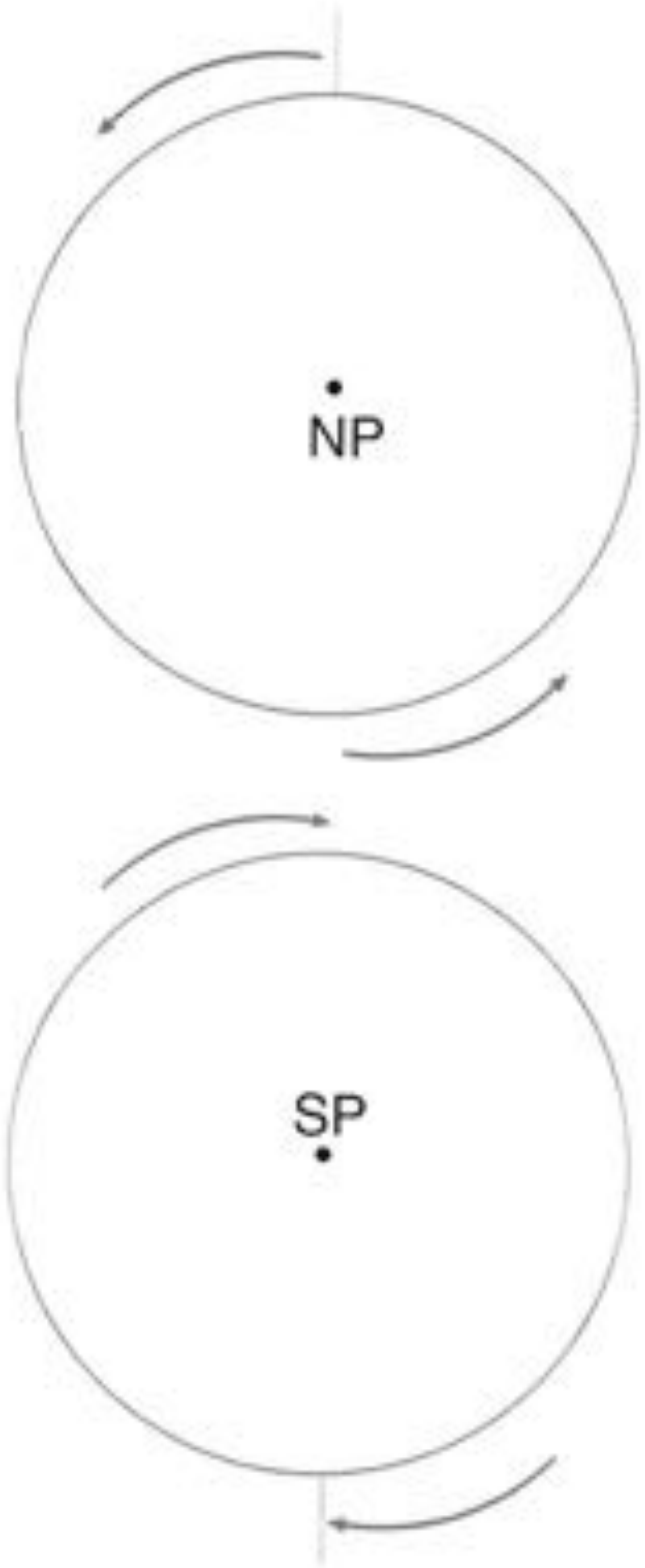


Figure 8-4

To reinforce your understanding of the direction of the Coriolis force, consider an unguided rocket fired from the North Pole toward Point A. As viewed from space, the rocket travels in the same direction throughout its flight. Of course, the earth rotates while the rocket travels. Figures 8-5a through 8-5c show the position of the rocket and rotation of the earth over a 4-hour period.

To observers on the earth's surface, the rocket is deflected from its intended path. This apparent deflection occurs because the frame of reference has changed for observers on the rotating earth.

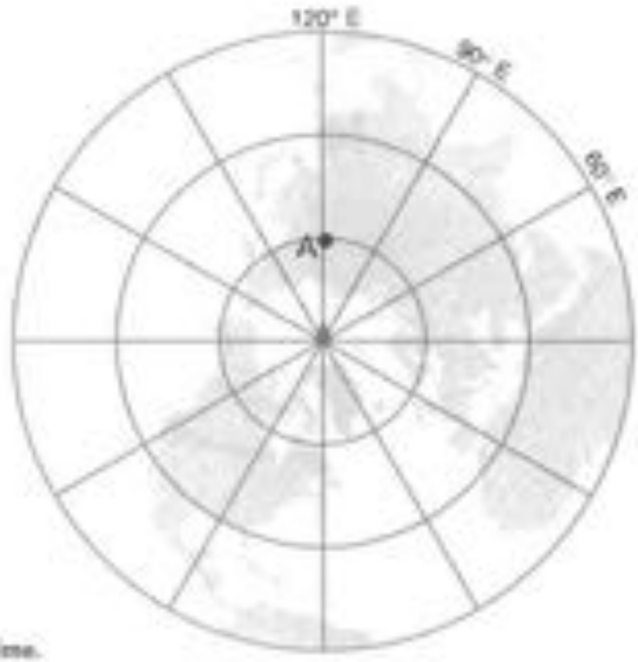


Figure 8-5a. Initial time.

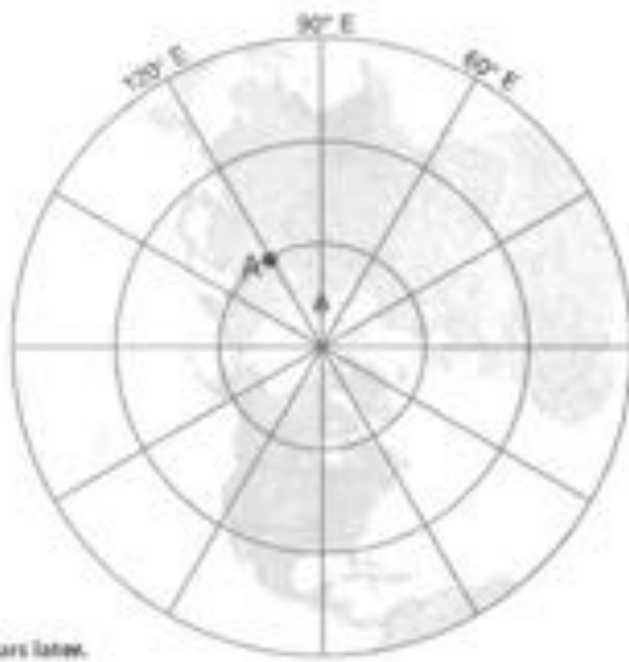


Figure 8-5b. Two hours later.

7. *Combine the position of the rocket at all three times onto Figure 8-5d by using the latitude and longitude information from the previous three figures. This should show the relative deflection from the perspective of someone on the earth's surface.*

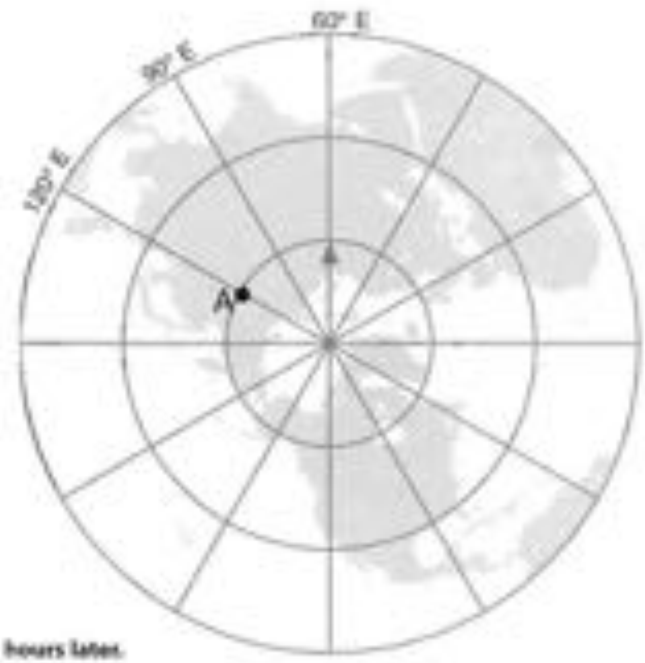


Figure 8-5c. Four hours later.

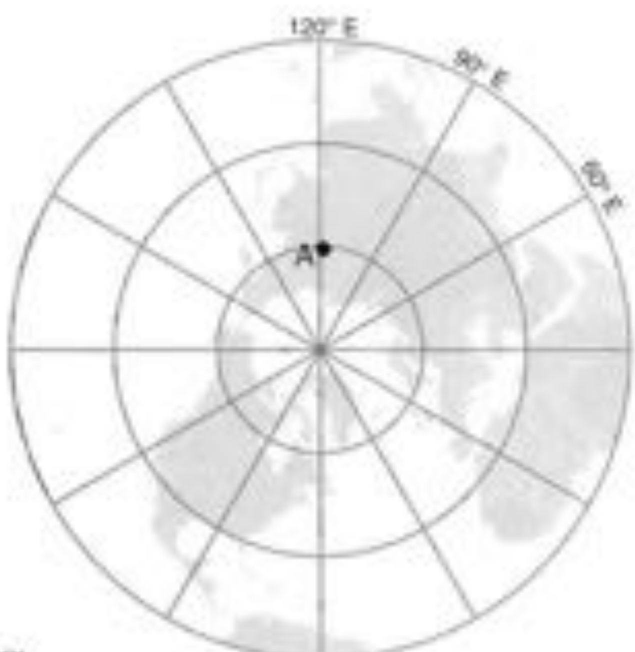


Figure 8-5d. Summary.

8. *Now show the apparent deflection in the Southern Hemisphere of a rocket fired from the South Pole. In Figure 8-6d, draw the position of the rocket at each of the three times depicted in Figures 8-6a through 8-6c.*

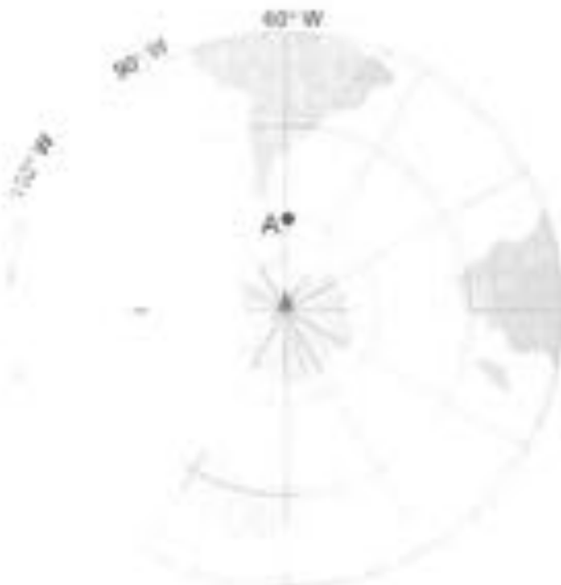


Figure 8-6a. Initial time.

Figure 8-6b. Two hours later.

Figure 8-6c. Four hours later.

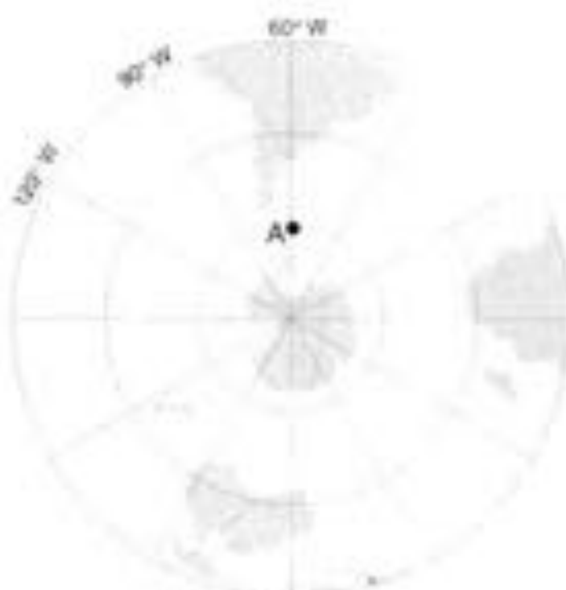


Figure 8-6d. Summary.

The Coriolis force varies with wind speed. Imagine in Figure 8-7 that the rocket travels twice the speed of the previous example (and therefore covers twice the distance in 4 hours). Its intended target is Point B.

9. *Notice that the rocket travels twice as fast as in the previous example. Now combine the position of the rocket at all three times onto Figure 8-7d by using the latitude and longitude information from the previous three figures.*

10. *Is the rocket in Figure 8-7d displaced from its intended target a greater or lesser distance than in Figure 8-5d? Extrapolating from this, does Coriolis force increase or decrease with wind speed?*

Figure 8-7a. Initial time.

Figure 8-7b. Two hours later.

Figure 8-7c. Four hours later.

Figure 8-7d. Summary.

Since the Coriolis force results from the earth's rotation, it is expressed perpendicular to the earth's axis (Figure 8-8). Therefore, at the poles it is completely horizontal and at the equator it is completely vertical. At other latitudes, it has both horizontal and vertical components (shown by the dashed lines at 40° W latitude). Because the vertical component of the Coriolis force is small compared with other vertical forces, we will ignore it and focus our attention on the horizontal component.

11. *The Coriolis force is depicted at two different latitudes in Figure 8-9. Draw the vertical and horizontal component of the Coriolis force at the two locations. Is the horizontal component greater at the higher latitude or the lower latitude?*

Figure 8-9

Upper-Level Winds

From Lab 1, you will remember that pressure decreases with height above the earth's surface. We express this decrease in a manner similar to the horizontal pressure gradient:

$$\frac{\Delta p}{\Delta z}$$

where Δp = pressure change
and Δz = height change

If a pressure gradient force is directed upward, it acts to move air vertically. Luckily for creatures breathing at the earth's surface, this force is counteracted by gravity, creating a balance we refer to as *hydrostatic equilibrium*. The hydrostatic equation shows this balance mathematically:

$$\frac{\Delta p}{\Delta z} = -\rho g$$

where

$\frac{\Delta p}{\Delta z}$ = the upward-directed pressure gradient force

ρ = density (kg m^{-3})

and g = gravity (9.8 m s^{-2})

This relationship is relevant to how we depict winds on upper-air maps.

12. *Explain why pressure decreases more rapidly with height near the surface than at higher altitudes.*

13. *Consider the two locations on the North American map in Figure 8-10. Following the example for 850 mb, plot the heights of the 500- and 300-mb pressure levels in Figure 8-11. Draw lines connecting the two points for each pressure level; label each line you draw with the appropriate pressure value.*

Figure 8-10

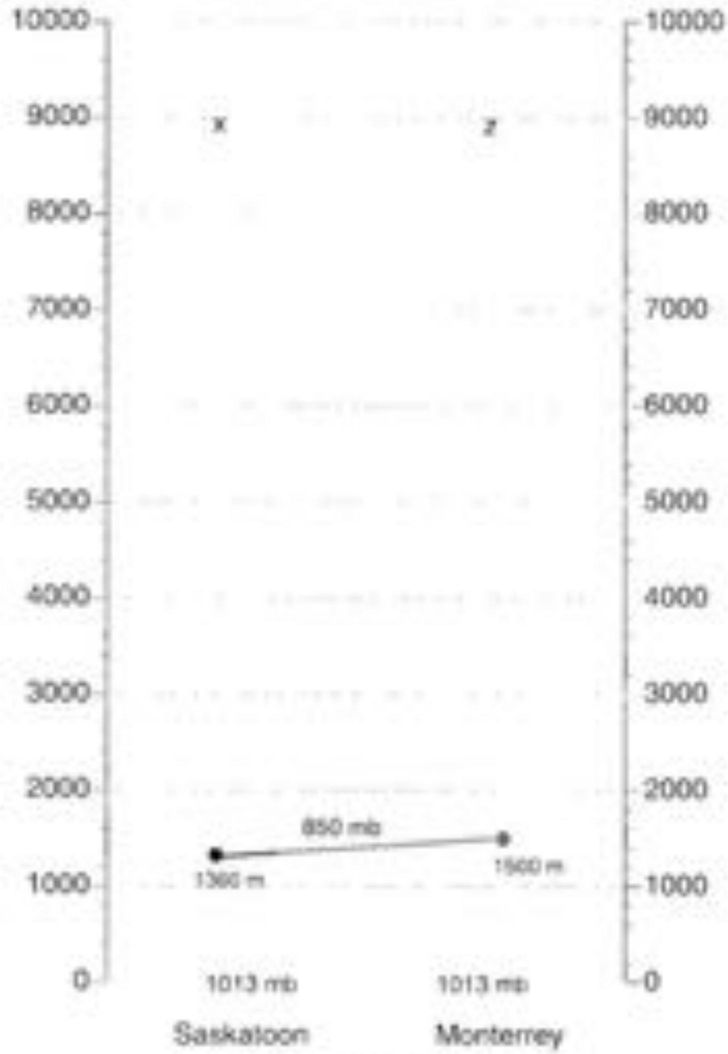


Figure 8-11

14. *At which location, Saskatoon or Monterrey, does pressure decrease with height most rapidly?*

15. *How does this relate to temperature differences between the two sites?*

16. *Both points x and z are at 9000 m. Which point has the highest pressure? Draw arrows between the points showing the direction of the horizontal pressure gradient force at 9000 m.*

17. *At what height, 1500 m or 9000 m, is the horizontal pressure gradient greater?*

18. *How should wind speeds at these two heights reflect this difference?*

Table 8-1

Force	Direction	Magnitude
Pressure gradient	From higher to lower pressure	Proportional to pressure difference between two points
Coriolis	At a right angle to the direction of airflow: • acts to the right in the Northern Hemisphere • acts to the left in the Southern Hemisphere	Depends on wind speed and latitude
Friction	Opposite direction of airflow	Depends on surface characteristics that obstruct airflow

Summary of Forces

The direction and magnitude of pressure gradient, Coriolis, and frictional forces determine wind speed and direction. The table above summarizes the direction and magnitude of each of these forces.

Geostrophic Winds

Because of the relationship between pressure and height, contours like those for 5460 and 5520 m in Figure 8-12 allow us to depict the pressure gradient on upper-air maps. Above the earth's friction layer the pressure gradient and the Coriolis force often balance each other. One way to understand this is to imagine releasing an air sample like that shown by the box in Figure 8-12. The pressure gradient force (F_{pg}) sets the sample in motion initially, and the Coriolis force (F_{co}) deflects it from its original path. As the parcel accelerates, the Coriolis force increases (recall that it is dependent on wind speed), until it equals the pressure gradient force. We define this balance as the *geostrophic wind*—one that flows parallel to straight contours. Note that the Coriolis force is expressed at a *right* angle to the wind. (In the Northern Hemisphere, to the right of the path of motion.)

19. *Now consider the Southern Hemisphere. In Figure 8-13, draw the pressure gradient force and the Coriolis force acting on the box, and the resulting geostrophic wind.*

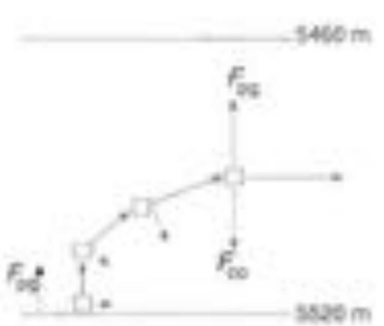


Figure 8-12. 500-mb geostrophic wind in the Northern Hemisphere.

Figure 8-13. 500 mb geostrophic wind in the Southern Hemisphere.

The Gradient Wind

In reality, contours are typically curved as in Figure 8-14, and upper-level winds often flow parallel to them. We define a *gradient wind* as one that blows parallel to the contours. Unlike the geostrophic wind, the gradient wind accelerates (since it is changing direction). The acceleration occurs because the pressure gradient and Coriolis forces no longer balance each other.

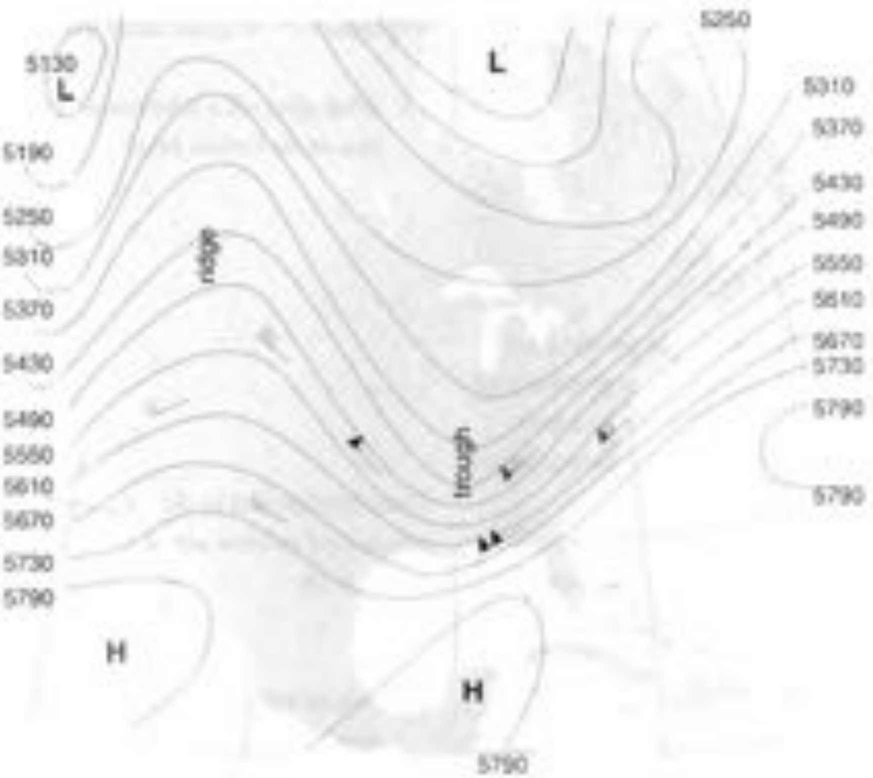


Figure 8-14

20. *In the figures below, draw arrows showing the pressure gradient and Coriolis force acting on each box. Since the pressure gradient is the same in both drawings, you should make the pressure gradient force vector the same for all six boxes. However, you should vary the size of the Coriolis vector in a way that would maintain the wind in a curved path.*

Since the gradient wind changes its direction, we say that it is accelerating. Differences between the pressure gradient and Coriolis force cause this acceleration, often called the centripetal acceleration.

Figure 8-15. Gradient wind around Northern Hemisphere trough and ridge.

21. In Figure 8-15, the pressure gradient force around the low is the same as that around the high. However, there is a difference in the magnitude of Coriolis force around each. What does this say about the wind speed around the low versus the high in this particular example?

Remember that we define the geostrophic wind as a balance between pressure gradient and Coriolis force. Subgeostrophic flow is slower than geostrophic, supergeostrophic flow is faster than geostrophic.

22. In Figure 8-15, label which pressure system has supergeostrophic flow and which has subgeostrophic flow.

23. Now reexamine Figure 8-14. Notice the wind speed differences between the trough (low pressure) vs. the ridge (high pressure). Does this conform or contrast with your previous answer about subgeostrophic and supergeostrophic flow?

24. What difference between the theoretical gradient wind depicted in Figure 8-15 and the actual wind shown in Figure 8-14 helps to explain wind speed differences?

Surface Winds and Friction

Winds close to the earth's surface are also influenced by friction, which acts in a direction opposite the wind, slowing the wind. The magnitude of friction depends on the "roughness" of the surface. For example, tall buildings or forests will reduce wind speed more than grasslands.

25. What affect will a reduction in surface wind speed have on the Coriolis force?

Since friction acts to slow air down, surface winds tend to blow across isobars, as shown in Figure 8-16.

26. Indicate with arrows the three forces (pressure gradient, Coriolis, and friction) acting on the Northern Hemisphere box in the diagram below.

Figure 8-16. Surface wind.

27. *Figure 8-17 shows winds circulating around surface high and low pressure centers in both the Northern and Southern Hemispheres. Label the correct hemispheres (Northern or Southern) and pressure system (high or low) for each of the four examples.*

28. *Choose one box on each example and draw the pressure gradient, Coriolis, and frictional forces associated with it.*

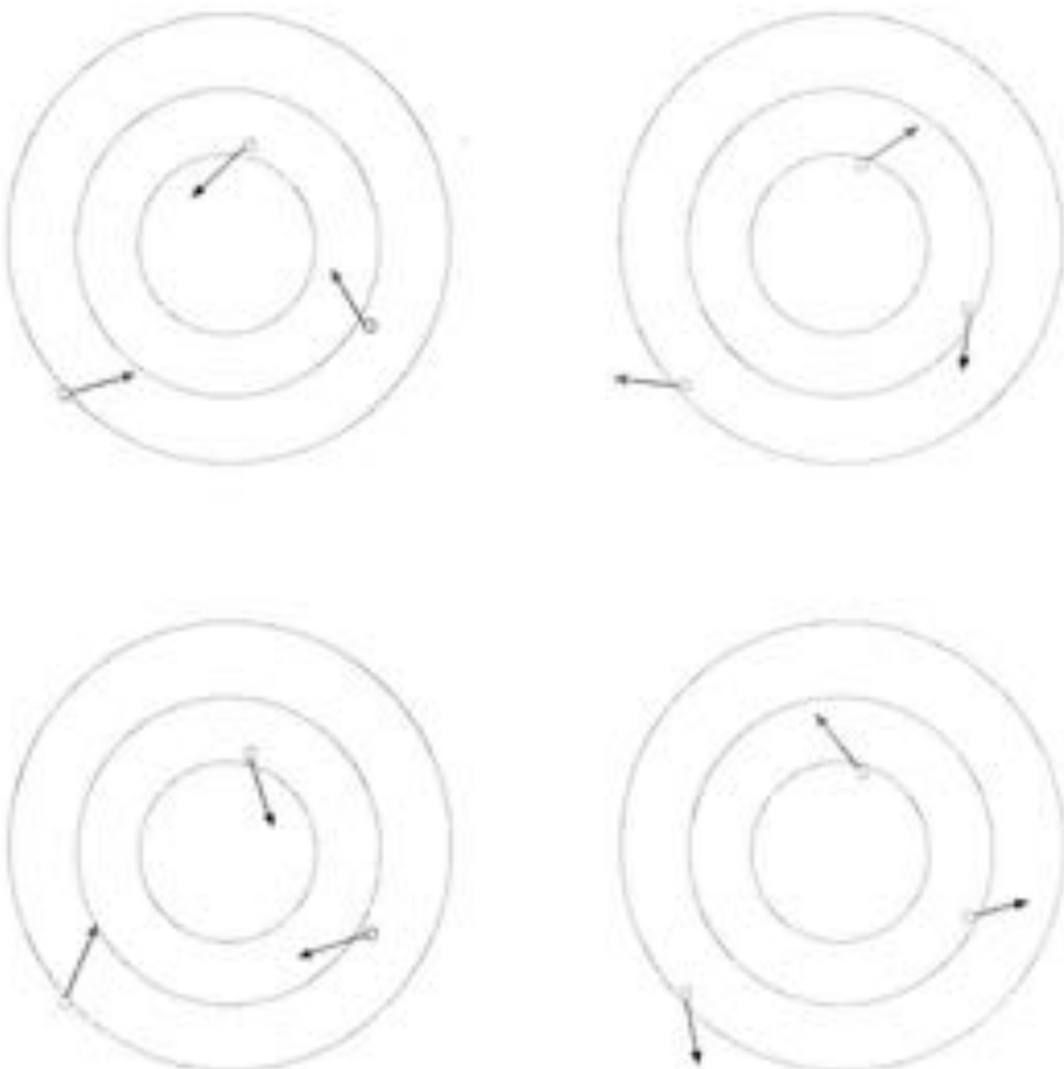
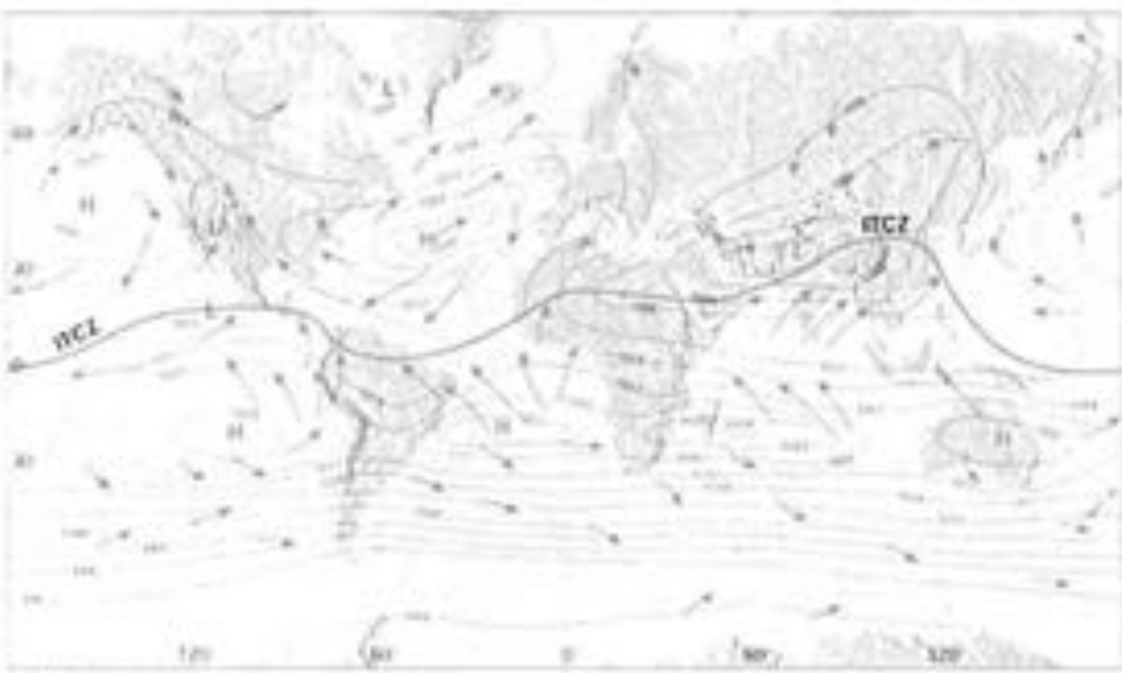


Figure 8-17

Surface Air Pressure and Associated Global Circulation

The forces producing the wind act at a variety of scales, from a few meters (microscale) to tens of thousands of meters (planetary scale). Note the January and July surface pressure and wind patterns in the maps below. As you can see, the circulation around high and low pressures at the global scale reflects the same patterns that you drew on the previous pages.

(a) January



(b) July

Figure 8-18. Surface pressure and wind patterns.

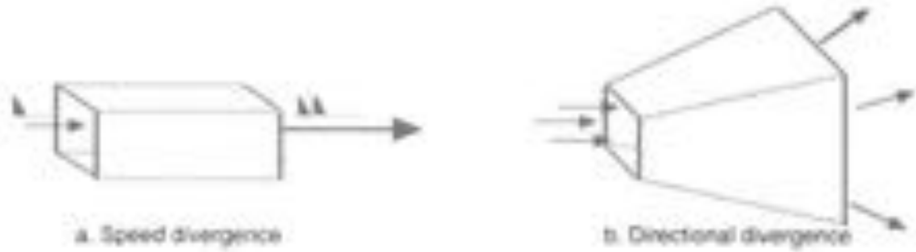


Figure 8-19

Winds and Vertical Motion

As a result of pressure gradient, Coriolis, and frictional forces, surface winds will converge toward low pressure centers. If a low pressure center is to be maintained, there should be a net outflow of air in a column extending from the surface to upper levels of the troposphere. In contrast, maintaining a surface high pressure center requires a net inflow of air to the column.

We can simplify the concept of net outflow by considering the volume of air entering and exiting a box in the upper troposphere. Two phenomena could contribute to a net outflow from the box: (1) speed divergence results from changes in wind speed between the entering and exiting regions of the box (Figure 8-19a), and (2) directional divergence (diffluence) results from changes in wind direction between the entering and exiting regions (Figure 8-19b).

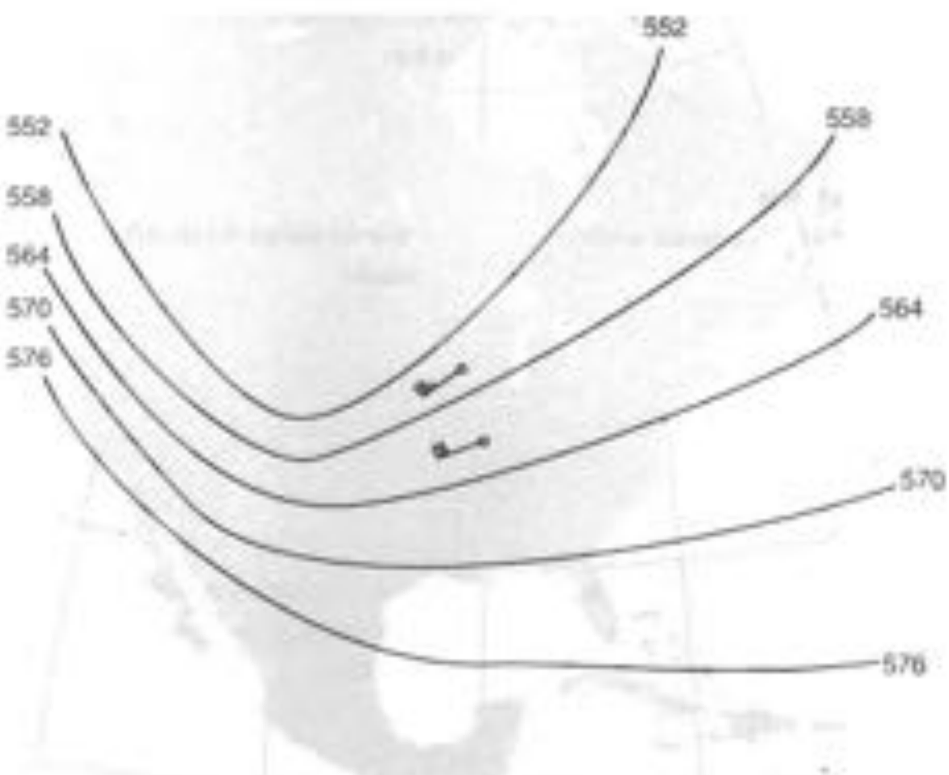


Figure 8-20. Directional divergence on a 850-mb map.

Directional divergence can also be viewed on an upper-air map (Figure 8-20).

Divergence and convergence of upper-air flow also cause vertical motions (Figure 8-21). Divergence aloft removes mass from a vertical column, decreasing surface pressure. As this occurs surface winds converge on the low pressure center and air is forced to rise. Convergence aloft adds mass to a vertical column of air and therefore increases pressure. When it occurs high in the troposphere, convergence causes sinking, as the inversion of the stratosphere restricts rising motion.

29. *Explain why high pressure systems are generally associated with fair weather and low pressure systems are generally associated with stormy weather.*

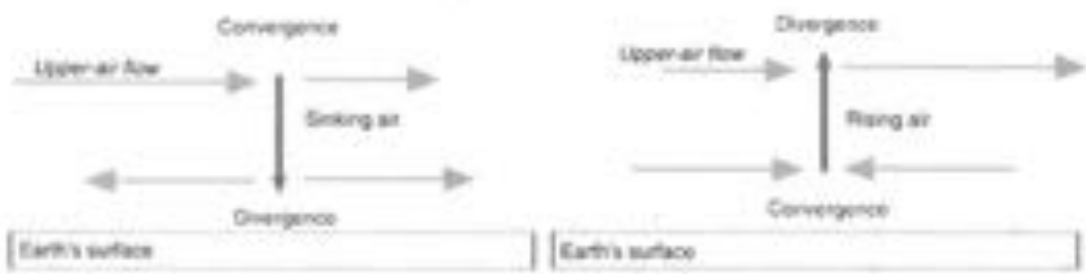


Figure 8-21

Review Questions

Which force initiates horizontal wind?

How do surface winds differ from upper-air winds?

Describe circulation around surface high and low pressure cells in the Northern and Southern Hemispheres.

How do horizontal winds cause air to rise or sink? What is the significance of this vertical motion?

Assignment 6: Analyzing and compiling your weather data

You have done all the hard work of gathering and collating your weather data for over a month. Now comes the time to start distilling it into an analysis of weather and climate patterns where you live.

What you'll need

- Your weather journal
- Pencil or pen
- Weather data from your location for the month of September (collated from your weather journal). You can use data from September 9 - October 9 to coincide with the creation of your weather station.
- Weather data from your New York Times location for the month of September (collated from your weather journal). Use the same timeframe for these as well.

What to do

At the end of each month, you need to summarize your data in a form that can be easily viewed as a "snapshot" of what has happened. The data you keep will include:

1. The highest high temperature and the lowest low temperature you recorded for that month, based on your weather journal observations.
2. The general trend of weather patterns during that month, noting any significant change in these patterns.
3. The cumulative rainfall for the month (also noting any snowfall or other strange precipitation events, like graupel!)
4. Build two temperature plots for the month, one for your location and one for your New York Times location. That is, estimate your daily high, daily low, and mean daily temperature for each day and plot these as a function of time. **Note:** For the first month, your location will likely not have all the data you need create a complete summary. That's ok. Consider the first month your "pioneer" month, and now we'll ramp up the observations. What further observations do you need? How can you record the daily high and the daily low *at your location*?

What to hand in

At the end of each month, create a new page in your journal and summarize your climate data. If it helps, note these pages with a sticky note or other marker for easy reference. We'll be using these to build a climograph later, so make sure they are neat, legible, and consistent.

Lab 9

Weather Map Analysis

Introduction

With a few exceptions (e.g., clouds), most atmospheric processes are invisible. How then do we "see" the weather in order to forecast its changes? The purpose of this lab is to learn how to construct and interpret weather maps. We will focus on the mid-latitudes, where identification of air masses, fronts, and mid-latitude cyclones can help meteorologists forecast changing weather patterns.

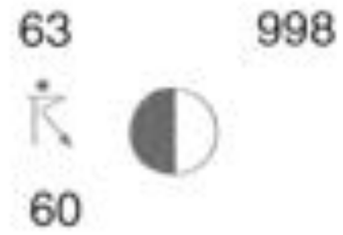
Surface Weather Maps

Every six hours atmospheric data are collected at approximately 10,000 surface weather stations around the world. These data are transmitted to one of three World Meteorological Centers, in Melbourne, Australia; Moscow, Russia; or Washington, D.C. Weather data are disseminated to national meteorological centers where *synoptic-scale* maps are generated. Synoptic means coincident in time, and a synoptic map is a map of weather conditions for a specific time. By convention, the time printed on many weather maps is Greenwich Mean Time (GMT, also called Coordinated Universal Time), the time at the prime meridian. Meteorologists often call this Zulu or z time. Thus, a map labeled 1200z shows conditions at noon in London, which is 7:00 AM EST in New York.

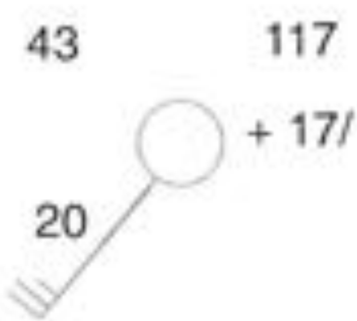
In the United States an automated weather network collects hourly surface data. Since each station collects data for as many as 18 weather characteristics, a compact method of symbolization must be used to include all this information on a single weather map. The station model, developed by the World Meteorological Organization, is the standard format for symbolizing weather characteristics. Figure 9-1 illustrates the arrangement of data in the WMO model; Appendix D provides a complete list of symbols used in this lab.

1. *Decode information from each of the following station models:*

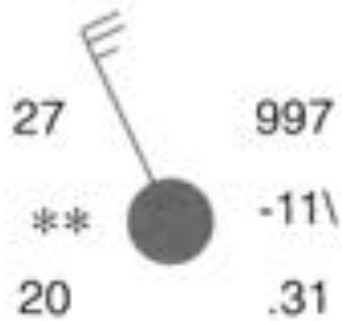
Barometric pressure __________
Temperature __________
Dew-point temperature __________



Barometric pressure __________
Temperature __________
Dew-point temperature __________
Sky coverage __________
Current weather __________



Barometric pressure __________
Temperature __________
Dew-point temperature __________
Sky coverage __________
Wind speed __________
Wind direction __________
Pressure change during last 3 hours __________
Pressure tendency __________



Barometric pressure __________
Temperature __________
Dew-point temperature __________
Sky coverage __________
Current weather __________
Wind speed __________
Wind direction __________
Pressure change during last 3 hours __________
Pressure tendency __________

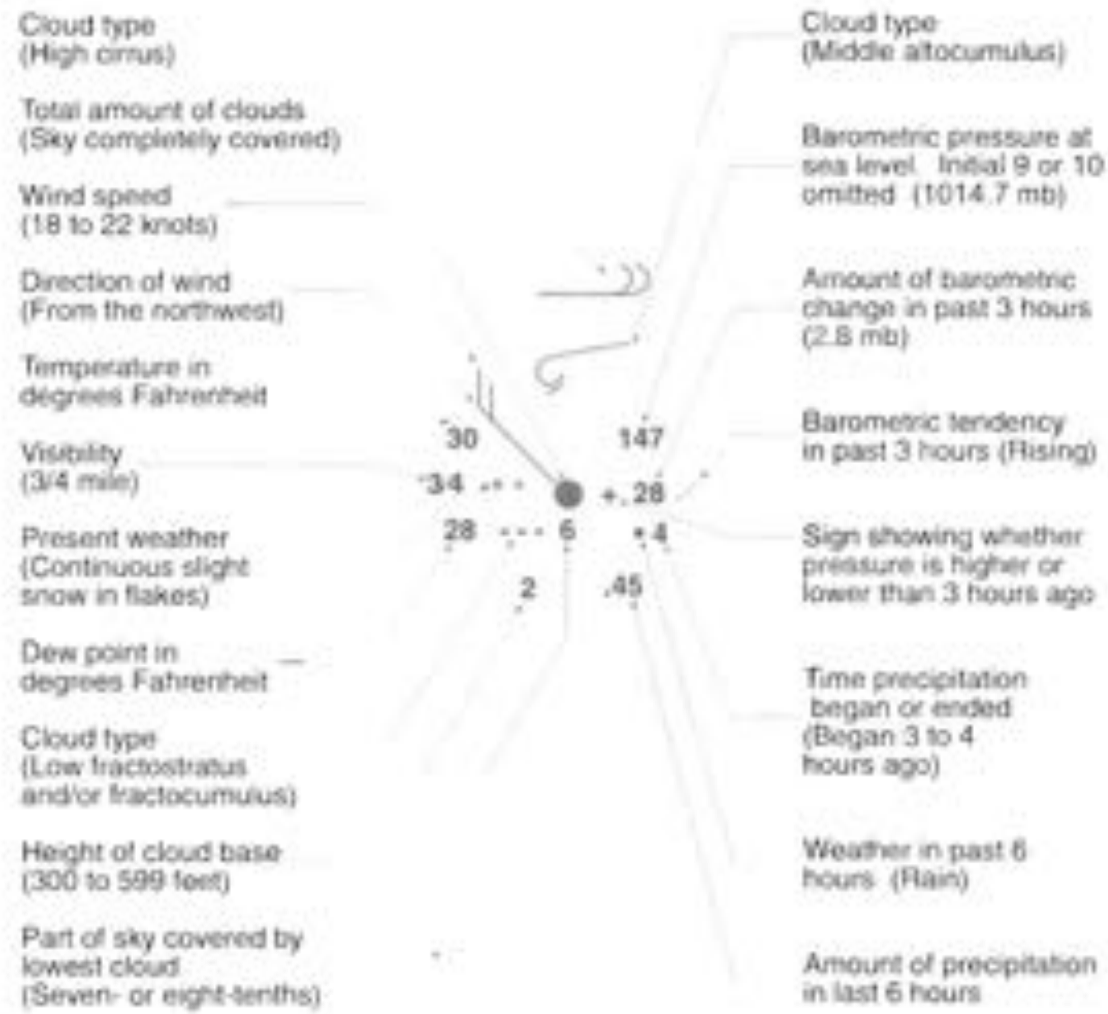


Figure 9-1. WMO station model.

Mapping Spatial Patterns of Meteorological Variables

Weather maps are most useful when their information is analyzed in some fashion. Highlighting the spatial patterns of specific variables—such as temperature, dew point, pressure, and winds—is a first step in weather analysis. We often use isolines (lines of constant value) for this purpose. Each type of isoline is named to reflect the variable being mapped: isotherms are lines of constant temperature; isobars are lines of constant barometric pressure; and isodrosotherms are lines of constant dew point.

Today meteorologists often use computer programs to draw isolines. Here we will construct some manually to better understand them. As a starting point, consider the isotherm drawn for 80°F in Figure 9-2.

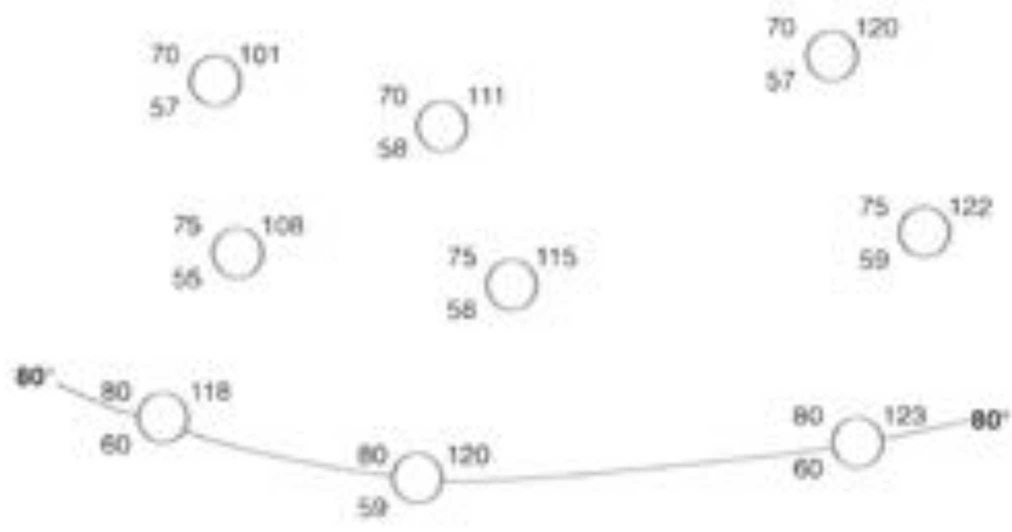
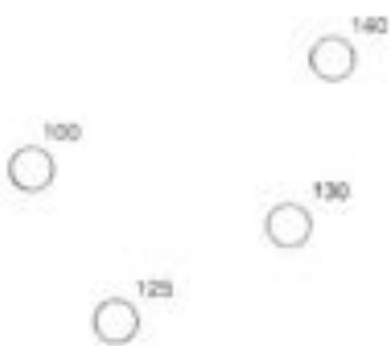


Figure 9-2

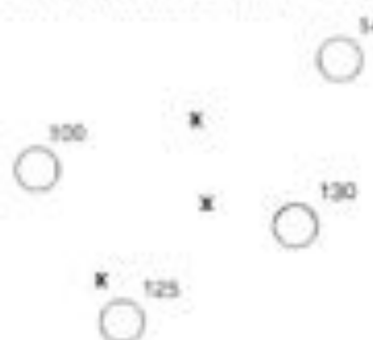
2. *Complete the analysis in Figure 9-2 by constructing isotherms at 70°F and 75°F.*

Drawing isolines in the previous example was straightforward, since the temperature at each station was exactly 80°, 75°, or 70°F. Because such patterns rarely occur in nature it is often necessary to *interpolate* between points. For example, we may want to draw a



1012-mb isobar (line of constant barometric pressure) using the following station data:

In a simple interpolation scheme we might decide that 1012 mb is exactly between 1010.0 and 1014.0 mb and would indicate this position with a small "x." A value of 1012 mb would also exist at two-thirds the distance between 1010.0 and 1013.0 mb, and at four-fifths the distance between 1010.0 and 1012.5 mb.



The "x's" that we draw represent new data points with a value of 1012 mb, through which we construct an isoline labeled "1012."

There are some conventions meteorologists use in constructing isolines. Study the isodrosotherms below.

- Because isolines are lines of constant value, they do not cross.
- Isolines should be relatively smooth. Sharp breaks are rare.
- They should be drawn at fixed intervals. Meteorologists traditionally use 4-mb intervals, centered on 1000 mb, for barometric pressure (e.g., 996 mb, 1000 mb, 1004 mb, etc.). For temperature and dew point, intervals of 5°F are commonly used.
- Isolines should be labeled near the edge of the map. When they form a closed figure, the label is inserted in a small break in the line.

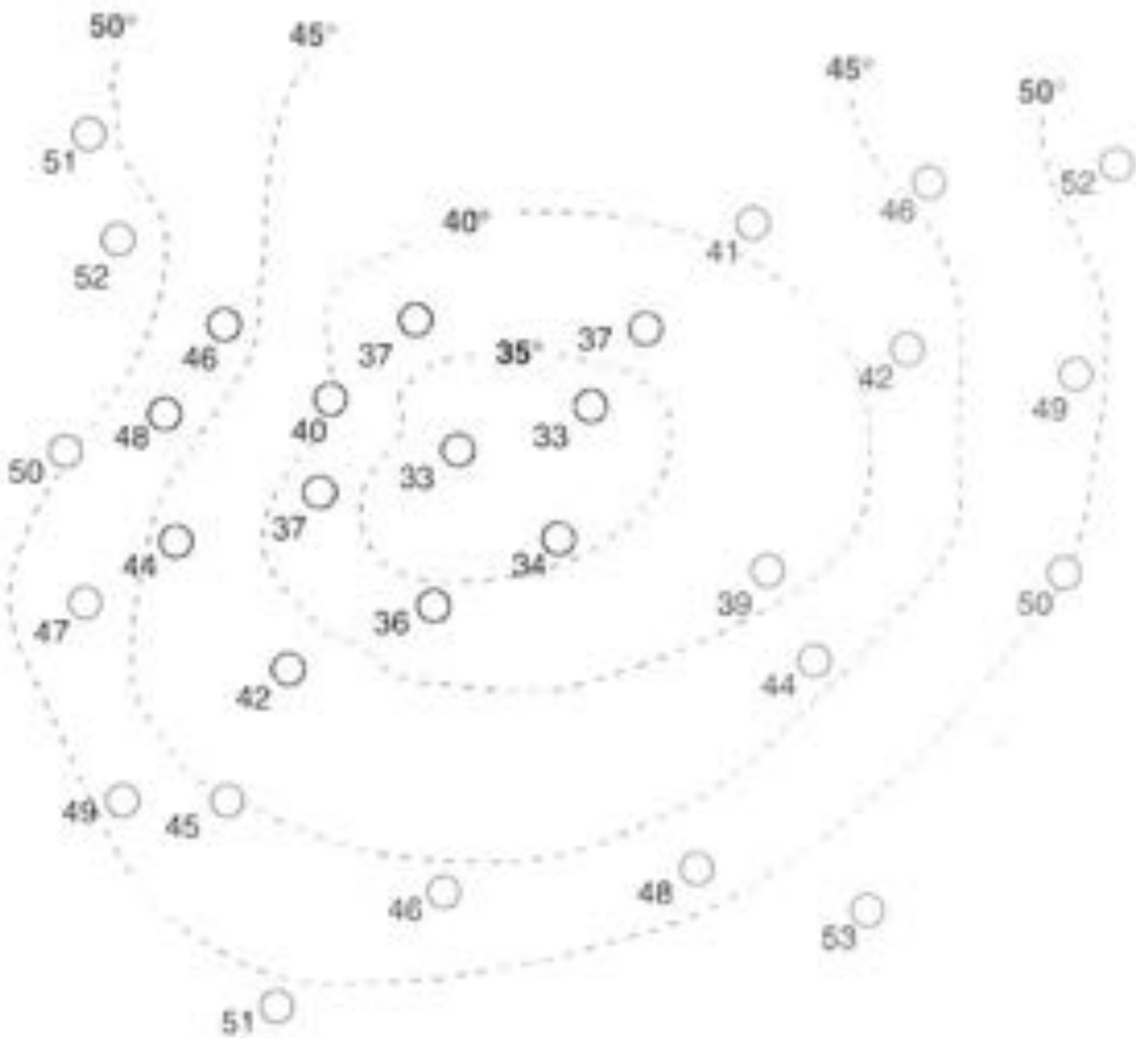


Figure 9-3

...on the map below.

Figure 9-5

We can show wind flow patterns using streamlines, drawn parallel to the wind barbs used in the station model. Streamlines begin at an upwind location and are drawn as long lines ending with an arrow where the wind shifts abruptly (Figure 9-6).

5. *Complete the analysis below by drawing 5 to 6 streamlines to illustrate the general wind flow.*

Figure 9-6

Air Masses and Fronts

An air mass is a large body of air with relatively uniform temperature and humidity characteristics. Air masses form over large land or water surfaces and take on the temperature and moisture characteristics of these surfaces, where they remain stationary for days or even weeks. Their moisture characteristics are classified as maritime or continental, and their temperature characteristics as equatorial, tropical, polar, or arctic. Maritime arctic and continental equatorial air masses are rarely found and therefore are not listed. Therefore, the following types of air masses result:

— maritime equatorial (mE)
— maritime tropical (mT)
— maritime polar (mP)
— continental tropical (cT)
— continental polar (cP)
— continental arctic (cA)

Air masses often migrate from their source regions and affect mid-latitude weather. Examine the diagram below showing air masses affecting North America.

6. *Based on the source regions shown by the ovals, indicate each type of air mass influencing North America (mT, mP, cT, cP, and cA).*

Figure 9-7

Fronts

A *front* marks the boundary between two unlike air masses. Fronts can be identified by any of the following characteristics: a sharp temperature gradient, a sharp moisture gradient, or a sharp change in wind direction. We categorize fronts according to their net movement. When air flows parallel to the boundary and neither air mass advances, the boundary is referred to as a *stationary front*.

Figure 9-8. Stationary front—surface depiction.

When a warm air mass advances on a cooler air mass, the boundary between them is called a *warm front*. Because warm air is less dense, it will cool adiabatically and usually forms clouds ahead of the surface front.

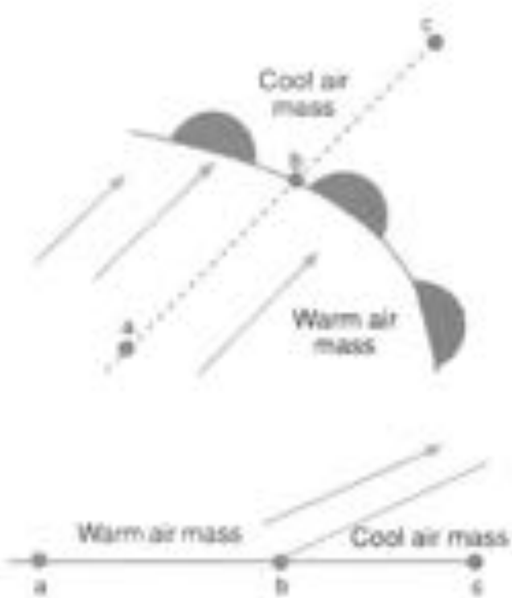


Figure 9-9. Warm front—surface depiction and cross section.

When a cold air mass advances on a warmer air mass, the boundary is called a *cold front*. In this case, cold air wedges itself beneath warm air because of its greater density. Surface friction creates a steep slope as the cold air advances. Since cold fronts generally move faster than warm fronts, warm air masses are lifted more rapidly along cold fronts and clouds grow to greater vertical extent than along most warm fronts.

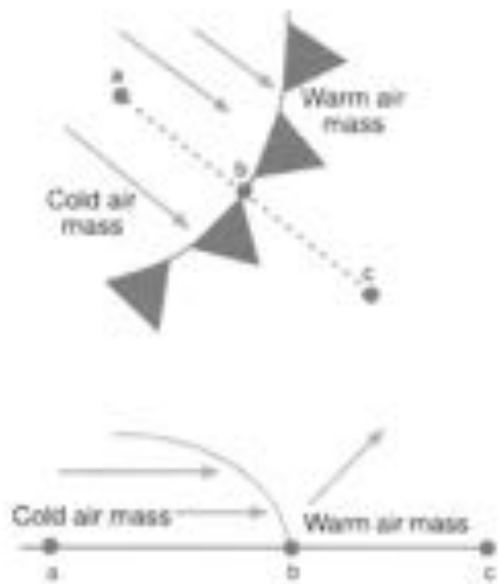


Figure 9-10. Cold front—surface depiction and cross section.

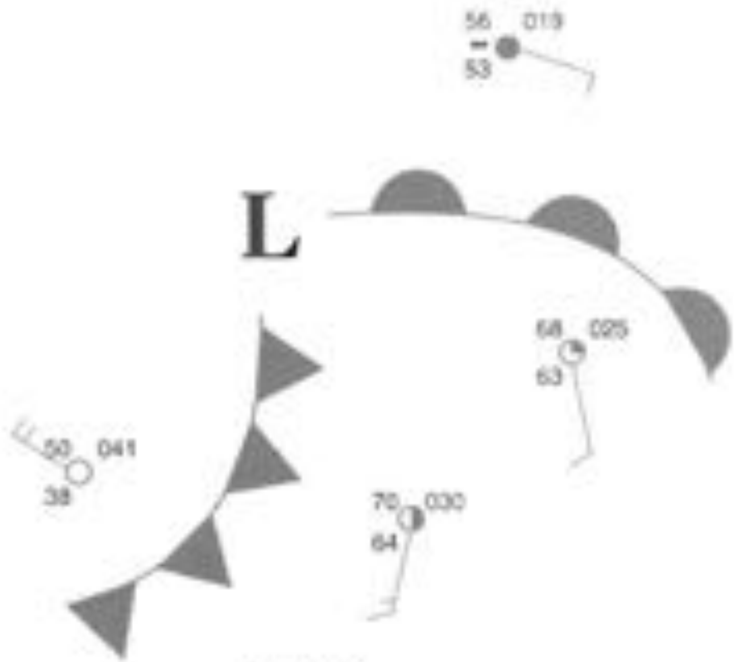


Figure 9-11

Usually, waves along a frontal boundary form a low pressure center. As air circulates around the low, warm and cold air masses advance, resulting in storm systems such as that illustrated in Figure 9-11. These fronts divide the contrasting air masses. Notice also how wind direction shifts across the frontal boundary.

As the wave amplifies, a cold front will often overtake a warm front. We define this new boundary as an *occluded front*.

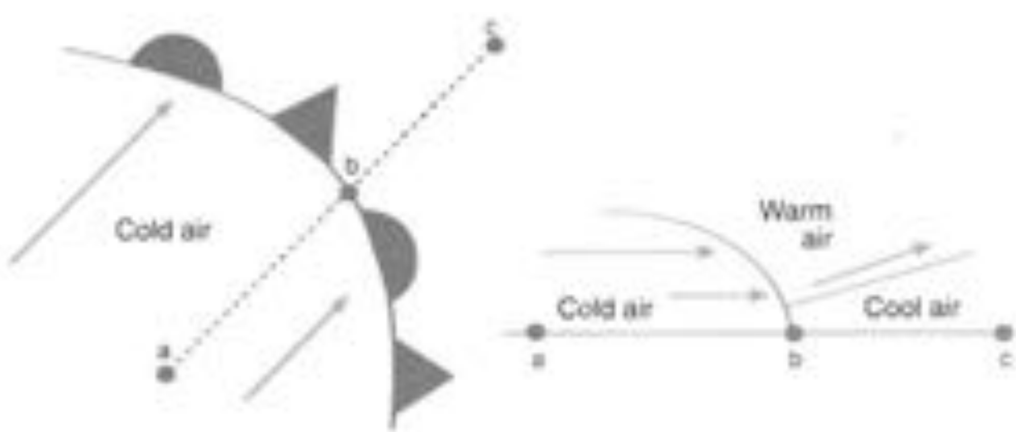


Figure 9-12. Occluded front—surface depiction and cross section.

7. Using the map below:

a. Draw isobars at 4-mb intervals (e.g., 1004 mb, 1008 mb, 1012 mb).

b. Label the low pressure center with an "L."

c. Draw the warm and cold fronts.

d. Label a maritime tropical (mT) and continental polar air mass (cP).

e. Outline the area where cloud cover exceeds 75%.

f. Shade the areas receiving precipitation.

Figure 9-13

Upper-Air Charts

Upper-air charts depict spatial patterns of meteorological variables above the earth's surface. By convention, such maps are constructed at 0000z and 1200z (midnight and noon GMT) for specific pressure levels rather than fixed heights. To display pressure gradient force above the earth's surface, we examine the gradient of height, i.e., how the height of a given pressure level (e.g., 850-mb, 700-mb, 500-mb, 300-mb, 200-mb) changes over space. Recall from Lab 1 our rule-of-thumb: for every 5.6 km rise in height, pressure is reduced by half. By this convention, one would expect the 500-mb surface to be at approximately 5500–5600 m. This height will vary as a function of temperature (and, therefore, air density). The relationship between pressure and height allows us to use codes for height on upper-air maps. Figure 9-14 shows a sample data point from a 500-mb map and the conventions often used for height on all upper-air charts. These codes will help you interpret upper-air charts on the Internet.

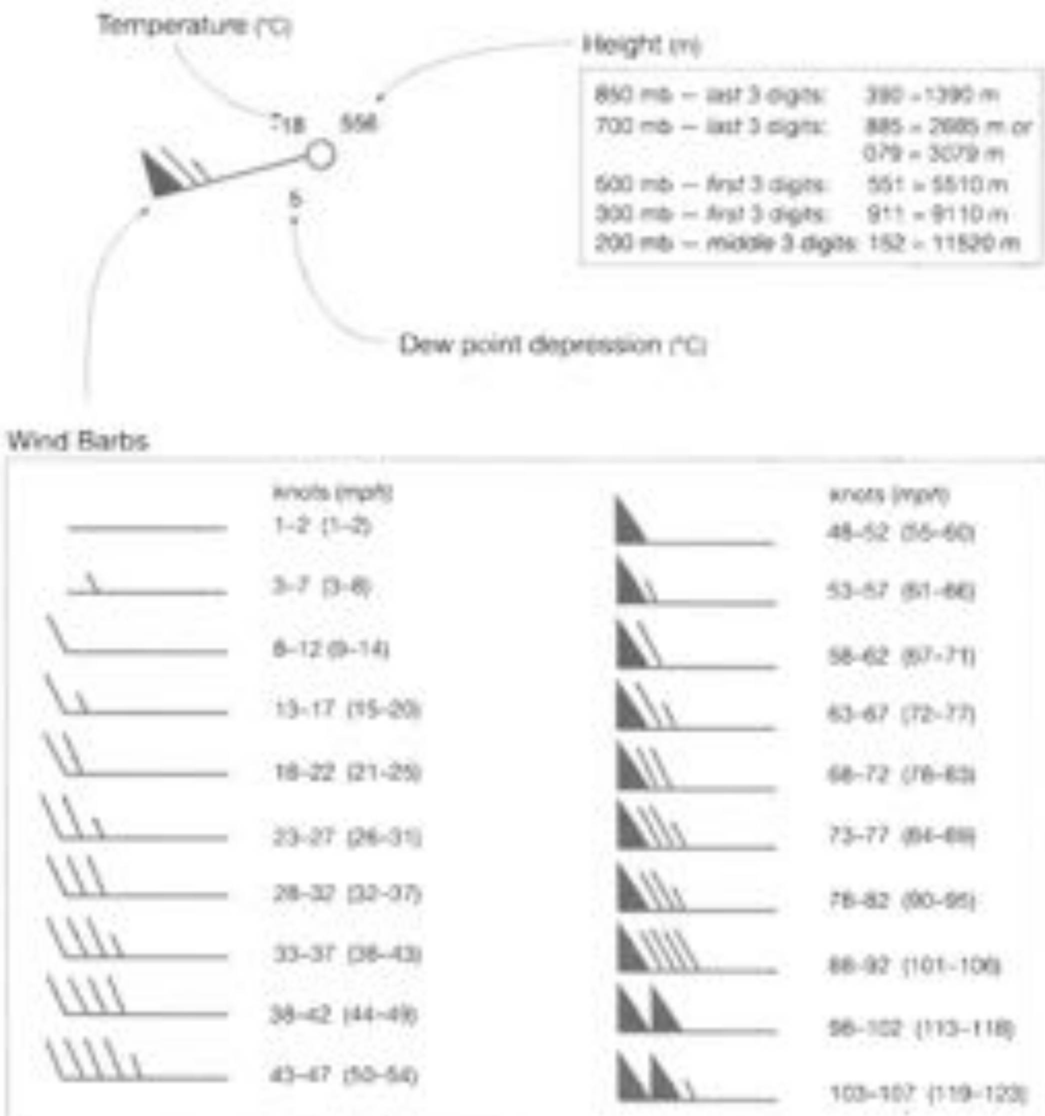


Figure 9-14. Conventions for reading upper air charts.

850-mb maps

The 850-mb map provides a view of the atmosphere above the boundary layer where diurnal temperatures are strongly influenced by warming and cooling of the earth's surface. The 850-mb chart includes raw data at each station, height contours, and isotherms (Figure 9-15). Meteorologists use the 850-mb layer to find areas influenced by the movement of warm and cold air masses. Warm-air advection exists when winds blow across isotherms from warmer to colder areas; cold-air advection occurs where winds blow across isotherms from colder to warmer areas. During the winter months, information on an 850-mb map can help forecasters determine the likely form of precipitation. As a rule of thumb forecasters look at the 0 °C isotherm at 850 mb as the division between snow and rain.

8. *What range of heights do you see in this example of the 850-mb surface?*

9. *Circle and label areas of warm- and cold-air advection on the 850-mb map.*

10. *Highlight the 0 °C isotherm.*

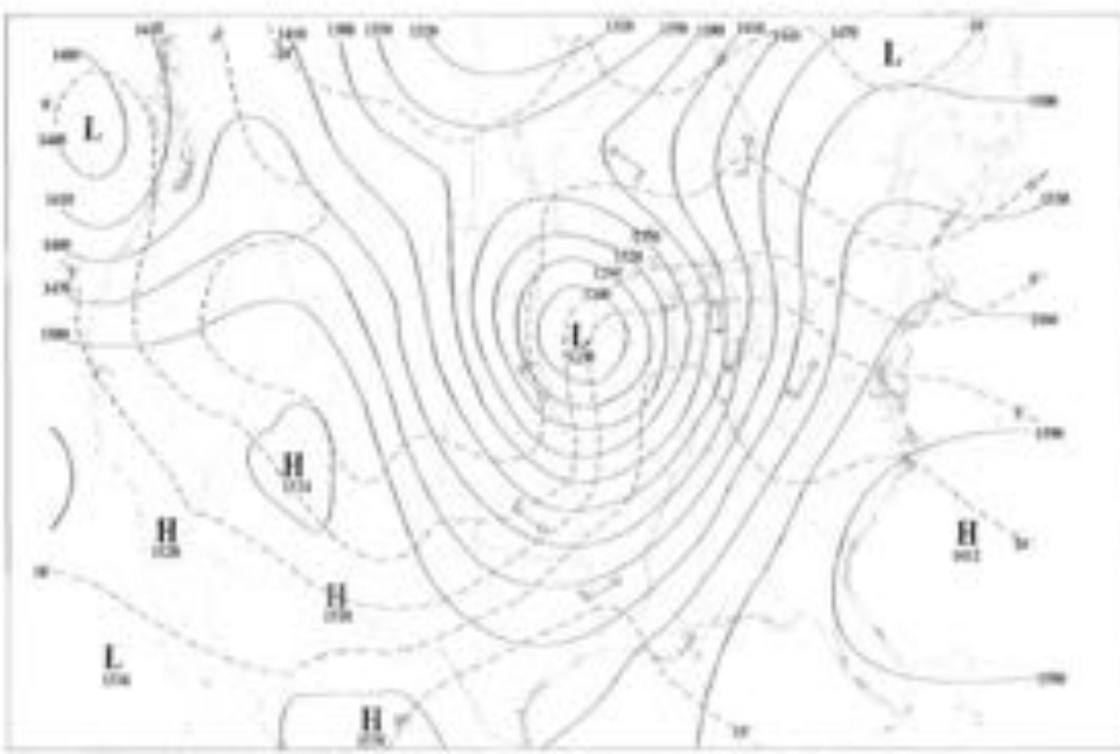


Figure 9-15. An 850 mb map.

500-mb maps

The 500-mb map generally includes the same raw data, contours, and isotherms as the 850-mb map. Occasionally, vorticity (a measure of eddies in the general wind flow) is also depicted. Maps at this level help to show how storms will move, since the speed and direction of 500-mb winds "steer" their paths.

11. *What contour interval is used to show heights on the 500-mb map?*

12. *What range of heights do you see on the 500-mb map?*

13. *How does the spatial pattern of heights illustrate the relationship between temperature, density, and the rate of vertical pressure change?*

14. *If a surface low pressure center developed in the Oklahoma panhandle, in which direction would it likely move?*

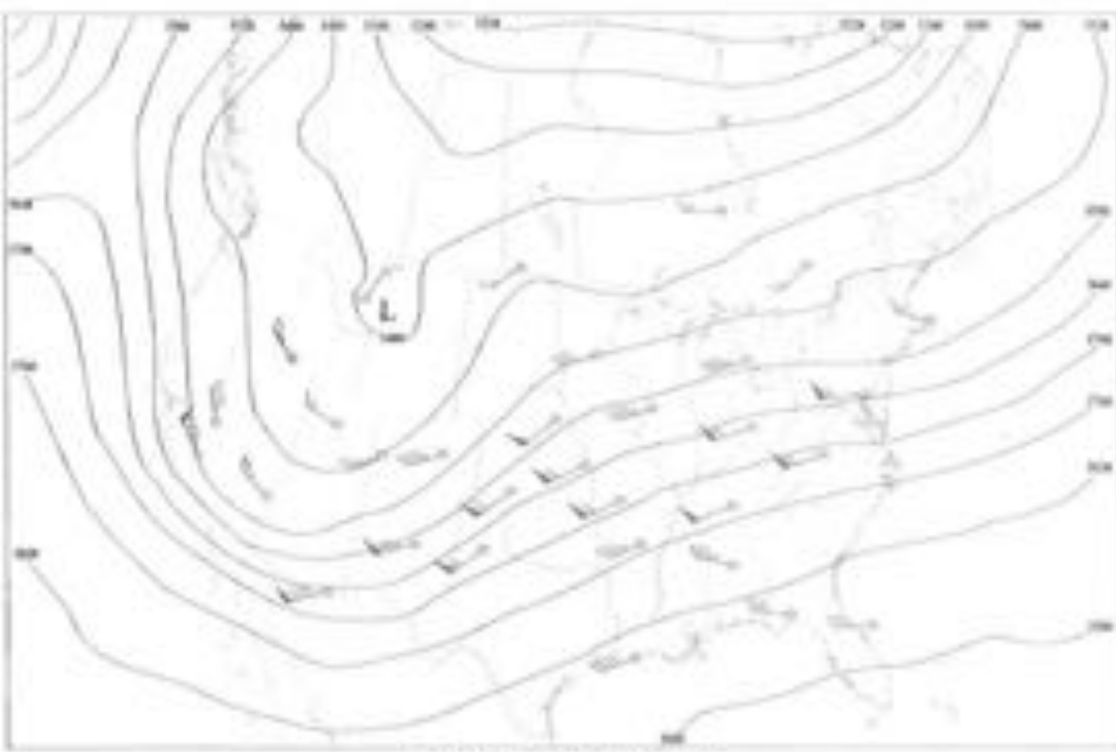


Figure 9-16. A 500-mb map.

300-mb and 200-mb maps

These maps help forecasters identify the jet stream. Typically, 300-mb maps are used during the coolest months, and 200-mb maps are used during warmest months because of seasonal variation in the jet-stream height. Sometimes 300- and 200-mb maps include shading to identify winds above 60 knots. In addition, the maximum jet stream winds, or jet streaks, are often identified with contours.

15. What contour interval is used to show heights on the 200-mb map below?

16. Shade areas with winds exceeding 60 knots.

17. Circle the two regions in Figure 9-17 that have the fastest winds.

Review Question

How does the drawing of isotherms, isodrosotherms, and streamlines help meteorologists identify potential areas of stormy weather?

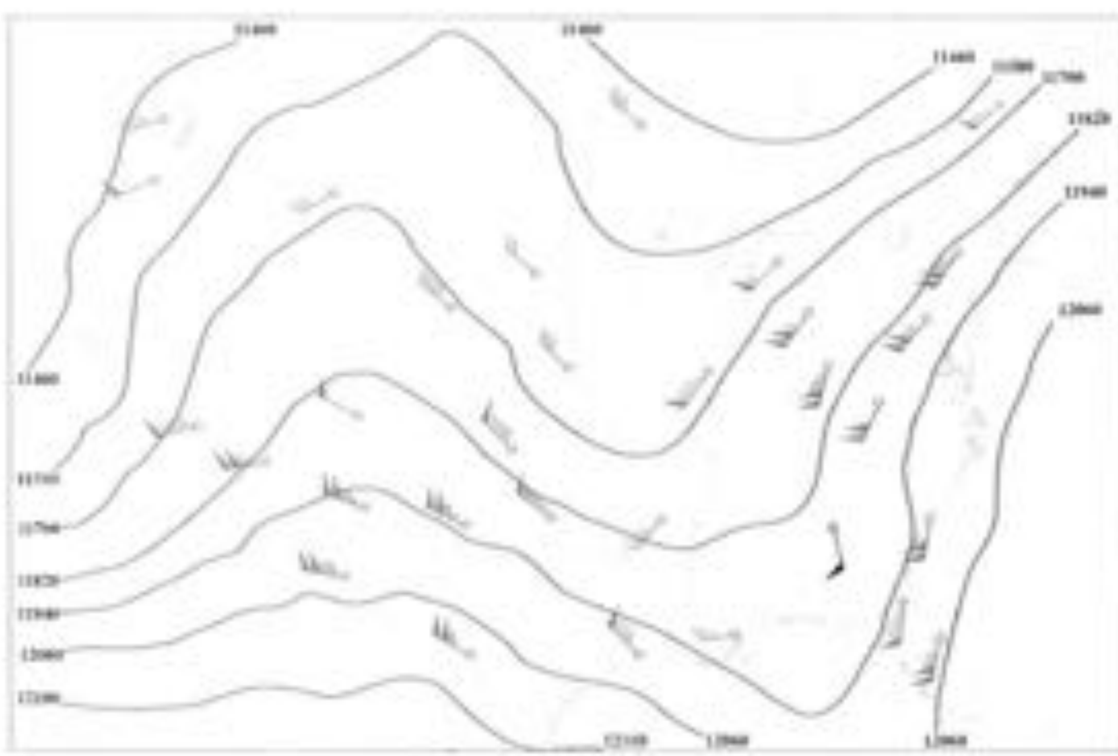


Figure 9-17. A 200-mb map.

Assignment 8: Be(at) the weather forecaster

You've been studying weather forecasting and analysis for a while now, and are probably getting pretty good at it. Now is the time to put those skills to the test.

What you'll need

- Your weather journal
- Pencil or pen
- Weather forecast information from the National Weather Service (http://www.nws.noaa.gov/)
- One full week (seven days) to do the assignment. You need to start this immediately and work on it every day until the due date.
- Some weather

What to do

For this exercise, you'll be monitoring the 7-day NOAA NWS forecast for both your location and your New York Times location.

1. Locate the 7-day NOAA NWS forecast for both of these areas. You can do this by navigating your web browser to http://www.nws.noaa.gov/ and searching by City, State and/or zip code.
2. For both locations
   a. On the first day, write down the weather forecast for the seventh day of the 7-day forecast *verbatim*. You can write it in your weather journal or just cut and paste into a document or spreadsheet and include a printed copy of this in the journal.
   b. On the second day, write down the sixth day forecast of the 7-day forecast (this was the former day seven from yesterday). Again, copy this *verbatim*.
   c. On the third day, write down the fifth day, and so on until you are recording *verbatim* the forecast for the current day.
3. In the mean time, write down your prediction for *tomorrow's* weather for your location based on any and all data you have access to. This can be your weather station, personal observations, other data from the NWS (but not their forecasts). Again, do this for seven days in a row. On the seventh day, write down a prediction for that day's weather. A sample of your data might look like this:

Day	Your Location	Your "NY Times" Location	Your predictions
1	The day 7 forecast	The day 7 forecast	The next day's (2) forecast
2	The day 6 forecast	The day 6 forecast	The next day's (3) forecast
3	The day 5 forecast	The day 5 forecast	The next day's (4) forecast
...	...	...	...
7	"Today's" forecast	"Today's" forecast	"Today's" forecast

What to hand in

You will record this information in your weather journal to be handed in at the end of the class. However, your entry must include an organized representation of the data indicated above, and answers to the following questions:

1. How accurate is the 7-day forecast on day 7 compared to what really happened in both locations?
2. How accurate is the 7-day forecast on day 6? On day 5? etc. In other words, what is the trend in accuracy as you approach the current date?
3. What criteria did you us to develop your personal forecast? Indicate the data you collected and the resources you used.
4. How accurate was your personal forecast day-to-day?
5. On day 6 of this experiment, your forecast will match up with the 2nd day of the 7-day forecast. How do they compare?
6. Who did a better job of predicting the weather on day 6, you or the National Weather Service?

Assignment 9: Climate Change Discussion

This is your chance to employ the baloney detection kit. Your assignment: find a climate change piece on the web, and discuss the implications on the eWeber class discussion board.

What you'll need

- A computer
- A piece on climate change from the web. This can be a blog, an article from online sources, an opinion piece, whatever. Try some google searches on "Climate Change", "Global Warming", etc. This piece can reflect data and analysis on climate change, a discussion of costs and implications, or an opinion piece (pro or con) on the subject of climate change.
- Access to eWeber and WSUOnline
- Some climate change facts, data, interpretations, and opinions
- Your IPCC summary (found on eWeber)
- Your baloney detection kit

What to do

1. Find and read your source.
2. Log on to eWeber and post the source to the Climate Change Discussion (found through the "Discussion" link in the left hand toolbar). Comment on your source, specifically:
    a. Copy the link into your post so other students can read the piece.
    b. Give a one or two sentence summary of the content or main conclusion.
    c. Describe in one or two paragraphs how this piece measures up to the evaluation of scientific claims described in your Baloney Detection Kit. Can you identify any major logical flaws or proper uses of the scientific method? Give examples.
    d. Comment on how this piece relates to the information in the IPCC summary report. Does it support this work? Is it critical of this work? Give examples.
    e. Read and comment on one other student's post. You can rate their posts with "Agree, disagree, or no opinion" if you like, but you must make a substantive comment.

What to hand in

Your grade on this assignment will be evaluated based on the quality and substance of your posts, including:

1. Your source (10 points) - is it appropriate to the topic? Is it a substantive piece?

2. Your comments on your source (10 points) - Did you read the piece? Are your posts thorough and substantive? Do they include a thoughtful analysis? Do you use proper spelling and grammar?

3. Your comments on another post (10 points) - Did you read the piece before commenting? Are your comments thorough and substantive? Do they include a thoughtful analysis? Are your comments constructive? Do you use proper spelling and grammar?

GEO 1130: Meteorology

Climate Change Resources

Instructor: John Armstrong
jcarmstrong@weber.edu

CARL SAGAN'S BALONEY DETECTION KIT

Based on the book The Demon Haunted World by Carl Sagan

The following are suggested as tools for testing arguments and detecting fallacious or fraudulent arguments:

- Wherever possible there must be independent confirmation of the facts
- Encourage substantive debate on the evidence by knowledgeable proponents of all points of view.
- Arguments from authority carry little weight (in science there are no "authorities").
- Spin more than one hypothesis - don't simply run with the first idea that caught your fancy.
- Try not to get overly attached to a hypothesis just because it's yours.
- Quantify, wherever possible.
- If there is a chain of argument every link in the chain must work.
- "Occam's razor" - if there are two hypothesis that explain the data equally well choose the simpler.
- Ask whether the hypothesis can, at least in principle, be falsified (shown to be false by some unambiguous test). In other words, it is testable? Can others duplicate the experiment or suggest other independent observations and get the same result?

Additional issues are

- Conduct control experiments - especially "double blind" experiments where the person taking measurements is not aware of the test and control subjects.
- Check for confounding factors - separate the variables.

Common fallacies of logic and rhetoric

- *Ad hominem* - attacking the arguer and not the argument.
- Argument from "authority".
- Argument from adverse consequences (putting pressure on the decision maker by pointing out dire consequences of an "unfavourable" decision).
- Appeal to ignorance (absence of evidence is not evidence of absence).
- Special pleading (typically referring to god's will).
- Begging the question (assuming an answer in the way the question is phrased).
- Observational selection (counting the hits and forgetting the misses).
- Statistics of small numbers (such as drawing conclusions from inadequate sample sizes).
- Misunderstanding the nature of statistics (*President Eisenhower expressing astonishment and alarm on discovering that fully half of all Americans have below average intelligence!*)
- Inconsistency (e.g. military expenditures based on worst case scenarios but scientific projections on environmental dangers thriftily ignored because they are not "proved").
- *Non sequitur* - "it does not follow" - the logic falls down.
- *Post hoc, ergo propter hoc* - "it happened after so it was caused by" - confusion of cause and effect.
- Meaningless question ("what happens when an irresistible force meets an immovable object?).

- Excluded middle - considering only the two extremes in a range of possibilities (making the "other side" look worse than it really is).
- Short-term v. long-term - a subset of excluded middle ("why pursue fundamental science when we have so huge a budget deficit?").
- Slippery slope - a subset of excluded middle - unwarranted extrapolation of the effects (give an inch and they will take a mile).
- Confusion of correlation and causation.
- Straw man - caricaturing (or stereotyping) a position to make it easier to attack..
- Suppressed evidence or half-truths.
- Weasel words - for example, use of euphemisms for war such as "police action" to get around limitations on Presidential powers. "*An important art of politicians is to find new names for institutions which under old names have become odious to the public*"

Above all - read the book!

Should the U.S. sign an agreement to reduce CO2 emissions?

China and India will join U.S. in war against global warming

By MATTHEW R. AUER
McClatchy-Tribune Information Services

BLOOMINGTON, Ind. — It seems like proponents for tough measures on climate change have fallen on hard times.

President Obama, who campaigned for strong American leadership to fight global warming, has backpedaled. The Senate, preoccupied with health care reform and a troubled economy, hasn't made climate change a priority. Majority leader Harry Reid of Nevada says the Senate may not vote on a climate change bill until well into 2010 — long after countries meet in Copenhagen for climate talks.

Meanwhile, atmospheric temperatures over the past few years haven't continued their steady upward climb, effectively idling Al Gore in that cherry picker he used so effectively in "An Inconvenient Truth." Has global warming hit the back burner with barely a pilot light to keep it warm? Keep an eye on that pilot light. Those stalled atmospheric temperatures may have to do with decades-long cycles in the movement of warm and cool oceanic waters.

Recent efforts to model these cycles actually predict, with considerable accuracy, the current global temperature plateau. They also predict a continued, overall warming trend in the long-term as carbon dioxide and other greenhouse gases accumulate in the atmosphere.

Meanwhile, in the policy arena, numerous retired U.S. military leaders, including Anthony Zinni, former commander of the U.S. Central Command, are calling climate change a "threat multiplier." Among other concerns, the Pentagon is pondering the consequences of chronic failed harvests and shrinking water supplies in unstable countries like Somalia, Sudan, Kenya and Nigeria — think: social unrest, mass migrations, breeding grounds for terrorists.

Leaders in China, India and Pakistan are mindful of these risks, too. They are among the countries most likely to suffer from water scarcity as climate change dries up mountain snowpack and disrupts the monsoon season.

Yet, China and India, the two largest greenhouse gas emitters in the developing world, steadfastly refuse to sign any agreement requiring cuts in their own emissions. So why should the United States sign an agreement that other major emitters reject? The answer depends on the architecture of the pact that replaces the current Kyoto Protocol. Using the House of Representatives' 2009 Waxman-Markey bill as a benchmark, the United States would agree to "Kyoto-lite" — a set of targets and a timetable that is arguably weaker than the provisions agreed to by most advanced industrialized countries in 1997. And in all likelihood, the final House-Senate compromise that lands on President Obama's desk will be less stringent than Waxman-Markey.

The United States could justify its insistence on Kyoto-lite because in sheer volumetric terms, it may end up agreeing to reduce more greenhouse gases than any other single nation. America will also be a big contributor to a future financial/technology aid package for developing countries that need help adapting to climate change.

An international agreement requiring the United States to do what it intends to do at the domestic level anyway, with or without China and India as treaty co-signers, is better than a feeble, "lowest common denominator" agreement that gets China and India on board, but requires no real action from anyone.

The United States, China and India could turn out to be climate heroes if they put their minds to it. Some tantalizing assets are in place.

With that kind of ingenuity and their newfound wealth, China and India, in partnership with the United States, could go a long way in fighting global warming, with or without a resounding diplomatic triumph at Copenhagen.

Matthew R. Auer is the dean of Hutton Honors College and a professor at Indiana University's School of Public and Environmental Affairs. Readers may write him at Indiana University, 811 East 7th Street, Bloomington, Ind. 47405.

Copenhagen does nothing to stall global warming

By BEN LIEBERMAN
McClatchy-Tribune Information Services

WASHINGTON — A new global warming treaty would be all economic pain and little environmental gain for America even if China and other fast-developing nations sign on as well. But if developing nations remain exempted, it would be all economic pain and no environmental gain. Either way, America should stay out! At the United Nations' Conference on Climate Change in Copenhagen in early December proponents of the 1997 Kyoto Protocol — which expires in 2012 — will try to hash out a new international agreement for lowering carbon dioxide and other greenhouse gas emissions. In other words, a new global energy tax may be in the works.

The United States did not ratify the Kyoto Protocol, and for good reason. Its provisions would have cost American consumers trillions, while having virtually no impact on world temperatures.

Nonetheless, many in the international community want to finalize stringent new post-2012 provisions at Copenhagen, or at least initiate the process that would lead to such measures. They have also expressed optimism that the Obama Administration would join in such an agreement.

However, the United States should follow the policy set out in the Senate's 1997 Byrd-Hagel resolution and not enter into any global warming treaty that harms the American economy or leaves out major developing nations. The resolution passed 95-0.

Despite that unanimous — and eminently reasonable — resolution, then-Vice President Al Gore led the American delegation to Kyoto and agreed to a treaty that violated both provisions.

President Clinton never submitted it for Senate ratification, knowing full well that he could not possibly get the two-thirds' support needed for a treaty that so unambiguously flouted Byrd-Hagel.

The Byrd-Hagel resolution remains in effect and still provides sound advice as we head into discussions about a post-Kyoto treaty in Copenhagen.

A U.S. Energy Information Administration study projected costs of U.S. compliance with the Kyoto treaty between $100 billion and $397 billion annually. Any serious attempt to create a new agreement in Copenhagen would likely be far more expensive.

Proponents of Kyoto described its five percent greenhouse gas emissions reduction targets as a "modest" step. Now, they say, much tougher — and costlier — provisions are necessary. Thus the Byrd-Hagel provision prohibiting economic harm would clearly be violated.

The other provision — that China and other developing nations must commit to emissions reductions — is also very important. The Byrd-Hagel resolution warned that "greenhouse gas emissions of developing country parties are rapidly increasing and are expected to surpass emissions of the United States and other (developed) countries as early as 2015." Turns out, that was a Pollyanna-ish projection. Emerging nations' emissions began to outpace the developed world's emissions in 2005. They are projected to continue increasing seven times faster than in the developed world.

In effect, any reduction in emissions from the U.S. and other developed nations would be swamped by growing emissions from developing nations — even more so if developed-nation constraints shift economic activity to exempted nations.

With or without America or China, any proposed solution to global warming makes sense only to the extent global warming is a serious problem in the first place, and there is growing reason for doubt. Indeed, since 1997 — the Year of Kyoto — world temperatures have been remarkably flat.

The lack of global warming won't stop global warming activists in Copenhagen, but it should stop the U.S. government from embracing an ineffective solution to an overstated problem.

Ben Lieberman is a senior policy analyst at the Thomas A. Roe Institute for Economic Policy Studies at the Heritage Foundation. Write to The Heritage Foundation, 214 Massachusetts Avenue NE, Washington, D.C. 20002.

Is global warming shrinking winter?

By BROCK VERGAKIS
The Associated Press

SALT LAKE CITY — Ski resorts across the country used the Thanksgiving weekend to jump start their winter seasons, but with every passing year comes a frightening realization: If global temperatures continue to rise, fewer and fewer resorts will be able to open for the traditional beginning of ski season.

Warmer temperatures at night are making it more difficult to make snow and the snow that falls naturally is melting earlier in the spring.

In few places is this a bigger concern than the American West, where skiing is one of the most lucrative segments of the tourism industry and often the only reason many people visit cash-strapped states like Utah during winter.

But even as world leaders descend on Copenhagen next month to figure out a way to reduce carbon emissions blamed in global warming, the industry is still grappling with leaders in some of their own ski-crazy states who refuse to concede that humans have any impact on climate change.

Chief among them is Republican Utah Gov. Gary Herbert, who says he will host what he calls the first "legitimate debate" about man's role in climate change in the spring.

While the world's leading scientific organizations agree the debate was settled long ago, the former Realtor who took office when Jon Huntsman resigned to become U.S. ambassador to China maintains that it wasn't.

"He's said to me that the jury is out in his mind whether it's man-caused and he thinks and believes that the public jury is still out," said Herbert's environmental adviser, Democrat Ted Wilson.

Herbert's reluctance to acknowledge that greenhouse gases contribute to global warming quietly frustrates Utah ski resorts that depend on state marketing money, but it openly infuriates industry officials elsewhere who liken it to having a debate about whether the world is flat.

"That's just kind of raging ignorance," said Auden Schendler, executive director of sustainability for Aspen (Colo.) Skiing Co.

"We're not environmentalists, we're business people. We have studied the hell out of the climate science. To have a neighboring governor not believe it ... It's absurd."

A climate study by the Aspen Global Change Institute is forecasting that if global emissions continue to rise, Aspen will warm 14 degrees by the end of this century, giving it a similar climate to that of Amarillo, Texas.

Many ski companies and the mountain towns they've created have been working to reduce their carbon footprints and advocating for significant policy changes for years.

In California, the ski industry was one of the first groups to support legislation requiring the state to reduce greenhouse gases to 1990 emission levels by 2020.

Aspen Skiing Co. is widely recognized as a national leader, but Schendler readily acknowledges that the nation's ski resorts can do little on their own to affect climate change.

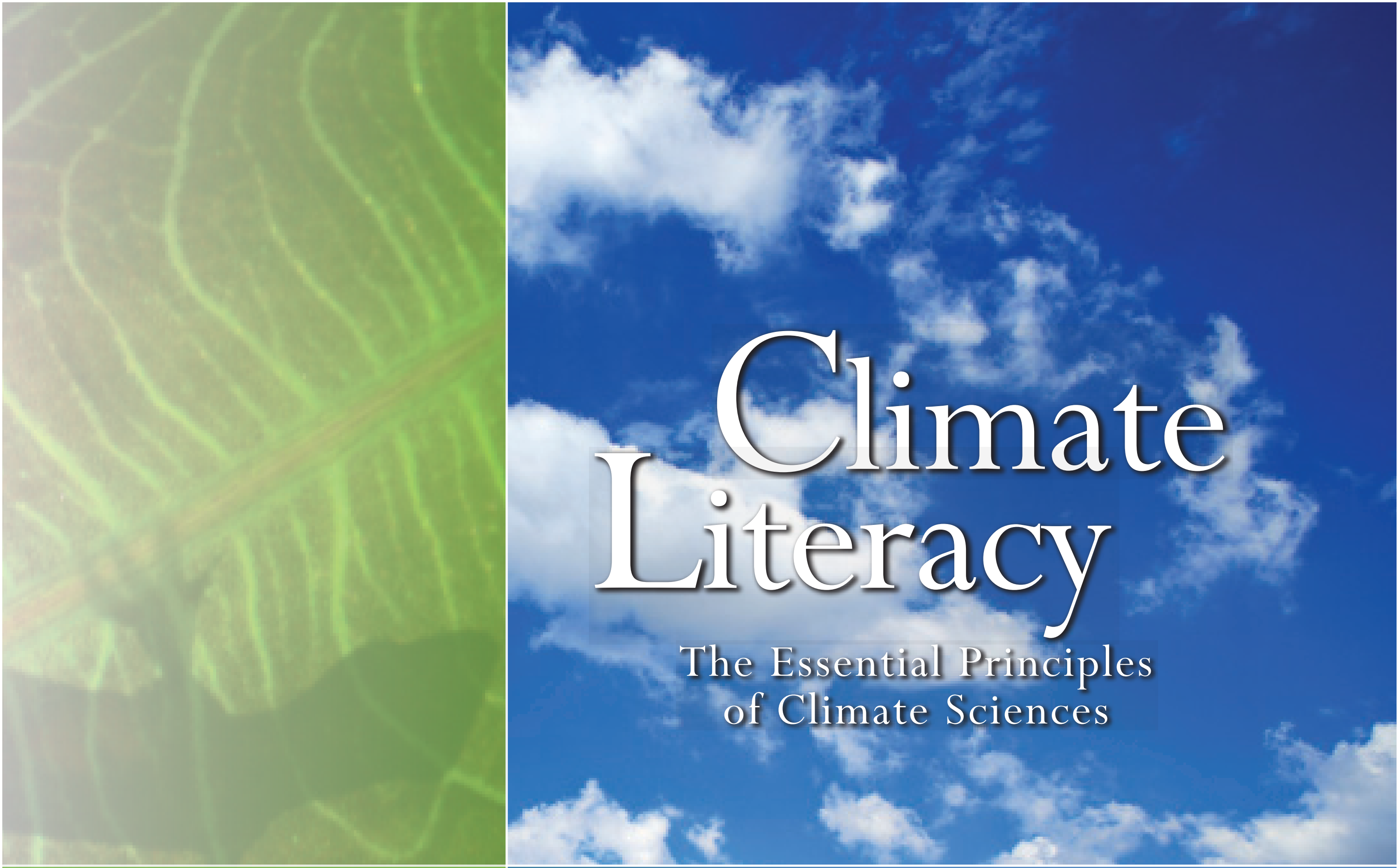
He said company resorts like Aspen and Snowmass are at their best when they educate their highly affluent — and politically connected — guests about global warming's effects.

"You need federal legislation in the U.S.," he said. "You need it to help drive an international agreement."

Herbert and Utah's senior U.S. Senator, Orrin Hatch, recently teamed up to oppose federal cap and trade legislation that many in the ski industry support, saying it could cost jobs in a state that's heavily dependent on coal for energy. In the posh ski resort town of Park City, a former mining town that played host to the 2002 Winter Olympics, Mayor Dana Williams says some state leaders don't seem to grasp how important the ski industry is to the state and what a threat global warming is.

Tourism is a growing $7 billion a year industry in Utah and the state's 13 ski resorts are directly responsible for roughly $1 billion of that. Williams says the very future of the city that hosts the Sundance Film Festival each winter is at stake with rising temperatures.

A consultant's report released by the nonprofit community Park City Foundation this fall warned that by 2030 the decrease in snowpack caused by global warming could lead to the loss of more than 1,100 jobs and a $120 million economic loss in that community alone. By 2050, the report says those figures could jump to more than 3,700 lost jobs and a $392 million economic loss as fewer and fewer slopes in the area are able to open and lure visitors from around the world.



Climate Literacy

The Essential Principles of Climate Sciences

A CLIMATE-ORIENTED APPROACH FOR LEARNERS OF ALL AGES

A Guide for Individuals and Communities

Second Version: March 2009

www.globalchange.gov

CLIMATE CHANGES

Throughout its history, Earth's climate has varied, reflecting the complex interactions and dependencies of the solar, oceanic, terrestrial, atmospheric, and living components that make up planet Earth's systems. For at least the last million years, our world has experienced cycles of warming and cooling that take approximately 100,000 years to complete. Over the course of each cycle, global average temperatures have fallen and then risen again by about 9°F (5°C), each time taking Earth into an ice age and then warming it again. This cycle is believed associated with regular changes in Earth's orbit that alter the intensity of solar energy the planet receives. Earth's climate has also been influenced on very long timescales by changes in ocean circulation that result from plate tectonic movements. Earth's climate has changed abruptly at times, sometimes as a result of slower natural processes such as shifts in ocean circulation, sometimes due to sudden events such as massive volcanic eruptions. Species and ecosystems have either adapted to these past climate variations or perished.

While global climate has been relatively stable over the last 10,000 years—the span of human civilization—regional variations in climate patterns have influenced human history in profound ways, playing an integral role in whether societies thrived or failed. We now know that the opposite is also true: human activities—burning fossil fuels and deforesting large areas of land, for instance—have had a profound influence on Earth's climate. In its 2007 Fourth Assessment, the Intergovernmental Panel on Climate Change (IPCC) stated that it had "very high confidence that the global average net effect of human activities since 1750 has been one of warming." The IPCC attributes humanity's global warming influence primarily to the increase in three key heat-trapping gases in the atmosphere: carbon dioxide, methane, and nitrous oxide. The U.S. Climate Change Science Program published findings in agreement with the IPCC report, stating that "studies to detect climate change and attribute its causes using patterns of observed temperature change in space and time show clear evidence of human influences on the climate system (due to changes in greenhouse gases, aerosols, and stratospheric ozone)."[1]

To protect fragile ecosystems and to build sustainable communities that are resilient to climate change—including extreme weather and climate events—a climate-literate citizenry is essential. This climate science literacy guide identifies the essential principles and fundamental concepts that individuals and communities should understand about Earth's climate system. Such understanding improves our ability to make decisions about activities that increase vulnerability to the impacts of climate change and to take precautionary steps in our lives and livelihoods that would reduce those vulnerabilities.

1. *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences*. Thomas R. Karl, Susan J. Hassol, Christopher D. Miller, and William L. Murray, editors, 2006. A Report by the Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC.

WHAT IS CLIMATE SCIENCE LITERACY?

Climate Science Literacy is an understanding of your influence on climate and climate's influence on you and society.

A climate-literate person:

- understands the essential principles of Earth's climate system,
- knows how to assess scientifically credible information about climate,
- communicates about climate and climate change in a meaningful way, and
- is able to make informed and responsible decisions with regard to actions that may affect climate.

WHY DOES CLIMATE SCIENCE LITERACY MATTER?

- During the 20th century, Earth's globally averaged surface temperature rose by approximately 1.08°F (0.6°C). Additional warming of more than 0.25°F (0.14°C) has been measured since 2000. Though the total increase may seem small, it likely represents an extraordinarily rapid rate of change compared to changes in the previous 10,000 years.
- Over the 21st century, climate scientists expect Earth's temperature to continue increasing, very likely more than it did during the 20th century. Two anticipated results are rising global sea level and increasing frequency and intensity of heat waves, droughts, and floods. These changes will affect almost every aspect of human society, including economic prosperity, human and environmental health, and national security.
- Scientific observations and climate model results indicate that human activities are now the primary cause of most of the ongoing increase in Earth's globally averaged surface temperature.
- Climate change will bring economic and environmental challenges as well as opportunities, and citizens who have an understanding of climate science will be better prepared to respond to both.
- Society needs citizens who understand the climate system and know how to apply that knowledge in their careers and in their engagement as active members of their communities.
- Climate change will continue to be a significant element of public discourse. Understanding the essential principles of climate science will enable all people to assess news stories and contribute to their everyday conversations as informed citizens.

CLIMATE SCIENCE LITERACY IS A PART OF SCIENCE LITERACY.

"Science, mathematics, and technology have a profound impact on our individual lives and our culture. They play a role in almost all human endeavors, and they affect how we relate to one another and the world around us. . . . Science Literacy enables us to make sense of real-world phenomena, informs our personal and social decisions, and serves as a foundation for a lifetime of learning."

From the American Association for the Advancement of Science, Atlas of Science Literacy, Volume 2, Project 2061.

People who are climate science literate know that climate science can inform our decisions that improve quality of life. They have a basic understanding of the climate system, including the natural and human-caused factors that affect it. Climate science literate individuals understand how climate observations and records as well as computer modeling contribute to scientific knowledge about climate. They are aware of the fundamental relationship between climate and human life and the many ways in which climate has always played a role in human health. They have the ability to assess the validity of scientific arguments about climate and to use that information to support their decisions.

CLIMATE SCIENCE LITERACY IS AN ONGOING PROCESS.

No single person is expected to understand every detail about all of the fundamental climate science literacy concepts. Full comprehension of these interconnected concepts will require a systems-thinking approach, meaning the ability to understand complex interconnections among all of the components of the climate system. Moreover, as climate science progresses and as efforts to educate the people about climate's influence on them and their influence on the climate system mature, public understanding will continue to grow.

Climate is an ideal interdisciplinary theme for lifelong learning about the scientific process and the ways in which humans affect and are affected by the Earth's systems. This rich topic can be approached at many levels, from comparing the daily weather with long-term records to exploring abstract representations of climate in computer models to examining how climate change impacts human and ecosystem health. Learners of all ages can use data from their own experiments, data collected by satellites and other observation systems, or records from a range of physical, chemical, biological, geographical, social, economic, and historical sources to explore the impacts of climate and potential adaptation and mitigation strategies.

HOW DO WE KNOW WHAT IS SCIENTIFICALLY CORRECT?

The Peer Review Process

Science is an on-going process of making observations and using evidence to test hypotheses. As new ideas are developed and new data are obtained, oftentimes enabled by new technologies, our understanding evolves. The scientific community uses a highly formalized version of peer review to validate research results and our understanding of their significance. Researchers describe their experiments, results, and interpretations in scientific manuscripts and submit them to a scientific journal that specializes in their field of science. Scientists who are experts in that field serve as "referees" for the journal: they read the manuscript carefully to judge the reliability of the research design and check that the interpretations are supported by the data. Based on the reviews, journal editors may accept or reject manuscripts or ask the authors to make revisions if the study has insufficient data or unsound interpretations. Through this process, only those concepts that have been described through well-documented research and subjected to the scrutiny of other experts in the field become published papers in science journals and accepted as current science knowledge. Although peer review does not guarantee that any particular published result is valid, it does provide a high assurance that the work has been carefully vetted for accuracy by informed experts prior to publication. The overwhelming majority of peer-reviewed papers about global climate change acknowledge that human activities are substantially contributing factors.

Source: *Roger J. Braithwaite, The University of Manchester, UK*

A meltwater stream on the Greenland Ice Sheet flows into the ice through a tunnel called a moulin. About half of the loss of Greenland's ice mass flows into the North Atlantic Ocean as melt water. Liquid water, which is denser than ice, can penetrate through the ice sheet, lubricating the underside, and also accelerate ice loss. Warmer temperatures cause melting in the summer months, which leads to faster flow, drawing more of the ice sheet down to warmer, lower altitudes.

Agricultural engineers inspect a dry stream.

Source: *Scott Bauer, USDA*

INFORMED CLIMATE DECISIONS REQUIRE AN INTEGRATED APPROACH.

In the coming decades, scientists expect climate change to have an increasing impact on human and natural systems. In a warmer world, accessibility to food, water, raw materials, and energy are likely to change. Human health, biodiversity, economic stability, and national security are also expected to be affected by climate change. Climate model projections suggest that negative effects of climate change will significantly outweigh positive ones. The nation's ability to prepare for and adapt to new conditions may be exceeded as the rate of climate change increases.

Reducing our vulnerability to these impacts depends not only upon our ability to understand climate science and the implications of climate change, but also upon our ability to integrate and use that knowledge effectively. Changes in our economy and infrastructure as well as individual attitudes, societal values, and government policies will be required to alter the current trajectory of climate's impact on human lives. The resolve of individuals, communities, and countries to identify and implement effective management strategies for critical institutional and natural resources will be necessary to ensure the stability of both human and natural systems as temperatures rise.

This climate science literacy document focuses primarily on the physical and biological science aspects of climate and climate change. Yet as nations and the international community seek solutions to global climate change over the coming decades, a more comprehensive, interdisciplinary approach to climate literacy—one that includes economic and social considerations—will play a vital role in knowledgeable planning, decision making, and governance. A new effort is in development within the social sciences community to produce a companion document that will address these aspects of climate literacy. Together, these documents will promote informed decision-making and effective systems-level responses to climate change that reflect a fundamental understanding of climate science. It is imperative that these responses to climate change embrace the following guiding principle.

GUIDING PRINCIPLE FOR INFORMED CLIMATE DECISION:

Humans can take actions to reduce climate change and its impacts.

A. Climate information can be used to reduce vulnerabilities or enhance the resilience of communities and ecosystems affected by climate change. Continuing to improve scientific understanding of the climate system and the quality of reports to policy and decision-makers is crucial.

B. Reducing human vulnerability to the impacts of climate change depends not only upon our ability to understand climate science, but also upon our ability to integrate that knowledge into human society. Decisions that involve Earth's climate must be made with an understanding of the complex inter-connections among the physical and biological components of the Earth system as well as the consequences of such decisions on social, economic, and cultural systems.

C. The impacts of climate change may affect the security of nations. Reduced availability of water, food, and land can lead to competition and conflict among humans, potentially resulting in large groups of climate refugees.

D. Humans may be able to mitigate climate change or lessen its severity by reducing greenhouse gas concentrations through processes that move carbon out of the atmosphere or reduce greenhouse gas emissions.

E. A combination of strategies is needed to reduce greenhouse gas emissions. The most immediate strategy is conservation of oil, gas, and coal, which we rely on as fuels for most of our transportation, heating, cooling, agriculture, and electricity. Short-term strategies involve switching from carbon-intensive to renewable energy sources, which also requires building new infrastructure for alternative energy sources. Long-term strategies involve innovative research and a fundamental change in the way humans use energy.

F. Humans can adapt to climate change by reducing their vulnerability to its impacts. Actions such as moving to higher ground to avoid rising sea levels, planting new crops that will thrive under new climate conditions, or using new building technologies represent adaptation strategies. Adaptation often requires financial investment in new or enhanced research, technology, and infrastructure.

G. Actions taken by individuals, communities, states, and countries all influence climate. Practices and policies followed in homes, schools, businesses, and governments can affect climate. Climate-related decisions made by one generation can provide opportunities as well as limit the range of possibilities open to the next generation. Steps toward reducing the impact of climate change may influence the present generation by providing other benefits such as improved public health infrastructure and sustainable built environments.

This spectacular "blue marble" image is the most detailed true-color image of the entire Earth to date. Using a collection of satellite-based observations, scientists and visualizers stitched together months of observations of the land surface, oceans, sea ice, and clouds into a seamless, true-color mosaic of every square kilometer (.386 square mile) of our planet.

Source: *NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water, clouds)*

CLIMATE SCIENCE LITERACY IS AN UNDERSTANDING OF THE CLIMATE'S INFLUENCE ON YOU AND SOCIETY AND YOUR INFLUENCE ON CLIMATE

CLIMATE LITERACY:
The Essential Principles of Climate Science

Each essential principle is supported by fundamental concepts comparable to those underlying the National Science Education Standards (NSES) and the American Association for the Advancement of Science (AAAS) Benchmarks for Science Literacy.

1 THE SUN IS THE PRIMARY SOURCE OF ENERGY FOR EARTH'S CLIMATE SYSTEM.

A. Sunlight reaching the Earth can heat the land, ocean, and atmosphere. Some of that sunlight is reflected back to space by the surface, clouds, or ice. Much of the sunlight that reaches Earth is absorbed and warms the planet.

B. When Earth emits the same amount of energy as it absorbs, its energy budget is in balance, and its average temperature remains stable.

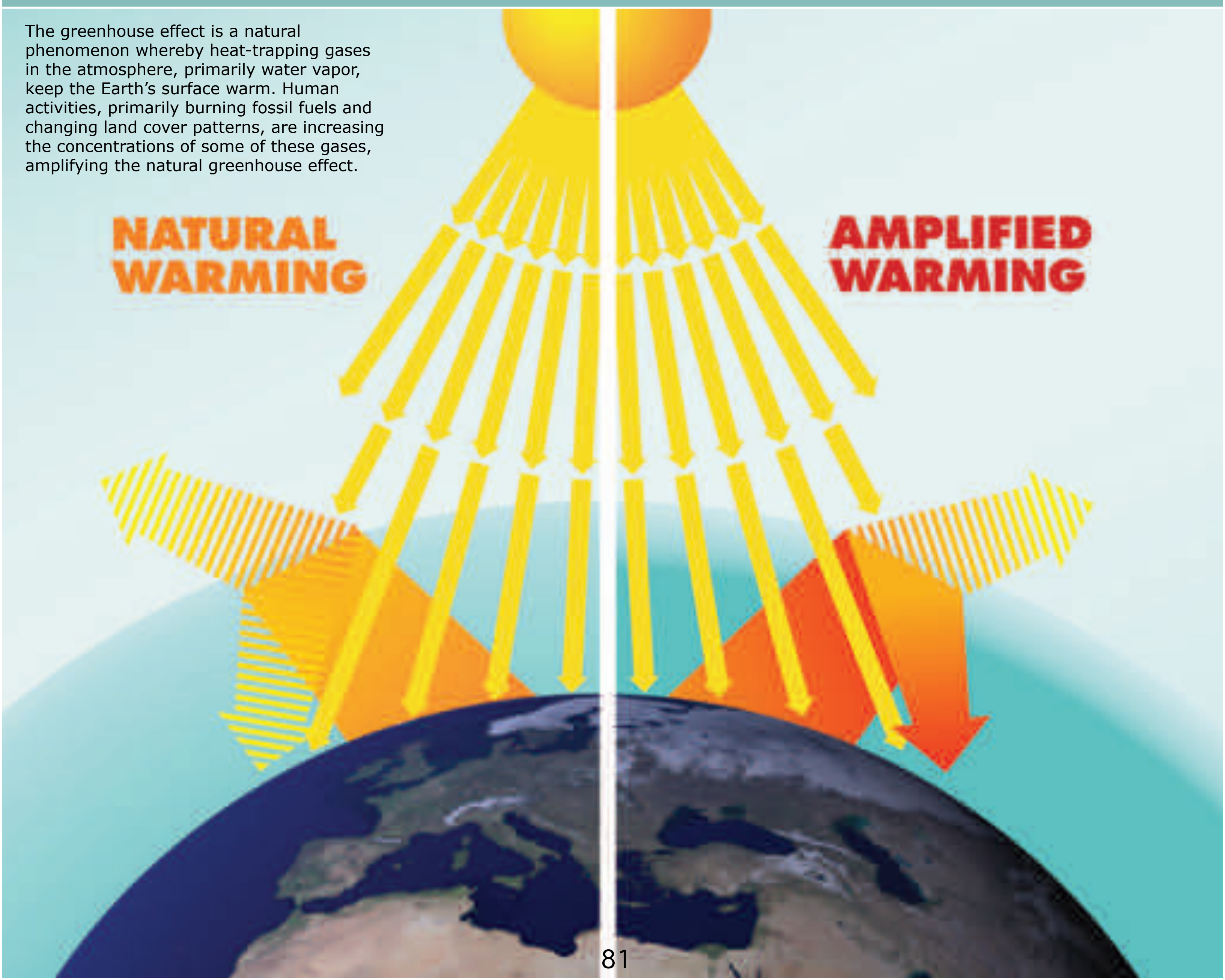
C. The tilt of Earth's axis relative to its orbit around the Sun results in predictable changes in the duration of daylight and the amount of sunlight received at any latitude throughout a year. These changes cause the annual cycle of seasons and associated temperature changes.

D. Gradual changes in Earth's rotation and orbit around the Sun change the intensity of sunlight received in our planet's polar and equatorial regions. For at least the last 1 million years, these changes occurred in 100,000-year cycles that produced ice ages and the shorter warm periods between them.

E. A significant increase or decrease in the Sun's energy output would cause Earth to warm or cool. Satellite measurements taken over the past 30 years show that the Sun's energy output has changed only slightly and in both directions. These changes in the Sun's energy are thought to be too small to be the cause of the recent warming observed on Earth.

Source: *Modified from the Marian Koshland Science Museum of the National Academy of Sciences' "Global Warming: Facts & Our Future" 2004*

The greenhouse effect is a natural phenomenon whereby heat-trapping gases in the atmosphere, primarily water vapor, keep the Earth's surface warm. Human activities, primarily burning fossil fuels and changing land cover patterns, are increasing the concentrations of some of these gases, amplifying the natural greenhouse effect.



2 CLIMATE IS REGULATED BY COMPLEX INTERACTIONS AMONG COMPONENTS OF THE EARTH SYSTEM.

A. Earth's climate is influenced by interactions involving the Sun, ocean, atmosphere, clouds, ice, land, and life. Climate varies by region as a result of local differences in these interactions.

B. Covering 70% of Earth's surface, the ocean exerts a major control on climate by dominating Earth's energy and water cycles. It has the capacity to absorb large amounts of solar energy. Heat and water vapor are redistributed globally through density-driven ocean currents and atmospheric circulation. Changes in ocean circulation caused by tectonic movements or large influxes of fresh water from melting polar ice can lead to significant and even abrupt changes in climate, both locally and on global scales.

C. The amount of solar energy absorbed or radiated by Earth is modulated by the atmosphere and depends on its composition. Greenhouse gases—such as water vapor, carbon dioxide, and methane—occur naturally in small amounts and absorb and release heat energy more efficiently than abundant atmospheric gases like nitrogen and oxygen. Small increases in carbon dioxide concentration have a large effect on the climate system.

D. The abundance of greenhouse gases in the atmosphere is controlled by biogeochemical cycles that continually move these components between their ocean, land, life, and atmosphere reservoirs. The abundance of carbon in the atmosphere is reduced through seafloor accumulation of marine sediments and accumulation of plant biomass and is increased through deforestation and the burning of fossil fuels as well as through other processes.

E. Airborne particulates, called "aerosols," have a complex effect on Earth's energy balance: they can cause both cooling, by reflecting incoming sunlight back out to space, and warming, by absorbing and releasing heat energy in the atmosphere. Small solid and liquid particles can be lofted into the atmosphere through a variety of natural and man-made processes, including volcanic eruptions, sea spray, forest fires, and emissions generated through human activities.

F. The interconnectedness of Earth's systems means that a significant change in any one component of the climate system can influence the equilibrium of the entire Earth system. Positive feedback loops can amplify these effects and trigger abrupt changes in the climate system. These complex interactions may result in climate change that is more rapid and on a larger scale than projected by current climate models.

Source: *Astronaut photograph ISS015-E- 10469, courtesy NASA/JSC Gateway to Astronaut Photography of Ea*

Solar power drives Earth's climate. Energy from the Sun heats the surface, warms the atmosphere, and powers the ocean currents.

3 LIFE ON EARTH DEPENDS ON, IS SHAPED BY, AND AFFECTS CLIMATE.

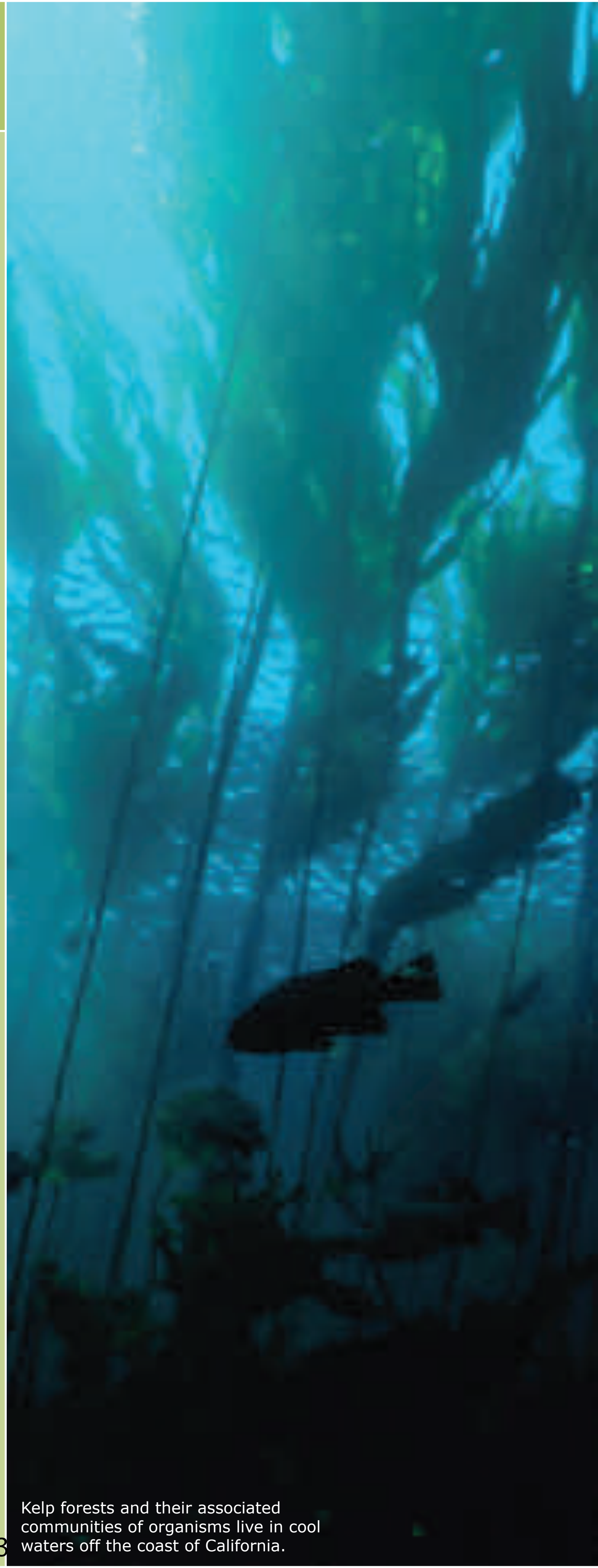
A. Individual organisms survive within specific ranges of temperature, precipitation, humidity, and sunlight. Organisms exposed to climate conditions outside their normal range must adapt or migrate, or they will perish.

B. The presence of small amounts of heat-trapping greenhouse gases in the atmosphere warms Earth's surface, resulting in a planet that sustains liquid water and life.

C. Changes in climate conditions can affect the health and function of ecosystems and the survival of entire species. The distribution patterns of fossils show evidence of gradual as well as abrupt extinctions related to climate change in the past.

D. A range of natural records shows that the last 10,000 years have been an unusually stable period in Earth's climate history. Modern human societies developed during this time. The agricultural, economic, and transportation systems we rely upon are vulnerable if the climate changes significantly.

E. Life—including microbes, plants, and animals and humans—is a major driver of the global carbon cycle and can influence global climate by modifying the chemical makeup of the atmosphere. The geologic record shows that life has significantly altered the atmosphere during Earth's history.



Source: *Steve Fisher*

Kelp forests and their associated communities of organisms live in cool waters off the coast of California.

4 CLIMATE VARIES OVER SPACE AND TIME THROUGH BOTH NATURAL AND MAN-MADE PROCESSES.

A. Climate is determined by the long-term pattern of temperature and precipitation averages and extremes at a location. Climate descriptions can refer to areas that are local, regional, or global in extent. Climate can be described for different time intervals, such as decades, years, seasons, months, or specific dates of the year.

B. Climate is not the same thing as weather. Weather is the minute-by-minute variable condition of the atmosphere on a local scale. Climate is a conceptual description of an area's average weather conditions and the extent to which those conditions vary over long time intervals.

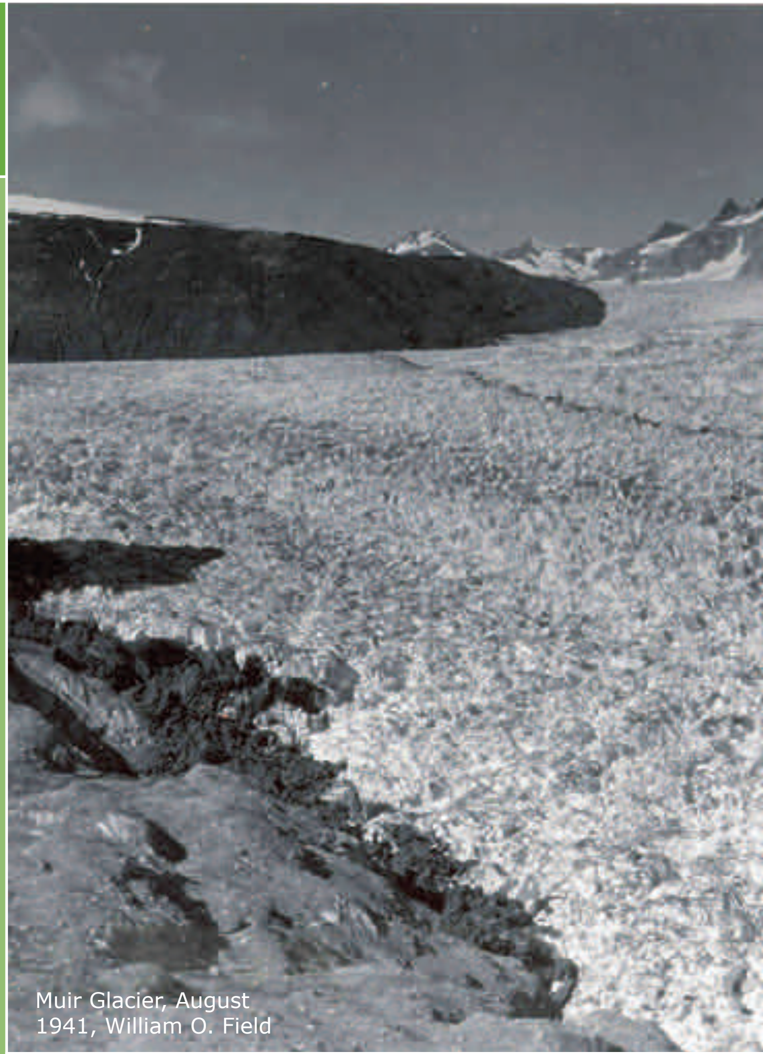
C. Climate change is a significant and persistent change in an area's average climate conditions or their extremes. Seasonal variations and multi-year cycles (for example, the El Niño Southern Oscillation) that produce warm, cool, wet, or dry periods across different regions are a natural part of climate variability. They do not represent climate change.

D. Scientific observations indicate that global climate has changed in the past, is changing now, and will change in the future. The magnitude and direction of this change is not the same at all locations on Earth.

E. Based on evidence from tree rings, other natural records, and scientific observations made around the world, Earth's average temperature is now warmer than it has been for at least the past 1,300 years. Average temperatures have increased markedly in the past 50 years, especially in the North Polar Region.

F. Natural processes driving Earth's long-term climate variability do not explain the rapid climate change observed in recent decades. The only explanation that is consistent with all available evidence is that human impacts are playing an increasing role in climate change. Future changes in climate may be rapid compared to historical changes.

G. Natural processes that remove carbon dioxide from the atmosphere operate slowly when compared to the processes that are now adding it to the atmosphere. Thus, carbon dioxide introduced into the atmosphere today may remain there for a century or more. Other greenhouse gases, including some created by humans, may remain in the atmosphere for thousands of years.



Muir Glacier, August 1941, William O. Field

Muir Glacier, August 2004, Bruce F. Molnia

Source: *National Snow and Ice Data Center, W. O. Field, B. F. Molnia*

5 OUR UNDERSTANDING OF THE CLIMATE SYSTEM IS IMPROVED THROUGH OBSERVATIONS, THEORETICAL STUDIES, AND MODELING.

A. The components and processes of Earth's climate system are subject to the same physical laws as the rest of the Universe. Therefore, the behavior of the climate system can be understood and predicted through careful, systematic study.

B. Environmental observations are the foundation for understanding the climate system. From the bottom of the ocean to the surface of the Sun, instruments on weather stations, buoys, satellites, and other platforms collect climate data. To learn about past climates, scientists use natural records, such as tree rings, ice cores, and sedimentary layers. Historical observations, such as native knowledge and personal journals, also document past climate change.

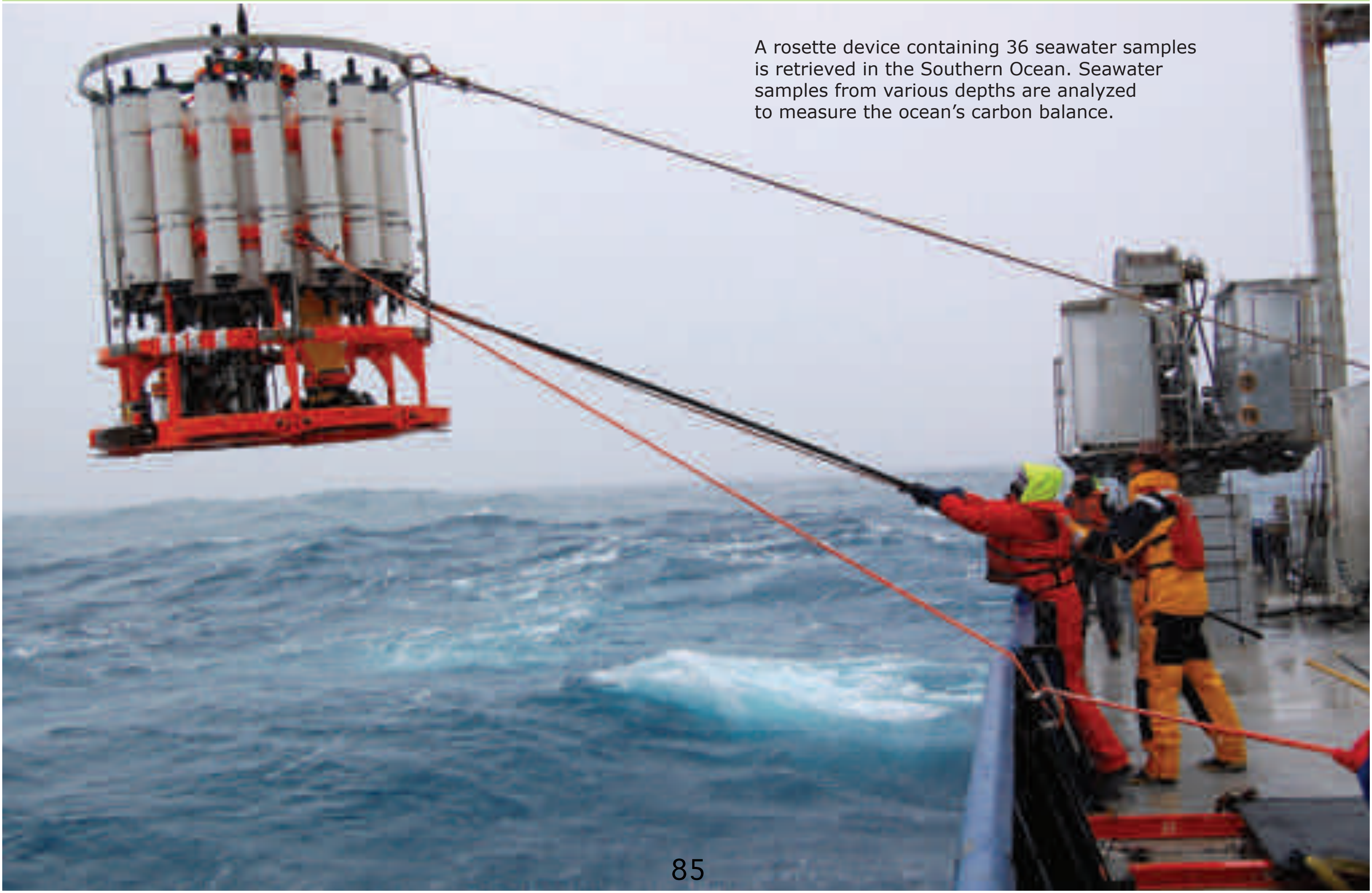
C. Observations, experiments, and theory are used to construct and refine computer models that represent the climate system and make predictions about its future behavior. Results from these models lead to better understanding of the linkages between the atmosphere-ocean system and climate conditions and inspire more observations and experiments. Over time, this iterative process will result in more reliable projections of future climate conditions.

D. Our understanding of climate differs in important ways from our understanding of weather. Climate scientists' ability to predict climate patterns months, years, or decades into the future is constrained by different limitations than those faced by meteorologists in forecasting weather days to weeks into the future.[1]

E. Scientists have conducted extensive research on the fundamental characteristics of the climate system and their understanding will continue to improve. Current climate change projections are reliable enough to help humans evaluate potential decisions and actions in response to climate change.

1. Based on "Climate Change: An Information Statement of the American Meteorological Society," 2007

Source: *B. Longworth © 2008*



A rosette device containing 36 seawater samples is retrieved in the Southern Ocean. Seawater samples from various depths are analyzed to measure the ocean's carbon balance.

6 HUMAN ACTIVITIES ARE IMPACTING THE CLIMATE SYSTEM.

A. The overwhelming consensus of scientific studies on climate indicates that most of the observed increase in global average temperatures since the latter part of the 20th century is very likely due to human activities, primarily from increases in greenhouse gas concentrations resulting from the burning of fossil fuels.[2]

B. Emissions from the widespread burning of fossil fuels since the start of the Industrial Revolution have increased the concentration of greenhouse gases in the atmosphere. Because these gases can remain in the atmosphere for hundreds of years before being removed by natural processes, their warming influence is projected to persist into the next century.

C. Human activities have affected the land, oceans, and atmosphere, and these changes have altered global climate patterns. Burning fossil fuels, releasing chemicals into the atmosphere, reducing the amount of forest cover, and rapid expansion of farming, development, and industrial activities are releasing carbon dioxide into the atmosphere and changing the balance of the climate system.

D. Growing evidence shows that changes in many physical and biological systems are linked to human-caused global warming.[3] Some changes resulting from human activities have decreased the capacity of the environment to support various species and have substantially reduced ecosystem biodiversity and ecological resilience.

E. Scientists and economists predict that there will be both positive and negative impacts from global climate change. If warming exceeds 2 to 3°C (3.6 to 5.4°F) over the next century, the consequences of the negative impacts are likely to be much greater than the consequences of the positive impacts.

2. Based on IPCC, 2007: *The Physical Science Basis: Contribution of Working Group I*

3. Based on IPCC, 2007: *Impacts, Adaptation and Vulnerability. Contribution of Working Group II*

Source:: *A. Palmer, 200[illegible]*

Society relies heavily on energy that is generated by burning fossil fuels—coal, oil, and natural gas.

7 CLIMATE CHANGE WILL HAVE CONSEQUENCES FOR THE EARTH SYSTEM AND HUMAN LIVES.

A. Melting of ice sheets and glaciers, combined with the thermal expansion of seawater as the oceans warm, is causing sea level to rise. Seawater is beginning to move onto low-lying land and to contaminate coastal fresh water sources and beginning to submerge coastal facilities and barrier islands. Sea-level rise increases the risk of damage to homes and buildings from storm surges such as those that accompany hurricanes.

B. Climate plays an important role in the global distribution of freshwater resources. Changing precipitation patterns and temperature conditions will alter the distribution and availability of freshwater resources, reducing reliable access to water for many people and their crops. Winter snowpack and mountain glaciers that provide water for human use are declining as a result of global warming.

C. Incidents of extreme weather are projected to increase as a result of climate change. Many locations will see a substantial increase in the number of heat waves they experience per year and a likely decrease in episodes of severe cold. Precipitation events are expected to become less frequent but more intense in many areas, and droughts will be more frequent and severe in areas where average precipitation is projected to decrease.[2]

D. The chemistry of ocean water is changed by absorption of carbon dioxide from the atmosphere. Increasing carbon dioxide levels in the atmosphere is causing ocean water to become more acidic, threatening the survival of shell-building marine species and the entire food web of which they are a part.

E. Ecosystems on land and in the ocean have been and will continue to be disturbed by climate change. Animals, plants, bacteria, and viruses will migrate to new areas with favorable climate conditions. Infectious diseases and certain species will be able to invade areas that they did not previously inhabit.

F. Human health and mortality rates will be affected to different degrees in specific regions of the world as a result of climate change. Although cold-related deaths are predicted to decrease, other risks are predicted to rise. The incidence and geographical range of climate-sensitive infectious diseases—such as malaria, dengue fever, and tick-borne diseases—will increase. Drought-reduced crop yields, degraded air and water quality, and increased hazards in coastal and low-lying areas will contribute to unhealthy conditions, particularly for the most vulnerable populations.[3]

Source: *Iowa National Guard photo by Sgt. Chad D. Nelso*

Iowa National Guard preparing to put sandbags in place on a levee in Kingston, Iowa, to protect roughly 50,000 acres of farmland threatened by flood waters.

KEY DEFINITIONS

Weather The specific conditions of the atmosphere at a particular place and time, measured in terms of variables that include temperature, precipitation, cloudiness, humidity, air pressure, and wind.

Weather Forecast A prediction about the specific atmospheric conditions expected for a location in the short-term future (hours to days).

Climate The long-term average of conditions in the atmosphere, ocean, and ice sheets and sea ice described by statistics, such as means and extremes.

Climate Forecast A prediction about average or extreme climate conditions for a region in the long-term future (seasons to decades).

Climate Variability Natural changes in climate that fall within the normal range of extremes for a particular region, as measured by temperature, precipitation, and frequency of events. Drivers of climate variability include the El Niño Southern Oscillation and other phenomena.

Climate Change A significant and persistent change in the mean state of the climate or its variability. Climate change occurs in response to changes in some aspect of Earth's environment: these include regular changes in Earth's orbit about the sun, re-arrangement of continents through plate tectonic motions, or anthropogenic modification of the atmosphere.

Global Warming The observed increase in average temperature near the Earth's surface and in the lowest layer of the atmosphere. In common usage, "global warming" often refers to the warming that has occurred as a result of increased emissions of greenhouse gases from human activities. Global warming is a type of climate change; it can also lead to other changes in climate conditions, such as changes in precipitation patterns.

Climate System The matter, energy, and processes involved in interactions among Earth's atmosphere, hydrosphere, cryosphere, lithosphere, biosphere, and Earth-Sun interactions.

Likely, Very Likely, Extremely Likely, Virtually Certain These terms are used by the Intergovernmental Panel on Climate Change (IPCC) to indicate how probable it is that a predicted outcome will occur in the climate system, according to expert judgment. A result that is deemed "likely" to occur has a greater than 66% probability of occurring. A "very likely" result has a greater than 90% probability. "Extremely likely" means greater than 95% probability, and "virtually certain" means greater than 99% probability.

Mitigation Human interventions to reduce the sources of greenhouse gases or enhance the sinks that remove them from the atmosphere.

Vulnerability The degree to which physical, biological, and socio-economic systems are susceptible to and unable to cope with adverse impacts of climate change. [2]

Adaptation Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects.[3]

Fossil fuels Energy sources such as petroleum, coal, or natural gas, which are derived from living matter that existed during a previous geologic time period.

Feedback The process through which a system is controlled, changed, or modulated in response to its own output. Positive feedback results in amplification of the system output; negative feedback reduces the output of a system.

Carbon Cycle Circulation of carbon atoms through the Earth systems as a result of photosynthetic conversion of carbon dioxide into complex organic compounds by plants, which are consumed by other organisms, and return of the carbon to the atmosphere as carbon dioxide as a result of respiration, decay of organisms, and combustion of fossil fuels.

1. *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences*. Thomas R. Karl, Susan J. Hassol, Christopher D. Miller, and William L. Murray, editors, 2006. A Report by the Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC.

2. Based on IPCC, 2007: *Impacts, Adaptation and Vulnerability. Contribution of Working Group II*

3. Based on IPCC, 2007: *Mitigation of Climate Change. Contribution of Working Group III*

ABOUT THIS GUIDE

Climate Literacy: The Essential Principles of Climate Science presents information that is deemed important for individuals and communities to know and understand about Earth's climate, impacts of climate change, and approaches to adaptation or mitigation. Principles in the guide can serve as discussion starters or launching points for scientific inquiry. The guide aims to promote greater *climate science literacy* by providing this educational framework of principles and concepts. The guide can also serve educators who teach climate science as a way to meet content standards in their science curricula.

Development of the guide began at a workshop sponsored by the National Oceanic and Atmospheric Administration (NOAA) and the American Association for the Advancement of Science (AAAS). Multiple science agencies, non-governmental organizations, and numerous individuals also contributed through extensive review and comment periods. Discussion at the National Science Foundation- and NOAA-sponsored Atmospheric Sciences and Climate Literacy workshop contributed substantially to the refinement of the document.

To download this guide and related documents, visit www.globalchange.gov.

FURTHER INFORMATION

For future revisions and changes to this document or to see documentation of the process used to develop this brochure, please visit www.climate.noaa.gov/education.

In addition, further information relating to climate literacy and climate resources can be found at:

- earthobservatory.nasa.gov
- www.epa.gov/climatechange
- http://nsdl.org
- www.education.noaa.gov

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Current Science and Educational Partners:

- American Association for the Advancement of Science Project 2061
- American Meteorological Society
- Association of Science-Technology Centers
- Bowman Global Change
- Centers for Disease Control & Prevention
- Challenger Center for Space Science Education
- Climate Literacy Network
- College of Exploration
- Cooperative Institute for Research in Environmental Sciences
- Federation of Earth Science Information Partners
- Lawrence Hall of Science, University of California, Berkeley
- National Environmental Education Foundation
- National Geographic Education Programs
- National Institute of Standards & Technology
- National Oceanic and Atmospheric Administration
- National Science Teachers Association
- North American Association For Environmental Education
- Sally Ride Science™
- TERC Inc.
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- The National Center for Atmospheric Research
- University Corporation for Atmospheric Research
- U.S. Geological Survey
- U.S. Forest Service

For an up to date list of partners please refer to U.S Climate Change Science Program at http://www.globalchange.gov.

Second Version: *March 2009*

Recycled Content Paper

May 2008

The Cost of Climate Change

What We'll Pay if Global Warming Continues Unchecked

Read the full report online at http://www.nrdc.org/globalwarming/cost/contents.asp.

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Global warming comes with a big price tag for every country in the world. The 80 percent reduction in U.S. emissions that will be needed to lead international action to stop climate change may not come cheaply, but the cost of failing to act will be much greater. New research shows that if present trends continue, the total cost of global warming will be as high as 3.6 percent of gross domestic product (GDP). Four global warming impacts alone—hurricane damage, real estate losses, energy costs, and water costs—will come with a price tag of 1.8 percent of U.S. GDP, or almost $1.9 trillion annually (in today's dollars) by 2100.

We know how to avert most of these damages through strong national and international action to reduce the emissions that cause global warming. But we must act now. The longer we wait, the more painful—and expensive—the consequences will be.

NRDC
THE EARTH'S BEST DEFENSE

The Cost of Climate Change

This report focuses on a "business-as-usual" future in which the world continues to emit heat-trapping gases at an increasing rate. We base our economic projections on the most pessimistic of the business-as-usual climate forecasts considered "likely" by the scientific community.[1] In this projected climate future, which is still far from the worst-case scenario, global warming causes drastic changes to the planet's climate, with average temperature increases of 13 degrees Fahrenheit in most of the United States and 18 degrees Fahrenheit in Alaska over the next 100 years. The effects of climate change will be felt in the form of more severe heat waves, hurricanes, droughts, and other erratic weather events—and in their impact on our economy's bottom line.

We estimate U.S. economic impacts from global warming in two ways: a detailed focus on four specific impacts, and a comprehensive look at the costs to the country as a whole. Our detailed accounting of costs begins with historical data for four especially important climate impacts: hurricane damages, real estate losses, energy costs, and water costs. We then build upward to estimate the impact of future climatic conditions in these four impact areas. The second part of our analysis is a comprehensive view of climate change impacts: We take a general rule about how the climate affects the country as a whole and then apply that rule to business-as-usual climate forecasts. Although the detailed impact studies can provide only a partial accounting of the full economic costs estimated by our comprehensive model, the impact studies allow us to examine the costs of climate change with greater specificity for the particular case of the United States.

Global warming could cost the United States more than $1.9 trillion each year in hurricane damages, real estate losses, energy costs, and water costs by 2100.

Change in Temperature in U.S. Cities as a Result of Global Warming (in degrees Fahrenheit)

In 2100, this U.S. city	will feel like …does today	Temperature Change between 2008 and 2100 averages, in degrees
Anchorage, AK	New York, NY	+18
Minneapolis, MN	San Francisco, CA	+13
Milwaukee, WI	Charlotte, NC	+13
Albany, NY	Charlotte, NC	+13
Boston, MA	Memphis, TN	+12
Detroit, MI	Memphis, TN	+13
Denver, CO	Memphis, TN	+13
Chicago, IL	Los Angeles, CA	+14
Omaha, NE	Los Angeles, CA	+13
Columbus, OH	Las Vegas, NV	+13
Seattle, WA	Las Vegas, NV	+13
Indianapolis, IN	Las Vegas, NV	+13
New York, NY	Las Vegas, NV	+12
Portland, OR	Las Vegas, NV	+12
Philadelphia, PA	Las Vegas, NV	+12
Kansas City, MO	Houston, TX	+13
Washington, DC	Houston, TX	+12
Albuquerque, NM	Houston, TX	+12
San Francisco, CA	New Orleans, LA	+12
Baltimore, MD	New Orleans, LA	+12
Charlotte, NC	Honolulu, HI	+13
Oklahoma City, OK	Honolulu, HI	+13
Atlanta, GA	Honolulu, HI	+13
Memphis, TN	Miami, FL	+13
Los Angeles, CA	Miami, FL	+12
El Paso, TX	Miami, FL	+13
Las Vegas, NV	San Juan, PR	+12
Houston, TX	San Juan, PR	+11
Jacksonville, FL	San Juan, PR	+10
New Orleans, LA	San Juan, PR	+11
Honolulu, HI	Acapulco, Mexico	+7
Phoenix, AZ	Bangkok, Thailand	+12
Miami, FL	No comparable city	+10
San Juan, PR	No comparable city	+7

Source: IPCC, 2007; http://www.worldclimate.com; authors' calculations.

Putting a Price Tag on Global Warming

Droughts, floods, wildfires, and hurricanes have already caused multibillion-dollar losses, and these extreme weather events will likely become more frequent and more devastating as the climate continues to change. Tourism, agriculture, and other weather-dependent industries will be hit especially hard, but no one will be exempt. Household budgets as well as business balance sheets will feel the impact of higher energy and water costs. This report estimates what the United States will pay as a result of four of the most serious impacts of global warming in a business-as-usual scenario—that is, if we do not take steps to push back against climate change:[2]

Hurricane damages: $422 billion in economic losses caused by the increasing intensity of Atlantic and Gulf Coast storms.

In the business-as-usual climate future, higher sea-surface temperatures result in stronger and more damaging hurricanes along the Atlantic and Gulf coasts. Even with storms of the same intensity, future hurricanes will cause more damage as higher sea levels exacerbate storm surges, flooding, and erosion. In recent years, hurricane damages have averaged $12 billion and more than 120 deaths per year. With business-as-usual emissions, average annual hurricane damages in 2100 will have grown by $422 billion and an astounding 760 deaths just from climate change impacts.

Real estate losses: $360 billion in damaged or destroyed residential real estate as a result of rising sea levels.

Our business-as-usual scenario forecasts 23 inches of sea-level rise by 2050 and 45 inches by 2100. If nothing is done to hold back the waves, rising sea levels will inundate low-lying coastal properties. Even those properties that remain above water will be more likely to sustain storm damage, as encroachment of the sea allows storm surges to reach inland areas that were not previously affected. By 2100, U.S. residential real estate losses because of climate change will be $360 billion per year.

Energy costs: $141 billion in increasing energy costs as a result of the rising demand for energy.

As temperatures rise, higher demand for air conditioning and refrigeration across the country will increase energy costs, and many households and businesses, especially in the North, that currently don't have air conditioners will purchase them. Only a fraction of these increased costs will be offset by reduced demand for heat in Northern states. The highest net energy costs—after taking into consideration savings from lower heating bills—will fall on Southeast and Southwest states. Total costs will add up to more than $200 billion for extra electricity and new air conditioners, compared with almost $60 billion in reduced heating costs. The net result is that energy sector costs will be $141 billion higher in 2100 due to global warming.

Water costs: $950 billion to provide water to the driest and most water-stressed parts of the United States as climate change exacerbates drought conditions and disrupts existing patterns of water supply.

The business-as-usual case forecasts less rainfall in much of the United States—or, in some states, less rain at the times of year when it is needed most. By 2100, providing the water we need throughout the country will cost an estimated $950 billion more per year as a result of climate change. Drought conditions, already a problem in Western states and in the Southeast, will become more frequent and more severe.

Our analysis finds that, if present trends continue, these four global warming impacts alone will come with a price tag of almost $1.9 trillion annually (in today's dollars), or 1.8 percent of U.S. GDP per year by 2100. And this bottom line represents only the cost of the four categories we examined in detail; the total cost of continuing on a business-as-usual path will be even greater—as high as 3.6 percent of GDP when economic and noneconomic costs such as health impacts and wildlife damages are factored in.

The Global Warming Price Tag in Four Impact Areas, 2025 through 2100

	Cost in billions of 2006 dollars				Cost as a percentage of GDP				U.S. Regions Most at Risk
	2025	2050	2075	2100	2025	2050	2075	2100	
Hurricane Damages	$10	$43	$142	$422	0.05%	0.12%	0.24%	0.41%	Atlantic and Gulf Coast states
Real Estate Losses	$34	$80	$173	$360	0.17%	0.23%	0.29%	0.35%	Atlantic and Gulf Coast states
Energy-Sector Costs	$28	$47	$82	$141	0.14%	0.14%	0.14%	0.14%	Southeast and Southwest
Water Costs	$200	$336	$565	$950	1.00%	0.98%	0.95%	0.93%	Western states
SUBTOTAL OF THESE FOUR IMPACTS*	**$271**	**$506**	**$961**	**$1,873**	**1.36%**	**1.47%**	**1.62%**	**1.84%**	

*Note: Totals may not add up exactly due to rounding.

The Cost of Climate Change

New Model Provides More Accurate Picture of the Cost of Climate Change

Many economic models have attempted to capture the costs of climate change for the United States. For the most part, however, these analyses grossly underestimate costs by making predictions that are out of step with the scientific consensus on the daunting scope of climatic changes and the urgent need to reduce global warming emissions. *The Economics of Climate Change*—a report commissioned by the British government and released in 2006, also known as the Stern Review after its lead author, Nicholas Stern—employed a different model that represented a major step forward in economic analysis of climate impacts. We used a revised version of the Stern Review's model to provide a more accurate, comprehensive picture of the cost of global warming to the U.S. economy. This new model estimates that the true cost of all aspects of global warming—including economic losses, noneconomic damages, and increased risks of catastrophe—will reach 3.6 percent of U.S. GDP by 2100 if business-as-usual emissions are allowed to continue.

Global Warming and the International Economy

Damage on the order of a few percentage points of GDP each year would be a serious impact for any country, even a relatively rich one like the United States. And we will not experience the worst of the global problem: The sad irony is that while richer countries like the United States are responsible for much greater per person greenhouse gas emissions, many of the poorest countries around the world will experience damages that are much larger as a percentage of their national output.

For countries that have fewer resources with which to fend off the consequences of climate change, the impacts will be devastating. The question is not just how we value damages to future generations living in the United States, but also how we value costs to people around the world—today and in the future—whose economic circumstances make them much more vulnerable than we are. Decisions about when and how to respond to climate change must depend not only on our concern for our own comfort and economic well-being, but on the well-being of those who share the same small world with us. Our disproportionate contribution to the problem of climate change should be accompanied by elevated responsibility to participate, and even to lead the way, in its solution.

Conclusion: We Must Act Now to Avoid the Worst Economic Impacts of Global Warming

It is difficult to put a price tag on many of the costs of climate change: loss of human lives and health, species extinction, loss of unique ecosystems, increased social conflict, and other impacts extend far beyond any monetary measure. But by measuring the economic damage of global warming in the United States, we can begin to understand the magnitude of the challenges we will face if we continue to do nothing to push back against climate change. Curbing global warming pollution will require a substantial investment, but the cost of doing nothing will be far greater. Immediate action can save lives, avoid trillions of dollars of economic damage, and put us on a path to solving one of the greatest challenges of the 21st century.

NRDC's Policy Recommendations for Reducing U.S. Emissions

Continuing on the business-as-usual path will make global warming not just an environmental crisis, but an economic one as well. That's why we must act immediately to reduce global warming emissions 80 percent by 2050 and take ourselves off the business-as-usual path. NRDC recommends the following federal actions to curb emissions and avoid the worst economic impacts expected from global warming:

1. Enact comprehensive, mandatory limits on global warming pollution to stimulate investment in all sectors and guarantee that we meet emission targets. A mandatory cap will guarantee that we meet emissions targets in covered sectors and will drive investment toward the least costly reduction strategies. If properly designed to support efficiency and innovation, such a program can actually reduce energy bills for many consumers and businesses. A successful program will include 1) a long-term declining cap, 2) Comprehensive coverage of emitting sources, 3) pollution allowances used in the public interest, 4) allowance trading, and 5) limited use of offsets.

2. Overcome barriers to investment in energy efficiency to lower abatement cost starting now. Multiple market failures cause individuals and businesses to underinvest in cost-effective energy efficiency and emerging low-carbon technologies. Price signals alone will not adequately drive these investments, which are already profitable at current energy prices. Therefore, while a mandatory cap on emissions is essential (and the associated allowance value can substantially fund efficiency), many of the opportunities require additional federal, state, and/or local policy to overcome barriers to investments. Specifically, there are substantial gains to be realized in building, industry, and appliance efficiency and in smart transportation such as advanced vehicles and smart growth.

3. Accelerate the development and deployment of emerging clean energy technologies to lower long-term abatement costs. To accelerate the "learning by doing" needed to develop an affordable low-carbon energy supply, we must support rapid development and deployment of renewable electricity, low-carbon fuels, and carbon capture and disposal that sequesters carbon dioxide in geological formations deep beneath the earth's surface.

[1] Intergovernmental Panel on Climate Change, *Climate Change 2007: The Physical Science Basis,* Contribution of Working Group I to the Fourth Assessment Report of the ntergovernmental Panel on Climate Change (Cambridge, UK., Cambridge University Press, 2007).

[2] A thorough review of existing climate change impact studies for the United States has recently been produced by the University of Maryland's Center for Integrative Environmental Research (CIER, *The U.S. Economic Impacts of Climate Change and the Costs of Inaction* (University of Maryland, 2007). This report complements the CIER research, attempting to develop a single "bottom line" economic impact for several of the largest categories of damages – and to critique the misleading economic models that offer a more complacent picture of climate costs for the United States.

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A report of Working Group I of the Intergovernmental Panel on Climate Change

Summary for Policymakers

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Introduction

The Working Group I contribution to the IPCC Fourth Assessment Report describes progress in understanding of the human and natural drivers of climate change,[1] observed climate change, climate processes and attribution, and estimates of projected future climate change. It builds upon past IPCC assessments and incorporates new findings from the past six years of research. Scientific progress since the Third Assessment Report (TAR) is based upon large amounts of new and more comprehensive data, more sophisticated analyses of data, improvements in understanding of processes and their simulation in models and more extensive exploration of uncertainty ranges.

The basis for substantive paragraphs in this Summary for Policymakers can be found in the chapter sections specified in curly brackets.

Human and Natural Drivers of Climate Change

Changes in the atmospheric abundance of greenhouse gases and aerosols, in solar radiation and in land surface properties alter the energy balance of the climate system. These changes are expressed in terms of radiative forcing,[2] which is used to compare how a range of human and natural factors drive warming or cooling influences on global climate. Since the TAR, new observations and related modelling of greenhouse gases, solar activity, land surface properties and some aspects of aerosols have led to improvements in the quantitative estimates of radiative forcing.

Global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years (see Figure SPM.1). The global increases in carbon dioxide concentration are due primarily to fossil fuel use and land use change, while those of methane and nitrous oxide are primarily due to agriculture. {2.3, 6.4, 7.3}

- Carbon dioxide is the most important anthropogenic greenhouse gas (see Figure SPM.2). The global atmospheric concentration of carbon dioxide has increased from a pre-industrial value of about 280 ppm to 379 ppm[3] in 2005. The atmospheric concentration of carbon dioxide in 2005 exceeds by far the natural range over the last 650,000 years (180 to 300 ppm) as determined from ice cores. The annual carbon dioxide concentration growth rate was larger during the last 10 years (1995–2005 average: 1.9 ppm per year), than it has been since the beginning of continuous direct atmospheric measurements (1960–2005 average: 1.4 ppm per year) although there is year-to-year variability in growth rates. {2.3, 7.3}

- The primary source of the increased atmospheric concentration of carbon dioxide since the pre-industrial period results from fossil fuel use, with land-use change providing another significant but smaller contribution. Annual fossil carbon dioxide emissions[4] increased from an average of 6.4 [6.0 to 6.8][5] GtC (23.5 [22.0 to 25.0] $GtCO_2$) per year in the 1990s to 7.2 [6.9 to 7.5] GtC (26.4 [25.3 to 27.5] $GtCO_2$) per year in 2000–2005 (2004 and 2005 data are interim estimates). Carbon dioxide emissions associated with land-use change

[1] *Climate change* in IPCC usage refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the United Nations Framework Convention on Climate Change, where climate change refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods.

[2] *Radiative forcing* is a measure of the influence that a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism. Positive forcing tends to warm the surface while negative forcing tends to cool it. In this report, radiative forcing values are for 2005 relative to pre-industrial conditions defined at 1750 and are expressed in watts per square metre ($W m^{-2}$). See Glossary and Section 2.2 for further details.

[3] ppm (parts per million) or ppb (parts per billion, 1 billion = 1,000 million) is the ratio of the number of greenhouse gas molecules to the total number of molecules of dry air. For example, 300 ppm means 300 molecules of a greenhouse gas per million molecules of dry air.

[4] Fossil carbon dioxide emissions include those from the production, distribution and consumption of fossil fuels and as a by-product from cement production. An emission of 1 GtC corresponds to 3.67 $GtCO_2$.

[5] In general, uncertainty ranges for results given in this Summary for Policymakers are 90% uncertainty intervals unless stated otherwise, that is, there is an estimated 5% likelihood that the value could be above the range given in square brackets and 5% likelihood that the value could be below that range. Best estimates are given where available. Assessed uncertainty intervals are not always symmetric about the corresponding best estimate. Note that a number of uncertainty ranges in the Working Group I TAR corresponded to 2 standard deviations (95%), often using expert judgement.

Changes in Greenhouse Gases from Ice Core and Modern Data

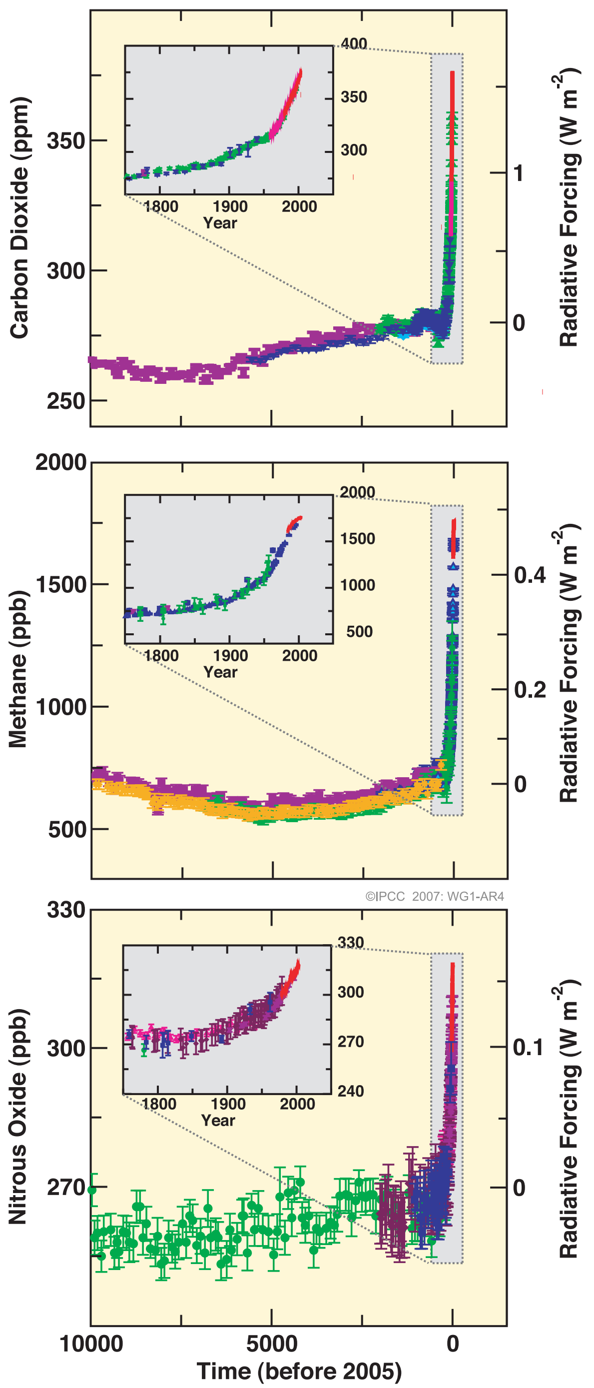

Figure SPM.1. *Atmospheric concentrations of carbon dioxide, methane and nitrous oxide over the last 10,000 years (large panels) and since 1750 (inset panels). Measurements are shown from ice cores (symbols with different colours for different studies) and atmospheric samples (red lines). The corresponding radiative forcings are shown on the right hand axes of the large panels. {Figure 6.4}*

are estimated to be 1.6 [0.5 to 2.7] GtC (5.9 [1.8 to 9.9] $GtCO_2$) per year over the 1990s, although these estimates have a large uncertainty. {7.3}

- The global atmospheric concentration of methane has increased from a pre-industrial value of about 715 ppb to 1732 ppb in the early 1990s, and was 1774 ppb in 2005. The atmospheric concentration of methane in 2005 exceeds by far the natural range of the last 650,000 years (320 to 790 ppb) as determined from ice cores. Growth rates have declined since the early 1990s, consistent with total emissions (sum of anthropogenic and natural sources) being nearly constant during this period. It is *very likely*[6] that the observed increase in methane concentration is due to anthropogenic activities, predominantly agriculture and fossil fuel use, but relative contributions from different source types are not well determined. {2.3, 7.4}

- The global atmospheric nitrous oxide concentration increased from a pre-industrial value of about 270 ppb to 319 ppb in 2005. The growth rate has been approximately constant since 1980. More than a third of all nitrous oxide emissions are anthropogenic and are primarily due to agriculture. {2.3, 7.4}

The understanding of anthropogenic warming and cooling influences on climate has improved since the TAR, leading to *very high confidence*[7] that the global average net effect of human activities since 1750 has been one of warming, with a radiative forcing of +1.6 [+0.6 to +2.4] $W\,m^{-2}$ (see Figure SPM.2). {2.3., 6.5, 2.9}

- The combined radiative forcing due to increases in carbon dioxide, methane, and nitrous oxide is +2.30 [+2.07 to +2.53] $W\,m^{-2}$, and its rate of increase during the industrial era is *very likely* to have been unprecedented in more than 10,000 years (see Figures

[6] In this Summary for Policymakers, the following terms have been used to indicate the assessed likelihood, using expert judgement, of an outcome or a result: *Virtually certain* > 99% probability of occurrence, *Extremely likely* > 95%, *Very likely* > 90%, *Likely* > 66%, *More likely than not* > 50%, *Unlikely* < 33%, *Very unlikely* < 10%, *Extremely unlikely* < 5% (see Box TS.1 for more details).

[7] In this Summary for Policymakers the following levels of confidence have been used to express expert judgements on the correctness of the underlying science: *very high confidence* represents at least a 9 out of 10 chance of being correct; *high confidence* represents about an 8 out of 10 chance of being correct (see Box TS.1)

SPM.1 and SPM.2). The carbon dioxide radiative forcing increased by 20% from 1995 to 2005, the largest change for any decade in at least the last 200 years. {2.3, 6.4}

- Anthropogenic contributions to aerosols (primarily sulphate, organic carbon, black carbon, nitrate and dust) together produce a cooling effect, with a total direct radiative forcing of –0.5 [–0.9 to –0.1] W m^{-2} and an indirect cloud albedo forcing of –0.7 [–1.8 to –0.3] W m^{-2}. These forcings are now better understood than at the time of the TAR due to improved *in situ*, satellite and ground-based measurements and more comprehensive modelling, but remain the dominant uncertainty in radiative forcing. Aerosols also influence cloud lifetime and precipitation. {2.4, 2.9, 7.5}

- Significant anthropogenic contributions to radiative forcing come from several other sources. Tropospheric ozone changes due to emissions of ozone-forming chemicals (nitrogen oxides, carbon monoxide, and hydrocarbons) contribute +0.35 [+0.25 to +0.65] W m^{-2}. The direct radiative forcing due to changes in halocarbons[8] is +0.34 [+0.31 to +0.37] W m^{-2}. Changes in surface albedo, due to land cover changes and deposition of black carbon aerosols on snow, exert

Radiative Forcing Components

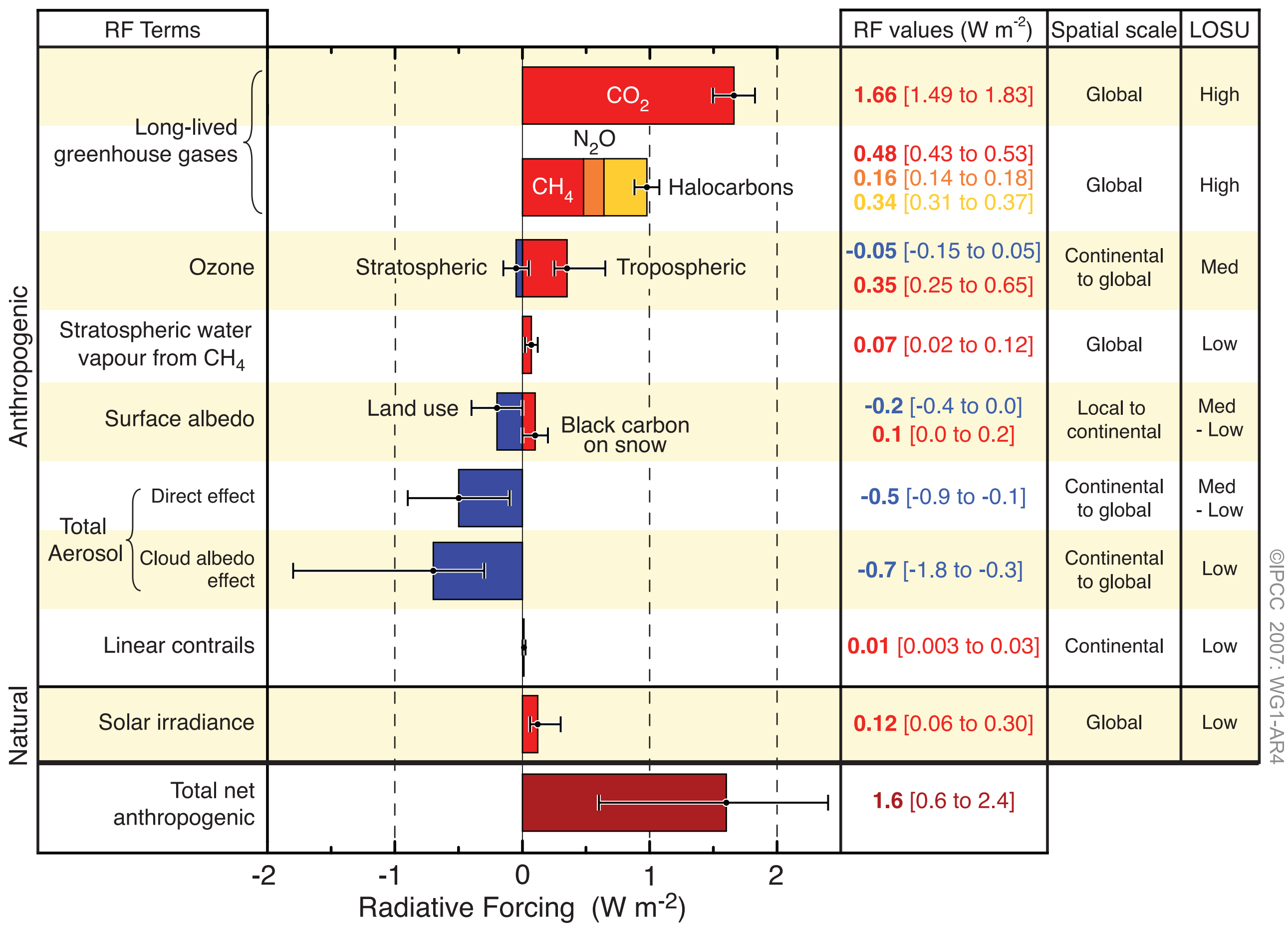

Figure SPM.2. *Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. These require summing asymmetric uncertainty estimates from the component terms, and cannot be obtained by simple addition. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. The range for linear contrails does not include other possible effects of aviation on cloudiness. {2.9, Figure 2.20}*

[8] Halocarbon radiative forcing has been recently assessed in detail in *IPCC's Special Report on Safeguarding the Ozone Layer and the Global Climate System* (2005).

respective forcings of –0.2 [–0.4 to 0.0] and +0.1 [0.0 to +0.2] W m^{-2}. Additional terms smaller than ±0.1 W m^{-2} are shown in Figure SPM.2. {2.3, 2.5, 7.2}

- Changes in solar irradiance since 1750 are estimated to cause a radiative forcing of +0.12 [+0.06 to +0.30] W m^{-2}, which is less than half the estimate given in the TAR. {2.7}

Direct Observations of Recent Climate Change

Since the TAR, progress in understanding how climate is changing in space and in time has been gained through improvements and extensions of numerous datasets and data analyses, broader geographical coverage, better understanding of uncertainties, and a wider variety of measurements. Increasingly comprehensive observations are available for glaciers and snow cover since the 1960s, and for sea level and ice sheets since about the past decade. However, data coverage remains limited in some regions.

Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level (see Figure SPM.3). {3.2, 4.2, 5.5}

- Eleven of the last twelve years (1995–2006) rank among the 12 warmest years in the instrumental record of global surface temperature[9] (since 1850). The updated 100-year linear trend (1906 to 2005) of 0.74°C [0.56°C to 0.92°C] is therefore larger than the corresponding trend for 1901 to 2000 given in the TAR of 0.6°C [0.4°C to 0.8°C]. The linear warming trend over the last 50 years (0.13°C [0.10°C to 0.16°C] per decade) is nearly twice that for the last 100 years. The total temperature increase from 1850–1899 to 2001–2005 is 0.76°C [0.57°C to 0.95°C]. Urban heat island effects are real but local, and have a negligible influence (less than 0.006°C per decade over land and zero over the oceans) on these values. {3.2}

- New analyses of balloon-borne and satellite measurements of lower- and mid-tropospheric temperature show warming rates that are similar to those of the surface temperature record and are consistent within their respective uncertainties, largely reconciling a discrepancy noted in the TAR. {3.2, 3.4}

- The average atmospheric water vapour content has increased since at least the 1980s over land and ocean as well as in the upper troposphere. The increase is broadly consistent with the extra water vapour that warmer air can hold. {3.4}

- Observations since 1961 show that the average temperature of the global ocean has increased to depths of at least 3000 m and that the ocean has been absorbing more than 80% of the heat added to the climate system. Such warming causes seawater to expand, contributing to sea level rise (see Table SPM.1). {5.2, 5.5}

- Mountain glaciers and snow cover have declined on average in both hemispheres. Widespread decreases in glaciers and ice caps have contributed to sea level rise (ice caps do not include contributions from the Greenland and Antarctic Ice Sheets). (See Table SPM.1.) {4.6, 4.7, 4.8, 5.5}

- New data since the TAR now show that losses from the ice sheets of Greenland and Antarctica have *very likely* contributed to sea level rise over 1993 to 2003 (see Table SPM.1). Flow speed has increased for some Greenland and Antarctic outlet glaciers, which drain ice from the interior of the ice sheets. The corresponding increased ice sheet mass loss has often followed thinning, reduction or loss of ice shelves or loss of floating glacier tongues. Such dynamical ice loss is sufficient to explain most of the Antarctic net mass loss and approximately half of the Greenland net mass loss. The remainder of the ice loss from Greenland has occurred because losses due to melting have exceeded accumulation due to snowfall. {4.6, 4.8, 5.5}

- Global average sea level rose at an average rate of 1.8 [1.3 to 2.3] mm per year over 1961 to 2003. The rate was faster over 1993 to 2003: about 3.1 [2.4 to 3.8] mm per year. Whether the faster rate for 1993 to 2003 reflects decadal variability or an increase in the longer-term trend is unclear. There is *high confidence* that

[9] The average of near-surface air temperature over land and sea surface temperature.

Changes in Temperature, Sea Level and Northern Hemisphere Snow Cover

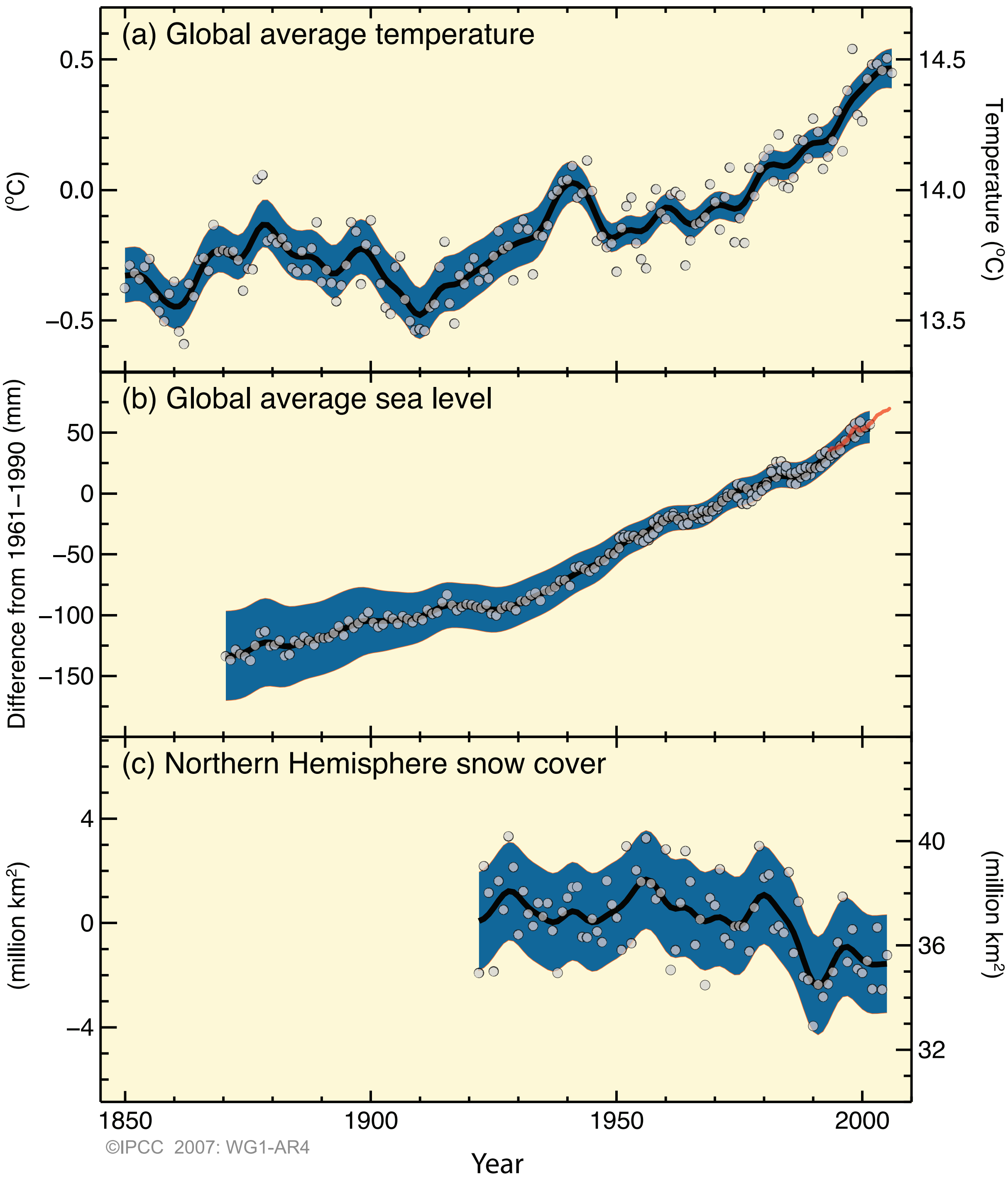

Figure SPM.3. *Observed changes in (a) global average surface temperature, (b) global average sea level from tide gauge (blue) and satellite (red) data and (c) Northern Hemisphere snow cover for March-April. All changes are relative to corresponding averages for the period 1961–1990. Smoothed curves represent decadal average values while circles show yearly values. The shaded areas are the uncertainty intervals estimated from a comprehensive analysis of known uncertainties (a and b) and from the time series (c). {FAQ 3.1, Figure 1, Figure 4.2, Figure 5.13}* the rate of observed sea level rise increased from the 19th to the 20th century. The total 20th-century rise is estimated to be 0.17 [0.12 to 0.22] m. {5.5}

- For 1993 to 2003, the sum of the climate contributions is consistent within uncertainties with the total sea level rise that is directly observed (see Table SPM.1). These estimates are based on improved satellite and *in situ* data now available. For the period 1961 to 2003, the sum of climate contributions is estimated to be smaller than the observed sea level rise. The TAR reported a similar discrepancy for 1910 to 1990. {5.5}

At continental, regional and ocean basin scales, numerous long-term changes in climate have been observed. These include changes in arctic temperatures and ice, widespread changes in precipitation amounts, ocean salinity, wind patterns and aspects of extreme weather including droughts, heavy precipitation, heat waves and the intensity of tropical cyclones.[10] {3.2, 3.3, 3.4, 3.5, 3.6, 5.2}

- Average arctic temperatures increased at almost twice the global average rate in the past 100 years. Arctic temperatures have high decadal variability, and a warm period was also observed from 1925 to 1945. {3.2}

- Satellite data since 1978 show that annual average arctic sea ice extent has shrunk by 2.7 [2.1 to 3.3]% per decade, with larger decreases in summer of 7.4 [5.0 to 9.8]% per decade. These values are consistent with those reported in the TAR. {4.4}

- Temperatures at the top of the permafrost layer have generally increased since the 1980s in the Arctic (by up to 3°C). The maximum area covered by seasonally frozen ground has decreased by about 7% in the Northern Hemisphere since 1900, with a decrease in spring of up to 15%. {4.7}

- Long-term trends from 1900 to 2005 have been observed in precipitation amount over many large regions.[11] Significantly increased precipitation has been observed in eastern parts of North and South America, northern Europe and northern and central Asia. Drying has been observed in the Sahel, the Mediterranean, southern Africa and parts of southern Asia. Precipitation is highly variable spatially and temporally, and data are limited in some regions. Long-term trends have not been observed for the other large regions assessed.[11] {3.3, 3.9}

- Changes in precipitation and evaporation over the oceans are suggested by freshening of mid- and high-latitude waters together with increased salinity in low-latitude waters. {5.2}

Table SPM.1. *Observed rate of sea level rise and estimated contributions from different sources. {5.5, Table 5.3}*

Source of sea level rise	Rate of sea level rise (mm per year) 1961–2003	1993–2003
Thermal expansion	0.42 ± 0.12	1.6 ± 0.5
Glaciers and ice caps	0.50 ± 0.18	0.77 ± 0.22
Greenland Ice Sheet	0.05 ± 0.12	0.21 ± 0.07
Antarctic Ice Sheet	0.14 ± 0.41	0.21 ± 0.35
Sum of individual climate contributions to sea level rise	1.1 ± 0.5	2.8 ± 0.7
Observed total sea level rise	1.8 ± 0.5[a]	3.1 ± 0.7[a]
Difference (Observed minus sum of estimated climate contributions)	0.7 ± 0.7	0.3 ± 1.0

Table note:
[a] Data prior to 1993 are from tide gauges and after 1993 are from satellite altimetry.

[10] Tropical cyclones include hurricanes and typhoons.

[11] The assessed regions are those considered in the regional projections chapter of the TAR and in Chapter 11 of this report.

- Mid-latitude westerly winds have strengthened in both hemispheres since the 1960s. {3.5}

- More intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics. Increased drying linked with higher temperatures and decreased precipitation has contributed to changes in drought. Changes in sea surface temperatures, wind patterns and decreased snowpack and snow cover have also been linked to droughts. {3.3}

- The frequency of heavy precipitation events has increased over most land areas, consistent with warming and observed increases of atmospheric water vapour. {3.8, 3.9}

- Widespread changes in extreme temperatures have been observed over the last 50 years. Cold days, cold nights and frost have become less frequent, while hot days, hot nights and heat waves have become more frequent (see Table SPM.2). {3.8}

Table SPM.2. *Recent trends, assessment of human influence on the trend and projections for extreme weather events for which there is an observed late-20th century trend. {Tables 3.7, 3.8, 9.4; Sections 3.8, 5.5, 9.7, 11.2–11.9}*

Phenomenon[a] and direction of trend	Likelihood that trend occurred in late 20th century (typically post 1960)	Likelihood of a human contribution to observed trend[b]	Likelihood of future trends based on projections for 21st century using SRES scenarios
Warmer and fewer cold days and nights over most land areas	*Very likely*[c]	*Likely*[d]	*Virtually certain*[d]
Warmer and more frequent hot days and nights over most land areas	*Very likely*[e]	*Likely (nights)*[d]	*Virtually certain*[d]
Warm spells/heat waves. Frequency increases over most land areas	*Likely*	*More likely than not*[f]	*Very likely*
Heavy precipitation events. Frequency (or proportion of total rainfall from heavy falls) increases over most areas	*Likely*	*More likely than not*[f]	*Very likely*
Area affected by droughts increases	*Likely* in many regions since 1970s	*More likely than not*	*Likely*
Intense tropical cyclone activity increases	*Likely* in some regions since 1970	*More likely than not*[f]	*Likely*
Increased incidence of extreme high sea level (excludes tsunamis)[g]	*Likely*	*More likely than not*[f,h]	*Likely*[i]

Table notes:

[a] See Table 3.7 for further details regarding definitions.
[b] See Table TS.4, Box TS.5 and Table 9.4.
[c] Decreased frequency of cold days and nights (coldest 10%).
[d] Warming of the most extreme days and nights each year.
[e] Increased frequency of hot days and nights (hottest 10%).
[f] Magnitude of anthropogenic contributions not assessed. Attribution for these phenomena based on expert judgement rather than formal attribution studies.
[g] Extreme high sea level depends on average sea level and on regional weather systems. It is defined here as the highest 1% of hourly values of observed sea level at a station for a given reference period.
[h] Changes in observed extreme high sea level closely follow the changes in average sea level. {5.5} It is *very likely* that anthropogenic activity contributed to a rise in average sea level. {9.5}
[i] In all scenarios, the projected global average sea level at 2100 is higher than in the reference period. {10.6} The effect of changes in regional weather systems on sea level extremes has not been assessed.

- There is observational evidence for an increase in intense tropical cyclone activity in the North Atlantic since about 1970, correlated with increases of tropical sea surface temperatures. There are also suggestions of increased intense tropical cyclone activity in some other regions where concerns over data quality are greater. Multi-decadal variability and the quality of the tropical cyclone records prior to routine satellite observations in about 1970 complicate the detection of long-term trends in tropical cyclone activity. There is no clear trend in the annual numbers of tropical cyclones. {3.8}

Some aspects of climate have not been observed to change. {3.2, 3.8, 4.4, 5.3}

- A decrease in diurnal temperature range (DTR) was reported in the TAR, but the data available then extended only from 1950 to 1993. Updated observations reveal that DTR has not changed from 1979 to 2004 as both day- and night-time temperature have risen at about the same rate. The trends are highly variable from one region to another. {3.2}

- Antarctic sea ice extent continues to show interannual variability and localised changes but no statistically significant average trends, consistent with the lack of warming reflected in atmospheric temperatures averaged across the region. {3.2, 4.4}

- There is insufficient evidence to determine whether trends exist in the meridional overturning circulation (MOC) of the global ocean or in small-scale phenomena such as tornadoes, hail, lightning and dust-storms. {3.8, 5.3}

A Palaeoclimatic Perspective

Palaeoclimatic studies use changes in climatically sensitive indicators to infer past changes in global climate on time scales ranging from decades to millions of years. Such proxy data (e.g., tree ring width) may be influenced by both local temperature and other factors such as precipitation, and are often representative of particular seasons rather than full years. Studies since the TAR draw increased confidence from additional data showing coherent behaviour across multiple indicators in different parts of the world. However, uncertainties generally increase with time into the past due to increasingly limited spatial coverage.

Palaeoclimatic information supports the interpretation that the warmth of the last half century is unusual in at least the previous 1,300 years. The last time the polar regions were significantly warmer than present for an extended period (about 125,000 years ago), reductions in polar ice volume led to 4 to 6 m of sea level rise. {6.4, 6.6}

- Average Northern Hemisphere temperatures during the second half of the 20th century were *very likely* higher than during any other 50-year period in the last 500 years and *likely* the highest in at least the past 1,300 years. Some recent studies indicate greater variability in Northern Hemisphere temperatures than suggested in the TAR, particularly finding that cooler periods existed in the 12th to 14th, 17th and 19th centuries. Warmer periods prior to the 20th century are within the uncertainty range given in the TAR. {6.6}

- Global average sea level in the last interglacial period (about 125,000 years ago) was *likely* 4 to 6 m higher than during the 20th century, mainly due to the retreat of polar ice. Ice core data indicate that average polar temperatures at that time were 3°C to 5°C higher than present, because of differences in the Earth's orbit. The Greenland Ice Sheet and other arctic ice fields *likely* contributed no more than 4 m of the observed sea level rise. There may also have been a contribution from Antarctica. {6.4}

Understanding and Attributing Climate Change

This assessment considers longer and improved records, an expanded range of observations and improvements in the simulation of many aspects of climate and its variability based on studies since the TAR. It also considers the results of new attribution studies that have evaluated whether observed changes are quantitatively consistent with the expected response to external forcings and inconsistent with alternative physically plausible explanations.

Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations.[12] This is an advance since the TAR's conclusion that "most of the observed warming over the last 50 years is *likely* to have been due to the increase in greenhouse gas concentrations". Discernible human influences now extend to other aspects of climate, including ocean warming, continental-average temperatures, temperature extremes and wind patterns (see Figure SPM.4 and Table SPM.2). {9.4, 9.5}

- It is *likely* that increases in greenhouse gas concentrations alone would have caused more warming than observed because volcanic and anthropogenic aerosols have offset some warming that would otherwise have taken place. {2.9, 7.5, 9.4}

- The observed widespread warming of the atmosphere and ocean, together with ice mass loss, support the conclusion that it is *extremely unlikely* that global climate change of the past 50 years can be explained without external forcing, and *very likely* that it is not due to known natural causes alone. {4.8, 5.2, 9.4, 9.5, 9.7}

- Warming of the climate system has been detected in changes of surface and atmospheric temperatures in the upper several hundred metres of the ocean, and in contributions to sea level rise. Attribution studies have established anthropogenic contributions to all of these changes. The observed pattern of tropospheric warming and stratospheric cooling is *very likely* due to the combined influences of greenhouse gas increases and stratospheric ozone depletion. {3.2, 3.4, 9.4, 9.5}

- It is *likely* that there has been significant anthropogenic warming over the past 50 years averaged over each continent except Antarctica (see Figure SPM.4). The observed patterns of warming, including greater warming over land than over the ocean, and their changes over time, are only simulated by models that include anthropogenic forcing. The ability of coupled climate models to simulate the observed temperature evolution on each of six continents provides stronger evidence of human influence on climate than was available in the TAR. {3.2, 9.4}

- Difficulties remain in reliably simulating and attributing observed temperature changes at smaller scales. On these scales, natural climate variability is relatively larger, making it harder to distinguish changes expected due to external forcings. Uncertainties in local forcings and feedbacks also make it difficult to estimate the contribution of greenhouse gas increases to observed small-scale temperature changes. {8.3, 9.4}

- Anthropogenic forcing is *likely* to have contributed to changes in wind patterns,[13] affecting extra-tropical storm tracks and temperature patterns in both hemispheres. However, the observed changes in the Northern Hemisphere circulation are larger than simulated in response to 20th-century forcing change. {3.5, 3.6, 9.5, 10.3}

- Temperatures of the most extreme hot nights, cold nights and cold days are *likely* to have increased due to anthropogenic forcing. It is *more likely than not* that anthropogenic forcing has increased the risk of heat waves (see Table SPM.2). {9.4}

[12] Consideration of remaining uncertainty is based on current methodologies.

[13] In particular, the Southern and Northern Annular Modes and related changes in the North Atlantic Oscillation. {3.6, 9.5, Box TS.2}

Global and Continental Temperature Change

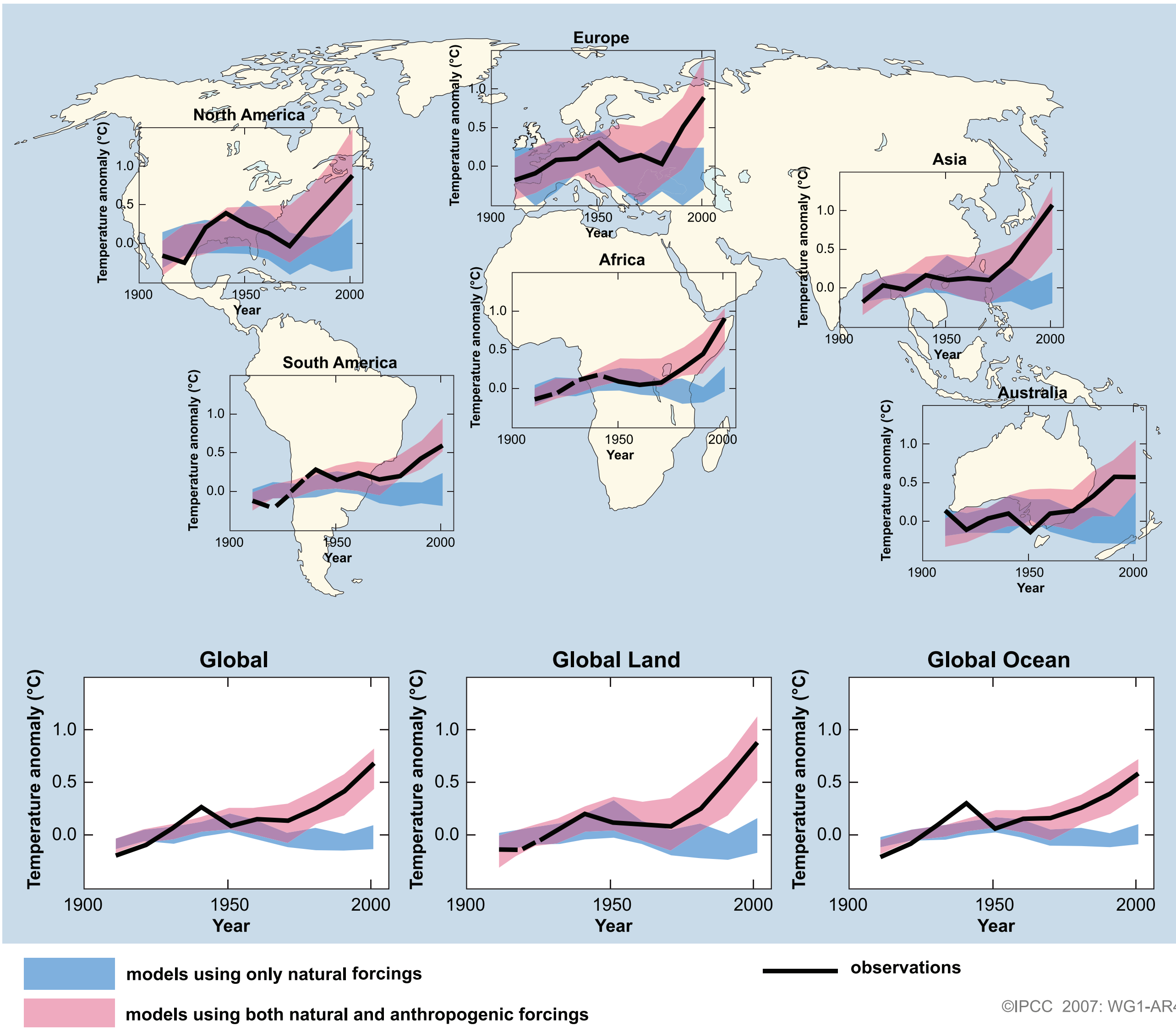

Figure SPM.4. *Comparison of observed continental- and global-scale changes in surface temperature with results simulated by climate models using natural and anthropogenic forcings. Decadal averages of observations are shown for the period 1906 to 2005 (black line) plotted against the centre of the decade and relative to the corresponding average for 1901–1950. Lines are dashed where spatial coverage is less than 50%. Blue shaded bands show the 5–95% range for 19 simulations from five climate models using only the natural forcings due to solar activity and volcanoes. Red shaded bands show the 5–95% range for 58 simulations from 14 climate models using both natural and anthropogenic forcings. {FAQ 9.2, Figure 1}*

Analysis of climate models together with constraints from observations enables an assessed *likely* range to be given for climate sensitivity for the first time and provides increased confidence in the understanding of the climate system response to radiative forcing. {6.6, 8.6, 9.6, Box 10.2}

- The equilibrium climate sensitivity is a measure of the climate system response to sustained radiative forcing. It is not a projection but is defined as the global average surface warming following a doubling of carbon dioxide concentrations. It is *likely* to be in the range 2°C to 4.5°C with a best estimate of about 3°C, and is *very unlikely* to be less than 1.5°C. Values substantially higher than 4.5°C cannot be excluded, but agreement of models with observations is not as good for those values. Water vapour changes represent the largest feedback affecting climate sensitivity and are now better understood than in the TAR. Cloud feedbacks remain the largest source of uncertainty. {8.6, 9.6, Box 10.2}

- It is *very unlikely* that climate changes of at least the seven centuries prior to 1950 were due to variability generated within the climate system alone. A significant fraction of the reconstructed Northern Hemisphere inter-decadal temperature variability over those centuries is *very likely* attributable to volcanic eruptions and changes in solar irradiance, and it is *likely* that anthropogenic forcing contributed to the early 20th-century warming evident in these records. {2.7, 2.8, 6.6, 9.3}

Projections of Future Changes in Climate

A major advance of this assessment of climate change projections compared with the TAR is the large number of simulations available from a broader range of models. Taken together with additional information from observations, these provide a quantitative basis for estimating likelihoods for many aspects of future climate change. Model simulations cover a range of possible futures including idealised emission or concentration assumptions. These include SRES[14] illustrative marker scenarios for the 2000 to 2100 period and model experiments with greenhouse gases and aerosol concentrations held constant after year 2000 or 2100.

For the next two decades, a warming of about 0.2°C per decade is projected for a range of SRES emission scenarios. Even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1°C per decade would be expected. {10.3, 10.7}

- Since IPCC's first report in 1990, assessed projections have suggested global average temperature increases between about 0.15°C and 0.3°C per decade for 1990 to 2005. This can now be compared with observed values of about 0.2°C per decade, strengthening confidence in near-term projections. {1.2, 3.2}

- Model experiments show that even if all radiative forcing agents were held constant at year 2000 levels, a further warming trend would occur in the next two decades at a rate of about 0.1°C per decade, due mainly to the slow response of the oceans. About twice as much warming (0.2°C per decade) would be expected if emissions are within the range of the SRES scenarios. Best-estimate projections from models indicate that decadal average warming over each inhabited continent by 2030 is insensitive to the choice among SRES scenarios and is *very likely* to be at least twice as large as the corresponding model-estimated natural variability during the 20th century. {9.4, 10.3, 10.5, 11.2–11.7, Figure TS-29}

[14] SRES refers to the *IPCC Special Report on Emission Scenarios* (2000). The SRES scenario families and illustrative cases, which did not include additional climate initiatives, are summarised in a box at the end of this Summary for Policymakers. Approximate carbon dioxide equivalent concentrations corresponding to the computed radiative forcing due to anthropogenic greenhouse gases and aerosols in 2100 (see p. 823 of the TAR) for the SRES B1, A1T, B2, A1B, A2 and A1FI illustrative marker scenarios are about 600, 700, 800, 850, 1250 and 1,550 ppm respectively. Scenarios B1, A1B and A2 have been the focus of model intercomparison studies and many of those results are assessed in this report.

Continued greenhouse gas emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would *very likely* be larger than those observed during the 20th century. {10.3}

- Advances in climate change modelling now enable best estimates and *likely* assessed uncertainty ranges to be given for projected warming for different emission scenarios. Results for different emission scenarios are provided explicitly in this report to avoid loss of this policy-relevant information. Projected global average surface warmings for the end of the 21st century (2090–2099) relative to 1980–1999 are shown in Table SPM.3. These illustrate the differences between lower and higher SRES emission scenarios, and the projected warming uncertainty associated with these scenarios. {10.5}

- Best estimates and *likely* ranges for global average surface air warming for six SRES emissions marker scenarios are given in this assessment and are shown in Table SPM.3. For example, the best estimate for the low scenario (B1) is 1.8°C (*likely* range is 1.1°C to 2.9°C), and the best estimate for the high scenario (A1FI) is 4.0°C (*likely* range is 2.4°C to 6.4°C). Although these projections are broadly consistent with the span quoted in the TAR (1.4°C to 5.8°C), they are not directly comparable (see Figure SPM.5). The Fourth Assessment Report is more advanced as it provides best estimates and an assessed likelihood range for each of the marker scenarios. The new assessment of the *likely* ranges now relies on a larger number of climate models of increasing complexity and realism, as well as new information regarding the nature of feedbacks from the carbon cycle and constraints on climate response from observations. {10.5}

- Warming tends to reduce land and ocean uptake of atmospheric carbon dioxide, increasing the fraction of anthropogenic emissions that remains in the atmosphere. For the A2 scenario, for example, the climate-carbon cycle feedback increases the corresponding global average warming at 2100 by more than 1°C. Assessed upper ranges for temperature projections are larger than in the TAR (see Table SPM.3) mainly because the broader range of models now available suggests stronger climate-carbon cycle feedbacks. {7.3, 10.5}

- Model-based projections of global average sea level rise at the end of the 21st century (2090–2099) are shown in Table SPM.3. For each scenario, the midpoint of the range in Table SPM.3 is within 10% of the

Table SPM.3. *Projected global average surface warming and sea level rise at the end of the 21st century. {10.5, 10.6, Table 10.7}*

	Temperature Change (°C at 2090-2099 relative to 1980-1999)[a]		Sea Level Rise (m at 2090-2099 relative to 1980-1999)
Case	**Best estimate**	***Likely* range**	**Model-based range excluding future rapid dynamical changes in ice flow**
Constant Year 2000 concentrations[b]	0.6	0.3 – 0.9	NA
B1 scenario	1.8	1.1 – 2.9	0.18 – 0.38
A1T scenario	2.4	1.4 – 3.8	0.20 – 0.45
B2 scenario	2.4	1.4 – 3.8	0.20 – 0.43
A1B scenario	2.8	1.7 – 4.4	0.21 – 0.48
A2 scenario	3.4	2.0 – 5.4	0.23 – 0.51
A1FI scenario	4.0	2.4 – 6.4	0.26 – 0.59

Table notes:
[a] These estimates are assessed from a hierarchy of models that encompass a simple climate model, several Earth System Models of Intermediate Complexity and a large number of Atmosphere-Ocean General Circulation Models (AOGCMs).
[b] Year 2000 constant composition is derived from AOGCMs only.

Multi-Model Averages and Assessed Ranges for Surface Warming

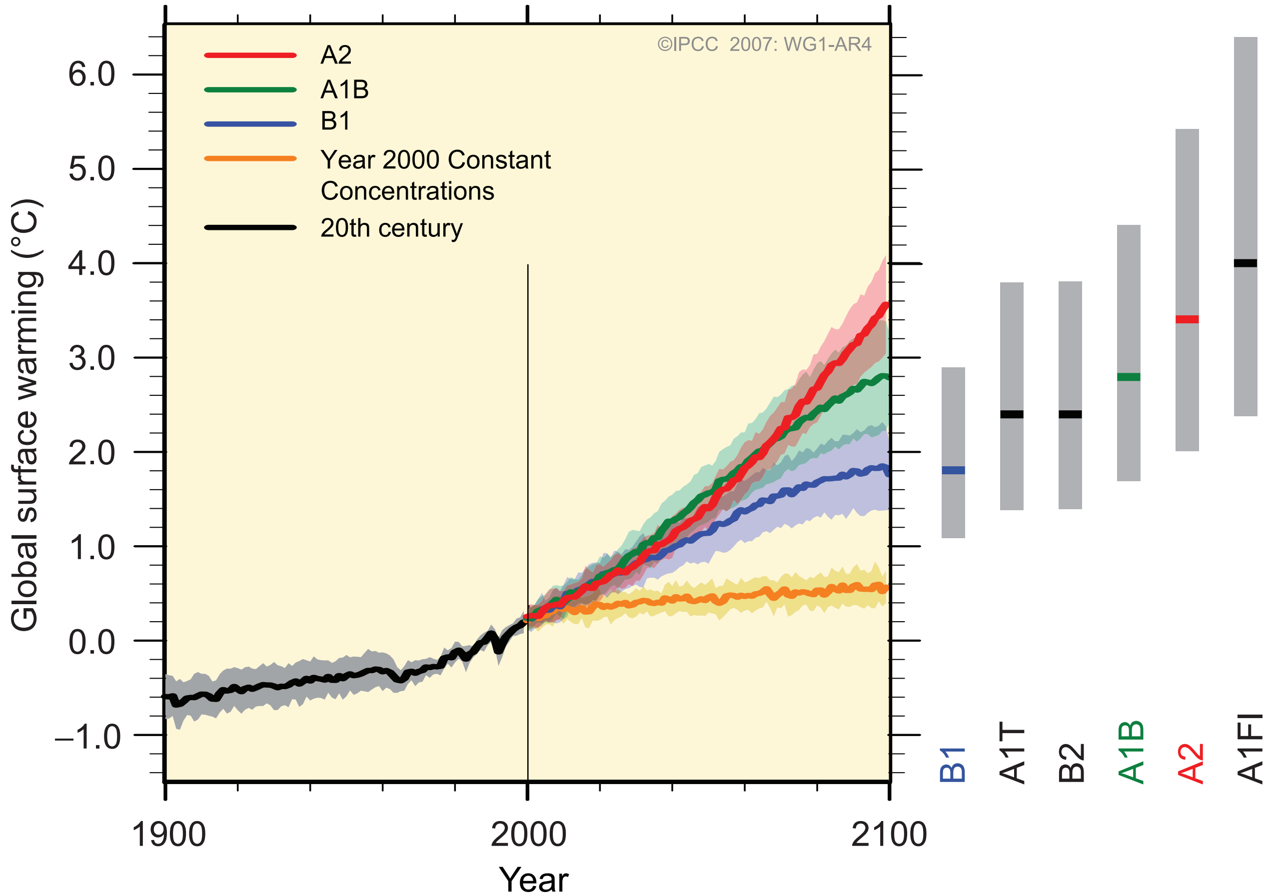

Figure SPM.5. *Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the* ***likely*** *range assessed for the six SRES marker scenarios. The assessment of the best estimate and* ***likely*** *ranges in the grey bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints. {Figures 10.4 and 10.29}*

TAR model average for 2090–2099. The ranges are narrower than in the TAR mainly because of improved information about some uncertainties in the projected contributions.[15] {10.6}

- Models used to date do not include uncertainties in climate-carbon cycle feedback nor do they include the full effects of changes in ice sheet flow, because a basis in published literature is lacking. The projections include a contribution due to increased ice flow from Greenland and Antarctica at the rates observed for 1993 to 2003, but these flow rates could increase or decrease in the future. For example, if this contribution were to grow linearly with global average temperature change, the upper ranges of sea level rise for SRES scenarios shown in Table SPM.3 would increase by 0.1 to 0.2 m. Larger values cannot be excluded, but understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise. {10.6}

- Increasing atmospheric carbon dioxide concentrations lead to increasing acidification of the ocean. Projections based on SRES scenarios give reductions in average global surface ocean pH[16] of between 0.14 and 0.35 units over the 21st century, adding to the present decrease of 0.1 units since pre-industrial times. {5.4, Box 7.3, 10.4}

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[15] TAR projections were made for 2100, whereas projections in this report are for 2090–2099. The TAR would have had similar ranges to those in Table SPM.3 if it had treated the uncertainties in the same way.

[16] Decreases in pH correspond to increases in acidity of a solution. See Glossary for further details.

There is now higher confidence in projected patterns of warming and other regional-scale features, including changes in wind patterns, precipitation and some aspects of extremes and of ice. {8.2, 8.3, 8.4, 8.5, 9.4, 9.5, 10.3, 11.1}

- Projected warming in the 21st century shows scenario-independent geographical patterns similar to those observed over the past several decades. Warming is expected to be greatest over land and at most high northern latitudes, and least over the Southern Ocean and parts of the North Atlantic Ocean (see Figure SPM.6). {10.3}

- Snow cover is projected to contract. Widespread increases in thaw depth are projected over most permafrost regions. {10.3, 10.6}

- Sea ice is projected to shrink in both the Arctic and Antarctic under all SRES scenarios. In some projections, arctic late-summer sea ice disappears almost entirely by the latter part of the 21st century. {10.3}

- It is *very likely* that hot extremes, heat waves and heavy precipitation events will continue to become more frequent. {10.3}

- Based on a range of models, it is *likely* that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical sea surface temperatures. There is less confidence in projections of a global decrease in numbers of tropical cyclones. The apparent increase in the proportion of very intense storms since 1970 in some regions is much larger than simulated by current models for that period. {9.5, 10.3, 3.8}

Projections of Surface Temperatures

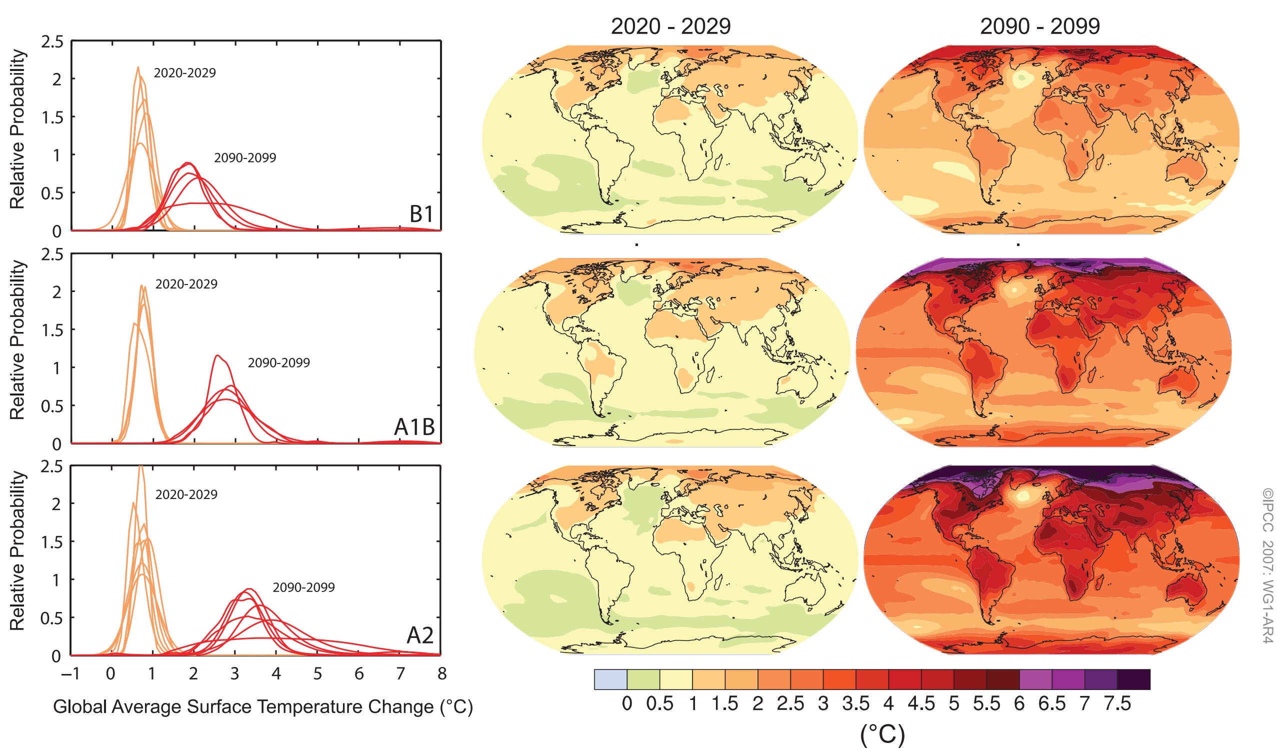

Figure SPM.6. *Projected surface temperature changes for the early and late 21st century relative to the period 1980–1999. The central and right panels show the AOGCM multi-model average projections for the B1 (top), A1B (middle) and A2 (bottom) SRES scenarios averaged over the decades 2020–2029 (centre) and 2090–2099 (right). The left panels show corresponding uncertainties as the relative probabilities of estimated global average warming from several different AOGCM and Earth System Model of Intermediate Complexity studies for the same periods. Some studies present results only for a subset of the SRES scenarios, or for various model versions. Therefore the difference in the number of curves shown in the left-hand panels is due only to differences in the availability of results. {Figures 10.8 and 10.28}*

Projected Patterns of Precipitation Changes

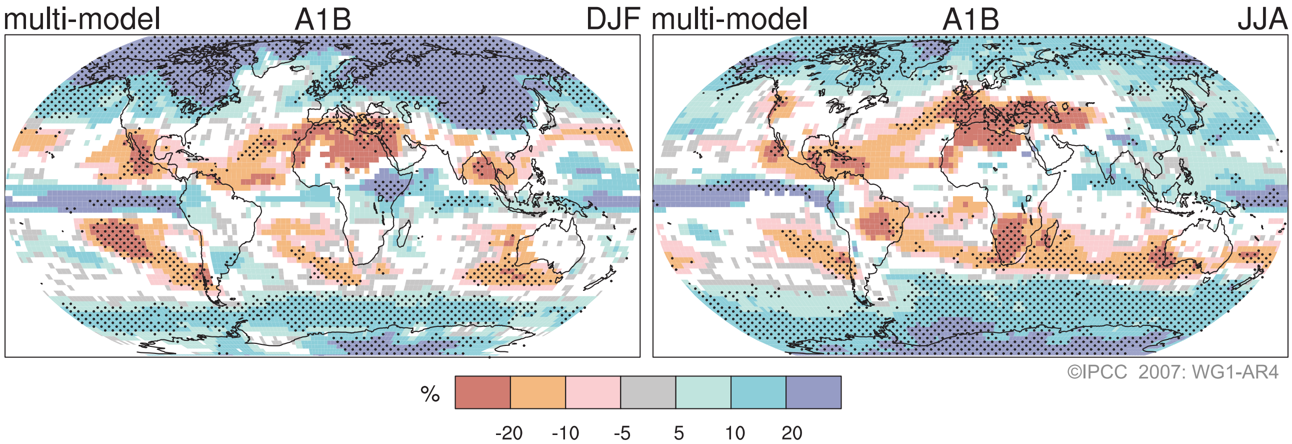

Figure SPM.7. *Relative changes in precipitation (in percent) for the period 2090–2099, relative to 1980–1999. Values are multi-model averages based on the SRES A1B scenario for December to February (left) and June to August (right). White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change. {Figure 10.9}*

- Extratropical storm tracks are projected to move poleward, with consequent changes in wind, precipitation and temperature patterns, continuing the broad pattern of observed trends over the last half-century. {3.6, 10.3}

- Since the TAR, there is an improving understanding of projected patterns of precipitation. Increases in the amount of precipitation are *very likely* in high latitudes, while decreases are *likely* in most subtropical land regions (by as much as about 20% in the A1B scenario in 2100, see Figure SPM.7), continuing observed patterns in recent trends. {3.3, 8.3, 9.5, 10.3, 11.2 to 11.9}

- Based on current model simulations, it is *very likely* that the meridional overturning circulation (MOC) of the Atlantic Ocean will slow down during the 21st century. The multi-model average reduction by 2100 is 25% (range from zero to about 50%) for SRES emission scenario A1B. Temperatures in the Atlantic region are projected to increase despite such changes due to the much larger warming associated with projected increases in greenhouse gases. It is *very unlikely* that the MOC will undergo a large abrupt transition during the 21st century. Longer-term changes in the MOC cannot be assessed with confidence. {10.3, 10.7}

Anthropogenic warming and sea level rise would continue for centuries due to the time scales associated with climate processes and feedbacks, even if greenhouse gas concentrations were to be stabilised. {10.4, 10.5, 10.7}

- Climate-carbon cycle coupling is expected to add carbon dioxide to the atmosphere as the climate system warms, but the magnitude of this feedback is uncertain. This increases the uncertainty in the trajectory of carbon dioxide emissions required to achieve a particular stabilisation level of atmospheric carbon dioxide concentration. Based on current understanding of climate-carbon cycle feedback, model studies suggest that to stabilise at 450 ppm carbon dioxide could require that cumulative emissions over the 21st century be reduced from an average of approximately 670 [630 to 710] GtC (2460 [2310 to 2600] $GtCO_2$) to approximately 490 [375 to 600] GtC (1800 [1370 to 2200] $GtCO_2$). Similarly, to stabilise at 1000 ppm, this feedback could require that cumulative emissions be reduced from a model average of approximately 1415 [1340 to 1490] GtC (5190 [4910 to 5460] $GtCO_2$) to approximately 1100 [980 to 1250] GtC (4030 [3590 to 4580] $GtCO_2$). {7.3, 10.4}

- If radiative forcing were to be stabilised in 2100 at B1 or A1B levels[14] a further increase in global average temperature of about 0.5°C would still be expected, mostly by 2200. {10.7}

- If radiative forcing were to be stabilised in 2100 at A1B levels[14], thermal expansion alone would lead to 0.3 to 0.8 m of sea level rise by 2300 (relative to 1980–1999). Thermal expansion would continue for many centuries, due to the time required to transport heat into the deep ocean. {10.7}

- Contraction of the Greenland Ice Sheet is projected to continue to contribute to sea level rise after 2100. Current models suggest that ice mass losses increase with temperature more rapidly than gains due to precipitation and that the surface mass balance becomes negative at a global average warming (relative to pre-industrial values) in excess of 1.9°C to 4.6°C. If a negative surface mass balance were sustained for millennia, that would lead to virtually complete elimination of the Greenland Ice Sheet and a resulting contribution to sea level rise of about 7 m. The corresponding future temperatures in Greenland are comparable to those inferred for the last interglacial period 125,000 years ago, when palaeoclimatic information suggests reductions of polar land ice extent and 4 to 6 m of sea level rise. {6.4, 10.7}

- Dynamical processes related to ice flow not included in current models but suggested by recent observations could increase the vulnerability of the ice sheets to warming, increasing future sea level rise. Understanding of these processes is limited and there is no consensus on their magnitude. {4.6, 10.7}

- Current global model studies project that the Antarctic Ice Sheet will remain too cold for widespread surface melting and is expected to gain in mass due to increased snowfall. However, net loss of ice mass could occur if dynamical ice discharge dominates the ice sheet mass balance. {10.7}

- Both past and future anthropogenic carbon dioxide emissions will continue to contribute to warming and sea level rise for more than a millennium, due to the time scales required for removal of this gas from the atmosphere. {7.3, 10.3}

The Emission Scenarios of the IPCC Special Report on Emission Scenarios (SRES)[17]

A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil-intensive (A1FI), non-fossil energy sources (A1T) or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

A2. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

B1. The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

An illustrative scenario was chosen for each of the six scenario groups A1B, A1FI, A1T, A2, B1 and B2. All should be considered equally sound.

The SRES scenarios do not include additional climate initiatives, which means that no scenarios are included that explicitly assume implementation of the United Nations Framework Convention on Climate Change or the emissions targets of the Kyoto Protocol.

[17] Emission scenarios are not assessed in this Working Group I Report of the IPCC. This box summarising the SRES scenarios is taken from the TAR and has been subject to prior line-by-line approval by the Panel.

Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change

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Summary for Policymakers

This summary, approved in detail at the Eighth Session of IPCC Working Group II (Brussels, Belgium, 2-5 April 2007), represents the formally agreed statement of the IPCC concerning the sensitivity, adaptive capacity and vulnerability of natural and human systems to climate change, and the potential consequences of climate change.

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A. Introduction

This Summary sets out the key policy-relevant findings of the Fourth Assessment of Working Group II of the Intergovernmental Panel on Climate Change (IPCC).

The Assessment is of current scientific understanding of the impacts of climate change on natural, managed and human systems, the capacity of these systems to adapt and their vulnerability.[1] It builds upon past IPCC assessments and incorporates new knowledge gained since the Third Assessment.

Statements in this Summary are based on chapters in the Assessment and principal sources are given at the end of each paragraph.[2]

B. Current knowledge about observed impacts of climate change on the natural and human environment

A full consideration of observed climate change is provided in the Working Group I Fourth Assessment. This part of the Working Group II Summary concerns the relationship between observed climate change and recent observed changes in the natural and human environment.

The statements presented here are based largely on data sets that cover the period since 1970. The number of studies of observed trends in the physical and biological environment and their relationship to regional climate changes has increased greatly since the Third Assessment in 2001. The quality of the data sets has also improved. There is, however, a notable lack of geographical balance in the data and literature on observed changes, with marked scarcity in developing countries.

Recent studies have allowed a broader and more confident assessment of the relationship between observed warming and impacts than was made in the Third Assessment. That Assessment concluded that "there is high confidence[3] that recent regional changes in temperature have had discernible impacts on many physical and biological systems".

From the current Assessment we conclude the following.

Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases.

With regard to changes in snow, ice and frozen ground (including permafrost),[4] there is high confidence that natural systems are affected. Examples are:
- enlargement and increased numbers of glacial lakes [1.3];
- increasing ground instability in permafrost regions, and rock avalanches in mountain regions [1.3];
- changes in some Arctic and Antarctic ecosystems, including those in sea-ice biomes, and also predators high in the food chain [1.3, 4.4, 15.4].

Based on growing evidence, there is high confidence that the following effects on hydrological systems are occurring:
- increased runoff and earlier spring peak discharge in many glacier- and snow-fed rivers [1.3];
- warming of lakes and rivers in many regions, with effects on thermal structure and water quality [1.3].

There is very high confidence, based on more evidence from a wider range of species, that recent warming is strongly affecting terrestrial biological systems, including such changes as:
- earlier timing of spring events, such as leaf-unfolding, bird migration and egg-laying [1.3];
- poleward and upward shifts in ranges in plant and animal species [1.3, 8.2, 14.2].

Based on satellite observations since the early 1980s, there is high confidence that there has been a trend in many regions towards earlier 'greening'[5] of vegetation in the spring linked to longer thermal growing seasons due to recent warming [1.3, 14.2].

There is high confidence, based on substantial new evidence, that observed changes in marine and freshwater biological systems are associated with rising water temperatures, as well as related changes in ice cover, salinity, oxygen levels and circulation [1.3]. These include:
- shifts in ranges and changes in algal, plankton and fish abundance in high-latitude oceans [1.3];
- increases in algal and zooplankton abundance in high-latitude and high-altitude lakes [1.3];
- range changes and earlier migrations of fish in rivers [1.3].

[1] For definitions, see Endbox 1.
[2] Sources to statements are given in square brackets. For example, [3.3] refers to Chapter 3, Section 3. In the sourcing, F = Figure, T = Table, B = Box and ES = Executive Summary.
[3] See Endbox 2.
[4] See Working Group I Fourth Assessment.
[5] Measured by the Normalised Difference Vegetation Index, which is a relative measure of the amount of green vegetation in an area based on satellite images.

The uptake of anthropogenic carbon since 1750 has led to the ocean becoming more acidic, with an average decrease in pH of 0.1 units [IPCC Working Group I Fourth Assessment]. However, the effects of observed ocean acidification on the marine biosphere are as yet undocumented [1.3].

A global assessment of data since 1970 has shown it is likely[6] that anthropogenic warming has had a discernible influence on many physical and biological systems.

Much more evidence has accumulated over the past five years to indicate that changes in many physical and biological systems are linked to anthropogenic warming. There are four sets of evidence which, taken together, support this conclusion:

1. The Working Group I Fourth Assessment concluded that most of the observed increase in the globally averaged temperature since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations.

2. Of the more than 29,000 observational data series,[7] from 75 studies, that show significant change in many physical and biological systems, more than 89% are consistent with the direction of change expected as a response to warming (Figure SPM.1) [1.4].

3. A global synthesis of studies in this Assessment strongly demonstrates that the spatial agreement between regions of significant warming across the globe and the locations of significant observed changes in many systems consistent with warming is very unlikely to be due solely to natural variability of temperatures or natural variability of the systems (Figure SPM.1) [1.4].

4. Finally, there have been several modelling studies that have linked responses in some physical and biological systems to anthropogenic warming by comparing observed responses in these systems with modelled responses in which the natural forcings (solar activity and volcanoes) and anthropogenic forcings (greenhouse gases and aerosols) are explicitly separated. Models with combined natural and anthropogenic forcings simulate observed responses significantly better than models with natural forcing only [1.4].

Limitations and gaps prevent more complete attribution of the causes of observed system responses to anthropogenic warming. First, the available analyses are limited in the number of systems and locations considered. Second, natural temperature variability is larger at the regional than at the global scale, thus affecting identification of changes due to external forcing. Finally, at the regional scale other factors (such as land-use change, pollution, and invasive species) are influential [1.4].

Nevertheless, the consistency between observed and modelled changes in several studies and the spatial agreement between significant regional warming and consistent impacts at the global scale is sufficient to conclude with high confidence that anthropogenic warming over the last three decades has had a discernible influence on many physical and biological systems [1.4].

Other effects of regional climate changes on natural and human environments are emerging, although many are difficult to discern due to adaptation and non-climatic drivers.

Effects of temperature increases have been documented in the following (medium confidence):
- effects on agricultural and forestry management at Northern Hemisphere higher latitudes, such as earlier spring planting of crops, and alterations in disturbance regimes of forests due to fires and pests [1.3];
- some aspects of human health, such as heat-related mortality in Europe, infectious disease vectors in some areas, and allergenic pollen in Northern Hemisphere high and mid-latitudes [1.3, 8.2, 8.ES];
- some human activities in the Arctic (e.g., hunting and travel over snow and ice) and in lower-elevation alpine areas (such as mountain sports) [1.3].

Recent climate changes and climate variations are beginning to have effects on many other natural and human systems. However, based on the published literature, the impacts have not yet become established trends. Examples include:

- Settlements in mountain regions are at enhanced risk of glacier lake outburst floods caused by melting glaciers. Governmental institutions in some places have begun to respond by building dams and drainage works [1.3].

- In the Sahelian region of Africa, warmer and drier conditions have led to a reduced length of growing season with detrimental effects on crops. In southern Africa, longer dry seasons and more uncertain rainfall are prompting adaptation measures [1.3].

- Sea-level rise and human development are together contributing to losses of coastal wetlands and mangroves and increasing damage from coastal flooding in many areas [1.3].

6 See Endbox 2.

7 A subset of about 29,000 data series was selected from about 80,000 data series from 577 studies. These met the following criteria: (1) ending in 1990 or later; (2) spanning a period of at least 20 years; and (3) showing a significant change in either direction, as assessed in individual studies.

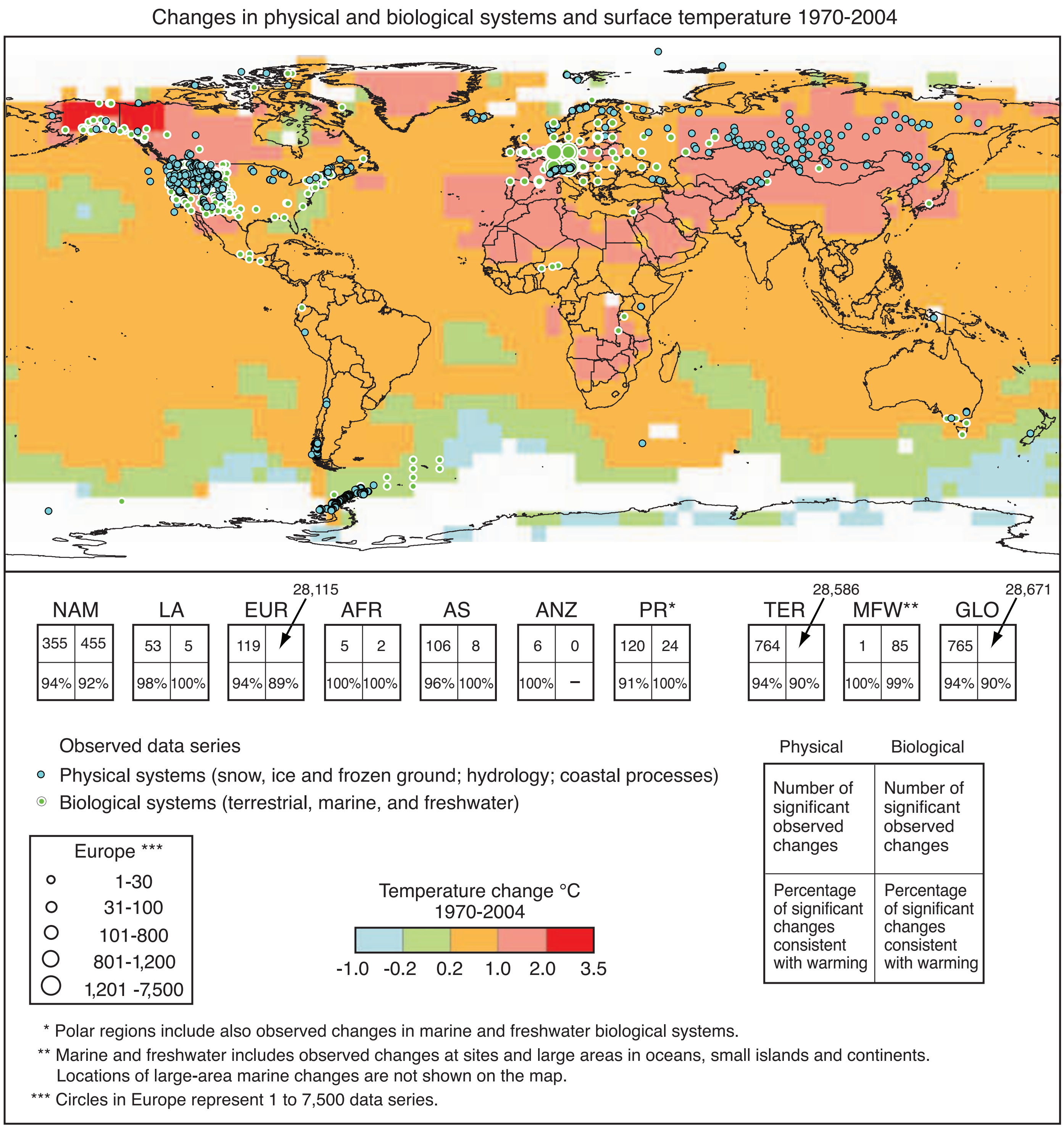


Figure SPM.1. *Locations of significant changes in data series of physical systems (snow, ice and frozen ground; hydrology; and coastal processes) and biological systems (terrestrial, marine, and freshwater biological systems), are shown together with surface air temperature changes over the period 1970-2004. A subset of about 29,000 data series was selected from about 80,000 data series from 577 studies. These met the following criteria: (1) ending in 1990 or later; (2) spanning a period of at least 20 years; and (3) showing a significant change in either direction, as assessed in individual studies. These data series are from about 75 studies (of which about 70 are new since the Third Assessment) and contain about 29,000 data series, of which about 28,000 are from European studies. White areas do not contain sufficient observational climate data to estimate a temperature trend. The 2 x 2 boxes show the total number of data series with significant changes (top row) and the percentage of those consistent with warming (bottom row) for (i) continental regions: North America (NAM), Latin America (LA), Europe (EUR), Africa (AFR), Asia (AS), Australia and New Zealand (ANZ), and Polar Regions (PR) and (ii) global-scale: Terrestrial (TER), Marine and Freshwater (MFW), and Global (GLO). The numbers of studies from the seven regional boxes (NAM, …, PR) do not add up to the global (GLO) totals because numbers from regions except Polar do not include the numbers related to Marine and Freshwater (MFW) systems. Locations of large-area marine changes are not shown on the map. [Working Group II Fourth Assessment F1.8, F1.9; Working Group I Fourth Assessment F3.9b].*

C. Current knowledge about future impacts

The following is a selection of the key findings regarding projected impacts, as well as some findings on vulnerability and adaptation, in each system, sector and region for the range of (unmitigated) climate changes projected by the IPCC over this century[8] judged to be relevant for people and the environment.[9] The impacts frequently reflect projected changes in precipitation and other climate variables in addition to temperature, sea level and concentrations of atmospheric carbon dioxide. The magnitude and timing of impacts will vary with the amount and timing of climate change and, in some cases, the capacity to adapt. These issues are discussed further in later sections of the Summary.

More specific information is now available across a wide range of systems and sectors concerning the nature of future impacts, including for some fields not covered in previous assessments.

Freshwater resources and their management

By mid-century, annual average river runoff and water availability are projected to increase by 10-40% at high latitudes and in some wet tropical areas, and decrease by 10-30% over some dry regions at mid-latitudes and in the dry tropics, some of which are presently water-stressed areas. In some places and in particular seasons, changes differ from these annual figures. ** D[10] [3.4]

Drought-affected areas will likely increase in extent. Heavy precipitation events, which are very likely to increase in frequency, will augment flood risk. ** N [Working Group I Fourth Assessment Table SPM-2, Working Group II Fourth Assessment 3.4]

In the course of the century, water supplies stored in glaciers and snow cover are projected to decline, reducing water availability in regions supplied by meltwater from major mountain ranges, where more than one-sixth of the world population currently lives. ** N [3.4]

Adaptation procedures and risk management practices for the water sector are being developed in some countries and regions that have recognised projected hydrological changes with related uncertainties. *** N [3.6]

Ecosystems

The resilience of many ecosystems is likely to be exceeded this century by an unprecedented combination of climate change, associated disturbances (e.g., flooding, drought, wildfire, insects, ocean acidification), and other global change drivers (e.g., land-use change, pollution, over-exploitation of resources). ** N [4.1 to 4.6]

Over the course of this century, net carbon uptake by terrestrial ecosystems is likely to peak before mid-century and then weaken or even reverse,[11] thus amplifying climate change. ** N [4.ES, F4.2]

Approximately 20-30% of plant and animal species assessed so far are likely to be at increased risk of extinction if increases in global average temperature exceed 1.5-2.5°C. * N [4.4, T4.1]

For increases in global average temperature exceeding 1.5-2.5°C and in concomitant atmospheric carbon dioxide concentrations, there are projected to be major changes in ecosystem structure and function, species' ecological interactions, and species' geographical ranges, with predominantly negative consequences for biodiversity, and ecosystem goods and services e.g., water and food supply. ** N [4.4]

The progressive acidification of oceans due to increasing atmospheric carbon dioxide is expected to have negative impacts on marine shell-forming organisms (e.g., corals) and their dependent species. * N [B4.4, 6.4]

Food, fibre and forest products

Crop productivity is projected to increase slightly at mid- to high latitudes for local mean temperature increases of up to 1-3°C depending on the crop, and then decrease beyond that in some regions. * D [5.4]

At lower latitudes, especially seasonally dry and tropical regions, crop productivity is projected to decrease for even small local temperature increases (1-2°C), which would increase the risk of hunger. * D [5.4]

Globally, the potential for food production is projected to increase with increases in local average temperature over a range of 1-3°C, but above this it is projected to decrease. * D [5.4, 5.6]

[8] Temperature changes are expressed as the difference from the period 1980-1999. To express the change relative to the period 1850-1899, add 0.5°C.
[9] Criteria of choice: magnitude and timing of impact, confidence in the assessment, representative coverage of the system, sector and region.
[10] In Section C, the following conventions are used:

<u>*Relationship to the Third Assessment:*</u>
D Further development of a conclusion in the Third Assessment
N New conclusion, not in the Third Assessment
<u>*Level of confidence in the whole statement:*</u>
**** Very high confidence*
*** High confidence*
** Medium confidence*

[11] Assuming continued greenhouse gas emissions at or above current rates and other global changes including land-use changes.

Increases in the frequency of droughts and floods are projected to affect local crop production negatively, especially in subsistence sectors at low latitudes. ** D [5.4, 5.ES]

Adaptations such as altered cultivars and planting times allow low- and mid- to high-latitude cereal yields to be maintained at or above baseline yields for modest warming. * N [5.5]

Globally, commercial timber productivity rises modestly with climate change in the short- to medium-term, with large regional variability around the global trend. * D [5.4]

Regional changes in the distribution and production of particular fish species are expected due to continued warming, with adverse effects projected for aquaculture and fisheries. ** D [5.4]

Coastal systems and low-lying areas

Coasts are projected to be exposed to increasing risks, including coastal erosion, due to climate change and sea-level rise. The effect will be exacerbated by increasing human-induced pressures on coastal areas. *** D [6.3, 6.4]

Corals are vulnerable to thermal stress and have low adaptive capacity. Increases in sea surface temperature of about 1-3°C are projected to result in more frequent coral bleaching events and widespread mortality, unless there is thermal adaptation or acclimatisation by corals. *** D [B6.1, 6.4]

Coastal wetlands including salt marshes and mangroves are projected to be negatively affected by sea-level rise especially where they are constrained on their landward side, or starved of sediment. *** D [6.4]

Many millions more people are projected to be flooded every year due to sea-level rise by the 2080s. Those densely-populated and low-lying areas where adaptive capacity is relatively low, and which already face other challenges such as tropical storms or local coastal subsidence, are especially at risk. The numbers affected will be largest in the mega-deltas of Asia and Africa while small islands are especially vulnerable. *** D [6.4]

Adaptation for coasts will be more challenging in developing countries than in developed countries, due to constraints on adaptive capacity. ** D [6.4, 6.5, T6.11]

Industry, settlement and society

Costs and benefits of climate change for industry, settlement and society will vary widely by location and scale. In the aggregate, however, net effects will tend to be more negative the larger the change in climate. ** N [7.4, 7.6]

The most vulnerable industries, settlements and societies are generally those in coastal and river flood plains, those whose economies are closely linked with climate-sensitive resources, and those in areas prone to extreme weather events, especially where rapid urbanisation is occurring. ** D [7.1, 7.3 to 7.5]

Poor communities can be especially vulnerable, in particular those concentrated in high-risk areas. They tend to have more limited adaptive capacities, and are more dependent on climate-sensitive resources such as local water and food supplies. ** N [7.2, 7.4, 5.4]

Where extreme weather events become more intense and/or more frequent, the economic and social costs of those events will increase, and these increases will be substantial in the areas most directly affected. Climate change impacts spread from directly impacted areas and sectors to other areas and sectors through extensive and complex linkages. ** N [7.4, 7.5]

Health

Projected climate change-related exposures are likely to affect the health status of millions of people, particularly those with low adaptive capacity, through:

- increases in malnutrition and consequent disorders, with implications for child growth and development;
- increased deaths, disease and injury due to heatwaves, floods, storms, fires and droughts;
- the increased burden of diarrhoeal disease;
- the increased frequency of cardio-respiratory diseases due to higher concentrations of ground-level ozone related to climate change; and,
- the altered spatial distribution of some infectious disease vectors. ** D [8.4, 8.ES, 8.2]

Climate change is expected to have some mixed effects, such as a decrease or increase in the range and transmission potential of malaria in Africa. ** D [8.4]

Studies in temperate areas[12] have shown that climate change is projected to bring some benefits, such as fewer deaths from cold exposure. Overall it is expected that these benefits will be outweighed by the negative health effects of rising temperatures worldwide, especially in developing countries. ** D [8.4]

The balance of positive and negative health impacts will vary from one location to another, and will alter over time as temperatures continue to rise. Critically important will be factors that directly shape the health of populations such as education, health care, public health initiatives and infrastructure and economic development. *** N [8.3]

[12] Studies mainly in industrialised countries.

More specific information is now available across the regions of the world concerning the nature of future impacts, including for some places not covered in previous assessments.

Africa

By 2020, between 75 million and 250 million people are projected to be exposed to increased water stress due to climate change. If coupled with increased demand, this will adversely affect livelihoods and exacerbate water-related problems. ** D [9.4, 3.4, 8.2, 8.4]

Agricultural production, including access to food, in many African countries and regions is projected to be severely compromised by climate variability and change. The area suitable for agriculture, the length of growing seasons and yield potential, particularly along the margins of semi-arid and arid areas, are expected to decrease. This would further adversely affect food security and exacerbate malnutrition in the continent. In some countries, yields from rain-fed agriculture could be reduced by up to 50% by 2020. ** N [9.2, 9.4, 9.6]

Local food supplies are projected to be negatively affected by decreasing fisheries resources in large lakes due to rising water temperatures, which may be exacerbated by continued over-fishing. ** N [9.4, 5.4, 8.4]

Towards the end of the 21st century, projected sea-level rise will affect low-lying coastal areas with large populations. The cost of adaptation could amount to at least 5-10% of Gross Domestic Product (GDP). Mangroves and coral reefs are projected to be further degraded, with additional consequences for fisheries and tourism. ** D [9.4]

New studies confirm that Africa is one of the most vulnerable continents to climate variability and change because of multiple stresses and low adaptive capacity. Some adaptation to current climate variability is taking place; however, this may be insufficient for future changes in climate. ** N [9.5]

Asia

Glacier melt in the Himalayas is projected to increase flooding, and rock avalanches from destabilised slopes, and to affect water resources within the next two to three decades. This will be followed by decreased river flows as the glaciers recede. * N [10.2, 10.4]

Freshwater availability in Central, South, East and South-East Asia, particularly in large river basins, is projected to decrease due to climate change which, along with population growth and increasing demand arising from higher standards of living, could adversely affect more than a billion people by the 2050s. ** N [10.4]

Coastal areas, especially heavily-populated megadelta regions in South, East and South-East Asia, will be at greatest risk due to increased flooding from the sea and, in some megadeltas, flooding from the rivers. ** D [10.4]

Climate change is projected to impinge on the sustainable development of most developing countries of Asia, as it compounds the pressures on natural resources and the environment associated with rapid urbanisation, industrialisation, and economic development. ** D [10.5]

It is projected that crop yields could increase up to 20% in East and South-East Asia while they could decrease up to 30% in Central and South Asia by the mid-21st century. Taken together, and considering the influence of rapid population growth and urbanisation, the risk of hunger is projected to remain very high in several developing countries. * N [10.4]

Endemic morbidity and mortality due to diarrhoeal disease primarily associated with floods and droughts are expected to rise in East, South and South-East Asia due to projected changes in the hydrological cycle associated with global warming. Increases in coastal water temperature would exacerbate the abundance and/or toxicity of cholera in South Asia. **N [10.4]

Australia and New Zealand

As a result of reduced precipitation and increased evaporation, water security problems are projected to intensify by 2030 in southern and eastern Australia and, in New Zealand, in Northland and some eastern regions. ** D [11.4]

Significant loss of biodiversity is projected to occur by 2020 in some ecologically rich sites including the Great Barrier Reef and Queensland Wet Tropics. Other sites at risk include Kakadu wetlands, south-west Australia, sub-Antarctic islands and the alpine areas of both countries. *** D [11.4]

Ongoing coastal development and population growth in areas such as Cairns and South-east Queensland (Australia) and Northland to Bay of Plenty (New Zealand), are projected to exacerbate risks from sea-level rise and increases in the severity and frequency of storms and coastal flooding by 2050. *** D [11.4, 11.6]

Production from agriculture and forestry by 2030 is projected to decline over much of southern and eastern Australia, and over parts of eastern New Zealand, due to increased drought and fire. However, in New Zealand, initial benefits are projected in western and southern areas and close to major rivers due to a longer growing season, less frost and increased rainfall. ** N [11.4]

The region has substantial adaptive capacity due to well-developed economies and scientific and technical capabilities, but there are considerable constraints to implementation and major challenges from changes in extreme events. Natural systems have limited adaptive capacity. ** N [11.2, 11.5]

Europe

For the first time, wide-ranging impacts of changes in current climate have been documented: retreating glaciers, longer growing seasons, shift of species ranges, and health impacts due to a heatwave of unprecedented magnitude. The observed changes described above are consistent with those projected for future climate change. *** N [12.2, 12.4, 12.6]

Nearly all European regions are anticipated to be negatively affected by some future impacts of climate change, and these will pose challenges to many economic sectors. Climate change is expected to magnify regional differences in Europe's natural resources and assets. Negative impacts will include increased risk of inland flash floods, and more frequent coastal flooding and increased erosion (due to storminess and sea-level rise). The great majority of organisms and ecosystems will have difficulty adapting to climate change. Mountainous areas will face glacier retreat, reduced snow cover and winter tourism, and extensive species losses (in some areas up to 60% under high emission scenarios by 2080). *** D [12.4]

In Southern Europe, climate change is projected to worsen conditions (high temperatures and drought) in a region already vulnerable to climate variability, and to reduce water availability, hydropower potential, summer tourism and, in general, crop productivity. It is also projected to increase health risks due to heat-waves, and the frequency of wildfires. ** D [12.2, 12.4, 12.7]

In Central and Eastern Europe, summer precipitation is projected to decrease, causing higher water stress. Health risks due to heatwaves are projected to increase. Forest productivity is expected to decline and the frequency of peatland fires to increase. ** D [12.4]

In Northern Europe, climate change is initially projected to bring mixed effects, including some benefits such as reduced demand for heating, increased crop yields and increased forest growth. However, as climate change continues, its negative impacts (including more frequent winter floods, endangered ecosystems and increasing ground instability) are likely to outweigh its benefits. ** D [12.4]

Adaptation to climate change is likely to benefit from experience gained in reaction to extreme climate events, specifically by implementing proactive climate change risk management adaptation plans. *** N [12.5]

Latin America

By mid-century, increases in temperature and associated decreases in soil water are projected to lead to gradual replacement of tropical forest by savanna in eastern Amazonia. Semi-arid vegetation will tend to be replaced by arid-land vegetation. There is a risk of significant biodiversity loss through species extinction in many areas of tropical Latin America. ** D [13.4]

In drier areas, climate change is expected to lead to salinisation and desertification of agricultural land. Productivity of some important crops is projected to decrease and livestock productivity to decline, with adverse consequences for food security. In temperate zones soybean yields are projected to increase. ** N [13.4, 13.7]

Sea-level rise is projected to cause increased risk of flooding in low-lying areas. Increases in sea surface temperature due to climate change are projected to have adverse effects on Mesoamerican coral reefs, and cause shifts in the location of south-east Pacific fish stocks. ** N [13.4, 13.7]

Changes in precipitation patterns and the disappearance of glaciers are projected to significantly affect water availability for human consumption, agriculture and energy generation. ** D [13.4]

Some countries have made efforts to adapt, particularly through conservation of key ecosystems, early warning systems, risk management in agriculture, strategies for flood drought and coastal management, and disease surveillance systems. However, the effectiveness of these efforts is outweighed by: lack of basic information, observation and monitoring systems; lack of capacity building and appropriate political, institutional and technological frameworks; low income; and settlements in vulnerable areas, among others. ** D [13.2]

North America

Warming in western mountains is projected to cause decreased snowpack, more winter flooding, and reduced summer flows, exacerbating competition for over-allocated water resources. *** D [14.4, B14.2]

Disturbances from pests, diseases and fire are projected to have increasing impacts on forests, with an extended period of high fire risk and large increases in area burned. *** N [14.4, B14.1]

Moderate climate change in the early decades of the century is projected to increase aggregate yields of rain-fed agriculture by 5-

20%, but with important variability among regions. Major challenges are projected for crops that are near the warm end of their suitable range or which depend on highly utilised water resources. ** D [14.4]

Cities that currently experience heatwaves are expected to be further challenged by an increased number, intensity and duration of heatwaves during the course of the century, with potential for adverse health impacts. Elderly populations are most at risk. *** D [14.4].

Coastal communities and habitats will be increasingly stressed by climate change impacts interacting with development and pollution. Population growth and the rising value of infrastructure in coastal areas increase vulnerability to climate variability and future climate change, with losses projected to increase if the intensity of tropical storms increases. Current adaptation is uneven and readiness for increased exposure is low. *** N [14.2, 14.4]

Polar Regions

In the Polar Regions, the main projected biophysical effects are reductions in thickness and extent of glaciers and ice sheets, and changes in natural ecosystems with detrimental effects on many organisms including migratory birds, mammals and higher predators. In the Arctic, additional impacts include reductions in the extent of sea ice and permafrost, increased coastal erosion, and an increase in the depth of permafrost seasonal thawing. ** D [15.3, 15.4, 15.2]

For human communities in the Arctic, impacts, particularly those resulting from changing snow and ice conditions, are projected to be mixed. Detrimental impacts would include those on infrastructure and traditional indigenous ways of life. ** D [15.4]

Beneficial impacts would include reduced heating costs and more navigable northern sea routes. * D [15.4]

In both polar regions, specific ecosystems and habitats are projected to be vulnerable, as climatic barriers to species invasions are lowered. ** D [15.6, 15.4]

Arctic human communities are already adapting to climate change, but both external and internal stressors challenge their adaptive capacities. Despite the resilience shown historically by Arctic indigenous communities, some traditional ways of life are being threatened and substantial investments are needed to adapt or re-locate physical structures and communities. ** D [15.ES, 15.4, 15.5, 15.7]

Small islands

Small islands, whether located in the tropics or higher latitudes, have characteristics which make them especially vulnerable to the effects of climate change, sea-level rise and extreme events. *** D [16.1, 16.5]

Deterioration in coastal conditions, for example through erosion of beaches and coral bleaching, is expected to affect local resources, e.g., fisheries, and reduce the value of these destinations for tourism. ** D [16.4]

Sea-level rise is expected to exacerbate inundation, storm surge, erosion and other coastal hazards, thus threatening vital infrastructure, settlements and facilities that support the livelihood of island communities. *** D [16.4]

Climate change is projected by mid-century to reduce water resources in many small islands, e.g., in the Caribbean and Pacific, to the point where they become insufficient to meet demand during low-rainfall periods. *** D [16.4]

With higher temperatures, increased invasion by non-native species is expected to occur, particularly on mid- and high-latitude islands. ** N [16.4]

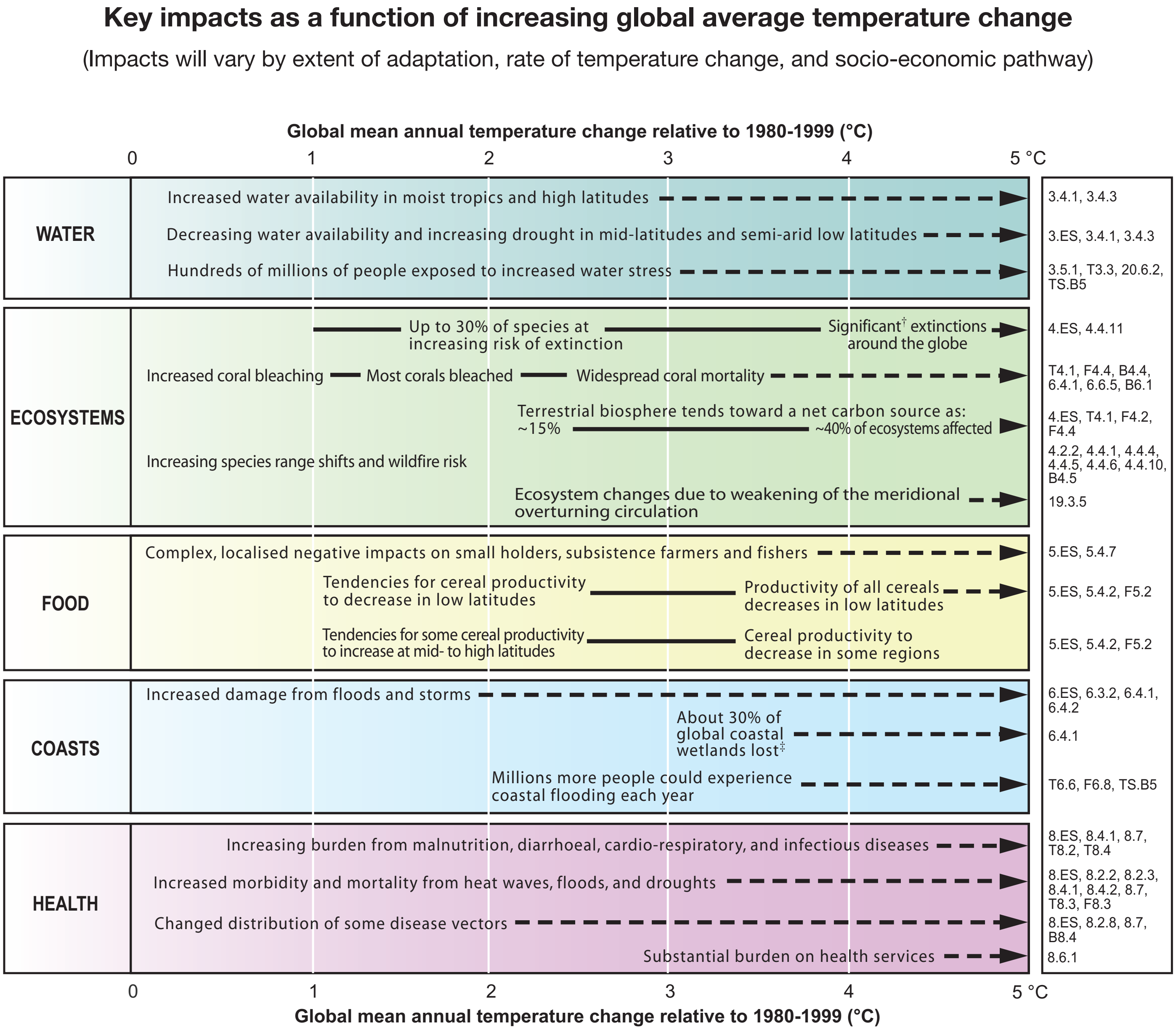
Magnitudes of impact can now be estimated more systematically for a range of possible increases in global average temperature.

Since the IPCC Third Assessment, many additional studies, particularly in regions that previously had been little researched, have enabled a more systematic understanding of how the timing and magnitude of impacts may be affected by changes in climate and sea level associated with differing amounts and rates of change in global average temperature.

Examples of this new information are presented in Figure SPM.2. Entries have been selected which are judged to be relevant for people and the environment and for which there is high confidence in the assessment. All examples of impact are drawn from chapters of the Assessment, where more detailed information is available.

Depending on circumstances, some of these impacts could be associated with 'key vulnerabilities', based on a number of criteria in the literature (magnitude, timing, persistence/reversibility, the potential for adaptation, distributional aspects, likelihood and 'importance' of the impacts). Assessment of potential key vulnerabilities is intended to provide information on rates and levels of climate change to help decision-makers make appropriate responses to the risks of climate change [19.ES, 19.1].

The 'reasons for concern' identified in the Third Assessment remain a viable framework for considering key vulnerabilities. Recent research has updated some of the findings from the Third Assessment [19.3].



† Significant is defined here as more than 40%.
‡ Based on average rate of sea level rise of 4.2 mm/year from 2000 to 2080.

Figure SPM.2. *Illustrative examples of global impacts projected for climate changes (and sea level and atmospheric carbon dioxide where relevant) associated with different amounts of increase in global average surface temperature in the 21st century [T20.8]. The black lines link impacts, dotted arrows indicate impacts continuing with increasing temperature. Entries are placed so that the left-hand side of the text indicates the approximate onset of a given impact. Quantitative entries for water stress and flooding represent the additional impacts of climate change relative to the conditions projected across the range of Special Report on Emissions Scenarios (SRES) scenarios A1FI, A2, B1 and B2 (see Endbox 3). Adaptation to climate change is not included in these estimations. All entries are from published studies recorded in the chapters of the Assessment. Sources are given in the right-hand column of the Table. Confidence levels for all statements are high.*

Impacts due to altered frequencies and intensities of extreme weather, climate and sea-level events are very likely to change.

Since the IPCC Third Assessment, confidence has increased that some weather events and extremes will become more frequent, more widespread and/or more intense during the 21st century; and more is known about the potential effects of such changes. A selection of these is presented in Table SPM.1.

The direction of trend and likelihood of phenomena are for IPCC SRES projections of climate change.

Some large-scale climate events have the potential to cause very large impacts, especially after the 21st century.

Very large sea-level rises that would result from widespread deglaciation of Greenland and West Antarctic ice sheets imply major changes in coastlines and ecosystems, and inundation of low-lying areas, with greatest effects in river deltas. Relocating populations, economic activity, and infrastructure would be costly and challenging. There is medium confidence that at least partial deglaciation of the Greenland ice sheet, and possibly the West Antarctic ice sheet, would occur over a period of time ranging from centuries to millennia for a global average temperature increase of 1-4°C (relative to 1990-2000), causing a contribution to sea-level rise of 4-6 m or more. The complete melting of the Greenland ice sheet and the West Antarctic ice sheet would lead to a contribution to sea-level rise of up to 7 m and about 5 m, respectively [Working Group I Fourth Assessment 6.4, 10.7; Working Group II Fourth Assessment 19.3].

Based on climate model results, it is very unlikely that the Meridional Overturning Circulation (MOC) in the North Atlantic will undergo a large abrupt transition during the 21st century. Slowing of the MOC during this century is very likely, but temperatures over the Atlantic and Europe are projected to increase nevertheless, due to global warming. Impacts of large-scale and persistent changes in the MOC are likely to include changes to marine ecosystem productivity, fisheries, ocean carbon dioxide uptake, oceanic oxygen concentrations and terrestrial vegetation [Working Group I Fourth Assessment 10.3, 10.7; Working Group II Fourth Assessment 12.6, 19.3].

Impacts of climate change will vary regionally but, aggregated and discounted to the present, they are very likely to impose net annual costs which will increase over time as global temperatures increase.

This Assessment makes it clear that the impacts of future climate change will be mixed across regions. For increases in global mean temperature of less than 1-3°C above 1990 levels, some impacts are projected to produce benefits in some places and some sectors, and produce costs in other places and other sectors. It is, however, projected that some low-latitude and polar regions will experience net costs even for small increases in temperature. It is very likely that all regions will experience either declines in net benefits or increases in net costs for increases in temperature greater than about 2-3°C [9.ES, 9.5, 10.6, T10.9, 15.3, 15.ES]. These observations confirm evidence reported in the Third Assessment that, while developing countries are expected to experience larger percentage losses, global mean losses could be 1-5% GDP for 4°C of warming [F20.3].

Many estimates of aggregate net economic costs of damages from climate change across the globe (i.e., the social cost of carbon (SCC), expressed in terms of future net benefits and costs that are discounted to the present) are now available. Peer-reviewed estimates of the SCC for 2005 have an average value of US$43 per tonne of carbon (i.e., US$12 per tonne of carbon dioxide), but the range around this mean is large. For example, in a survey of 100 estimates, the values ran from US$-10 per tonne of carbon (US$-3 per tonne of carbon dioxide) up to US$350 per tonne of carbon (US$95 per tonne of carbon dioxide) [20.6].

The large ranges of SCC are due in the large part to differences in assumptions regarding climate sensitivity, response lags, the treatment of risk and equity, economic and non-economic impacts, the inclusion of potentially catastrophic losses, and discount rates. It is very likely that globally aggregated figures underestimate the damage costs because they cannot include many non-quantifiable impacts. Taken as a whole, the range of published evidence indicates that the net damage costs of climate change are likely to be significant and to increase over time [T20.3, 20.6, F20.4].

It is virtually certain that aggregate estimates of costs mask significant differences in impacts across sectors, regions, countries and populations. In some locations and among some groups of people with high exposure, high sensitivity and/or low adaptive capacity, net costs will be significantly larger than the global aggregate [20.6, 20.ES, 7.4].

Phenomenon[a] and direction of trend	Likelihood of future trends based on projections for 21st century using SRES scenarios	Examples of major projected impacts by sector			
		Agriculture, forestry and ecosystems [4.4, 5.4]	Water resources [3.4]	Human health [8.2, 8.4]	Industry, settlement and society [7.4]
Over most land areas, warmer and fewer cold days and nights, warmer and more frequent hot days and nights	Virtually certain[b]	Increased yields in colder environments; decreased yields in warmer environments; increased insect outbreaks	Effects on water resources relying on snow melt; effects on some water supplies	Reduced human mortality from decreased cold exposure	Reduced energy demand for heating; increased demand for cooling; declining air quality in cities; reduced disruption to transport due to snow, ice; effects on winter tourism
Warm spells/heat waves. Frequency increases over most land areas	Very likely	Reduced yields in warmer regions due to heat stress; increased danger of wildfire	Increased water demand; water quality problems, e.g., algal blooms	Increased risk of heat-related mortality, especially for the elderly, chronically sick, very young and socially-isolated	Reduction in quality of life for people in warm areas without appropriate housing; impacts on the elderly, very young and poor
Heavy precipitation events. Frequency increases over most areas	Very likely	Damage to crops; soil erosion, inability to cultivate land due to waterlogging of soils	Adverse effects on quality of surface and groundwater; contamination of water supply; water scarcity may be relieved	Increased risk of deaths, injuries and infectious, respiratory and skin diseases	Disruption of settlements, commerce, transport and societies due to flooding; pressures on urban and rural infrastructures; loss of property
Area affected by drought increases	Likely	Land degradation; lower yields/crop damage and failure; increased livestock deaths; increased risk of wildfire	More widespread water stress	Increased risk of food and water shortage; increased risk of malnutrition; increased risk of water- and food-borne diseases	Water shortages for settlements, industry and societies; reduced hydropower generation potentials; potential for population migration
Intense tropical cyclone activity increases	Likely	Damage to crops; windthrow (uprooting) of trees; damage to coral reefs	Power outages causing disruption of public water supply	Increased risk of deaths, injuries, water- and food-borne diseases; post-traumatic stress disorders	Disruption by flood and high winds; withdrawal of risk coverage in vulnerable areas by private insurers, potential for population migrations, loss of property
Increased incidence of extreme high sea level (excludes tsunamis)[c]	Likely[d]	Salinisation of irrigation water, estuaries and freshwater systems	Decreased freshwater availability due to saltwater intrusion	Increased risk of deaths and injuries by drowning in floods; migration-related health effects	Costs of coastal protection versus costs of land-use relocation; potential for movement of populations and infrastructure; also see tropical cyclones above

[a] See Working Group I Fourth Assessment Table 3.7 for further details regarding definitions.
[b] Warming of the most extreme days and nights each year.
[c] Extreme high sea level depends on average sea level and on regional weather systems. It is defined as the highest 1% of hourly values of observed sea level at a station for a given reference period.
[d] In all scenarios, the projected global average sea level at 2100 is higher than in the reference period [Working Group I Fourth Assessment 10.6]. The effect of changes in regional weather systems on sea level extremes has not been assessed.

Table SPM.1. *Examples of possible impacts of climate change due to changes in extreme weather and climate events, based on projections to the mid- to late 21st century. These do not take into account any changes or developments in adaptive capacity. Examples of all entries are to be found in chapters in the full Assessment (see source at top of columns). The first two columns of the table (shaded yellow) are taken directly from the Working Group I Fourth Assessment (Table SPM-2). The likelihood estimates in Column 2 relate to the phenomena listed in Column 1.*

D. Current knowledge about responding to climate change

Some adaptation is occurring now, to observed and projected future climate change, but on a limited basis.

There is growing evidence since the IPCC Third Assessment of human activity to adapt to observed and anticipated climate change. For example, climate change is considered in the design of infrastructure projects such as coastal defence in the Maldives and The Netherlands, and the Confederation Bridge in Canada. Other examples include prevention of glacial lake outburst flooding in Nepal, and policies and strategies such as water management in Australia and government responses to heat-waves in, for example, some European countries [7.6, 8.2, 8.6, 17.ES, 17.2, 16.5, 11.5].

Adaptation will be necessary to address impacts resulting from the warming which is already unavoidable due to past emissions.

Past emissions are estimated to involve some unavoidable warming (about a further 0.6°C by the end of the century relative to 1980-1999) even if atmospheric greenhouse gas concentrations remain at 2000 levels (see Working Group I Fourth Assessment). There are some impacts for which adaptation is the only available and appropriate response. An indication of these impacts can be seen in Figure SPM.2.

A wide array of adaptation options is available, but more extensive adaptation than is currently occurring is required to reduce vulnerability to future climate change. There are barriers, limits and costs, but these are not fully understood.

Impacts are expected to increase with increases in global average temperature, as indicated in Figure SPM.2. Although many early impacts of climate change can be effectively addressed through adaptation, the options for successful adaptation diminish and the associated costs increase with increasing climate change. At present we do not have a clear picture of the limits to adaptation, or the cost, partly because effective adaptation measures are highly dependent on specific, geographical and climate risk factors as well as institutional, political and financial constraints [7.6, 17.2, 17.4].

The array of potential adaptive responses available to human societies is very large, ranging from purely technological (e.g., sea defences), through behavioural (e.g., altered food and recreational choices), to managerial (e.g., altered farm practices) and to policy (e.g., planning regulations). While most technologies and strategies are known and developed in some countries, the assessed literature does not indicate how effective various options[13] are at fully reducing risks, particularly at higher levels of warming and related impacts, and for vulnerable groups. In addition, there are formidable environmental, economic, informational, social, attitudinal and behavioural barriers to the implementation of adaptation. For developing countries, availability of resources and building adaptive capacity are particularly important [see Sections 5 and 6 in Chapters 3-16; also 17.2, 17.4].

Adaptation alone is not expected to cope with all the projected effects of climate change, and especially not over the long term as most impacts increase in magnitude [Figure SPM.2].

Vulnerability to climate change can be exacerbated by the presence of other stresses.

Non-climate stresses can increase vulnerability to climate change by reducing resilience and can also reduce adaptive capacity because of resource deployment to competing needs. For example, current stresses on some coral reefs include marine pollution and chemical runoff from agriculture as well as increases in water temperature and ocean acidification. Vulnerable regions face multiple stresses that affect their exposure and sensitivity as well as their capacity to adapt. These stresses arise from, for example, current climate hazards, poverty and unequal access to resources, food insecurity, trends in economic globalisation, conflict, and incidence of diseases such as HIV/AIDS [7.4, 8.3, 17.3, 20.3]. Adaptation measures are seldom undertaken in response to climate change alone but can be integrated within, for example, water resource management, coastal defence and risk-reduction strategies [17.2, 17.5].

Future vulnerability depends not only on climate change but also on development pathway.

An important advance since the IPCC Third Assessment has been the completion of impacts studies for a range of different development pathways taking into account not only projected climate change but also projected social and economic changes. Most have been based on characterisations of population and income level drawn from the IPCC Special Report on Emission Scenarios (SRES) (see Endbox 3) [2.4].

[13] A table of options is given in the Technical Summary

These studies show that the projected impacts of climate change can vary greatly due to the development pathway assumed. For example, there may be large differences in regional population, income and technological development under alternative scenarios, which are often a strong determinant of the level of vulnerability to climate change [2.4].

To illustrate, in a number of recent studies of global impacts of climate change on food supply, risk of coastal flooding and water scarcity, the projected number of people affected is considerably greater under the A2-type scenario of development (characterised by relatively low per capita income and large population growth) than under other SRES futures [T20.6]. This difference is largely explained, not by differences in changes of climate, but by differences in vulnerability [T6.6].

Sustainable development[14] can reduce vulnerability to climate change, and climate change could impede nations' abilities to achieve sustainable development pathways.

Sustainable development can reduce vulnerability to climate change by enhancing adaptive capacity and increasing resilience. At present, however, few plans for promoting sustainability have explicitly included either adapting to climate change impacts, or promoting adaptive capacity [20.3].

On the other hand, it is very likely that climate change can slow the pace of progress towards sustainable development, either directly through increased exposure to adverse impact or indirectly through erosion of the capacity to adapt. This point is clearly demonstrated in the sections of the sectoral and regional chapters of this report that discuss the implications for sustainable development [See Section 7 in Chapters 3-8, 20.3, 20.7].

The Millennium Development Goals (MDGs) are one measure of progress towards sustainable development. Over the next half-century, climate change could impede achievement of the MDGs [20.7].

Many impacts can be avoided, reduced or delayed by mitigation.

A small number of impact assessments have now been completed for scenarios in which future atmospheric concentrations of greenhouse gases are stabilised. Although these studies do not take full account of uncertainties in projected climate under stabilisation, they nevertheless provide indications of damages avoided or vulnerabilities and risks reduced for different amounts of emissions reduction [2.4, T20.6].

A portfolio of adaptation and mitigation measures can diminish the risks associated with climate change.

Even the most stringent mitigation efforts cannot avoid further impacts of climate change in the next few decades, which makes adaptation essential, particularly in addressing near-term impacts. Unmitigated climate change would, in the long term, be likely to exceed the capacity of natural, managed and human systems to adapt [20.7].

This suggests the value of a portfolio or mix of strategies that includes mitigation, adaptation, technological development (to enhance both adaptation and mitigation) and research (on climate science, impacts, adaptation and mitigation). Such portfolios could combine policies with incentive-based approaches, and actions at all levels from the individual citizen through to national governments and international organisations [18.1, 18.5].

One way of increasing adaptive capacity is by introducing the consideration of climate change impacts in development planning [18.7], for example, by:

- including adaptation measures in land-use planning and infrastructure design [17.2];
- including measures to reduce vulnerability in existing disaster risk reduction strategies [17.2, 20.8].

E. Systematic observing and research

Although the science to provide policymakers with information about climate change impacts and adaptation potential has improved since the Third Assessment, it still leaves many important questions to be answered. The chapters of the Working Group II Fourth Assessment include a number of judgements about priorities for further observation and research, and this advice should be considered seriously (a list of these recommendations is given in the Technical Summary Section TS-6).

[14] The Brundtland Commission definition of sustainable development is used in this Assessment: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". The same definition was used by the IPCC Working Group II Third Assessment and Third Assessment Synthesis Report.

Endbox 1. Definitions of key terms

Climate change in IPCC usage refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the Framework Convention on Climate Change, where climate change refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods.

Adaptive capacity is the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.

Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.

Endbox 2. Communication of Uncertainty in the Working Group II Fourth Assessment

A set of terms to describe uncertainties in current knowledge is common to all parts of the IPCC Fourth Assessment.

Description of confidence
Authors have assigned a confidence level to the major statements in the Summary for Policymakers on the basis of their assessment of current knowledge, as follows:

Terminology	*Degree of confidence in being correct*
Very high confidence	At least 9 out of 10 chance of being correct
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than a 1 out of 10 chance

Description of likelihood
Likelihood refers to a probabilistic assessment of some well-defined outcome having occurred or occurring in the future, and may be based on quantitative analysis or an elicitation of expert views. In the Summary for Policymakers, when authors evaluate the likelihood of certain outcomes, the associated meanings are:

Terminology	*Likelihood of the occurrence/ outcome*
Virtually certain	>99% probability of occurrence
Very likely	90 to 99% probability
Likely	66 to 90% probability
About as likely as not	33 to 66% probability
Unlikely	10 to 33% probability
Very unlikely	1 to 10% probability
Exceptionally unlikely	<1% probability

Endbox 3. The Emissions Scenarios of the IPCC Special Report on Emissions Scenarios (SRES)

A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

A2. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

B1. The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

An illustrative scenario was chosen for each of the six scenario groups A1B, A1FI, A1T, A2, B1 and B2. All should be considered equally sound.

The SRES scenarios do not include additional climate initiatives, which means that no scenarios are included that explicitly assume implementation of the United Nations Framework Convention on Climate Change or the emissions targets of the Kyoto Protocol.

Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change

Summary for Policymakers

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Table of Contents

A. Introduction

1. The Working Group III contribution to the IPCC Fourth Assessment Report (AR4) focuses on new literature on the scientific, technological, environmental, economic and social aspects of mitigation of climate change, published since the IPCC Third Assessment Report (TAR) and the Special Reports on CO_2 Capture and Storage (SRCCS) and on Safeguarding the Ozone Layer and the Global Climate System (SROC).

The following summary is organised into six sections after this introduction:

- Greenhouse gas (GHG) emission trends
- Mitigation in the short and medium term, across different economic sectors (until 2030)
- Mitigation in the long-term (beyond 2030)
- Policies, measures and instruments to mitigate climate change
- Sustainable development and climate change mitigation
- Gaps in knowledge.

References to the corresponding chapter sections are indicated at each paragraph in square brackets. An explanation of terms, acronyms and chemical symbols used in this SPM can be found in the glossary to the main report.

B. Greenhouse gas emission trends

2. Global greenhouse gas (GHG) emissions have grown since pre-industrial times, with an increase of 70% between 1970 and 2004 *(high agreement, much evidence)*[1].

- Since pre-industrial times, increasing emissions of GHGs due to human activities have led to a marked increase in atmospheric GHG concentrations [1.3; Working Group I SPM].
- Between 1970 and 2004, global emissions of CO_2, CH_4, N_2O, HFCs, PFCs and SF_6, weighted by their global warming potential (GWP), have increased by 70% (24% between 1990 and 2004), from 28.7 to 49 Gigatonnes of carbon dioxide equivalents ($GtCO_2$-eq)[2] (see Figure SPM.1). The emissions of these gases have increased at different rates. CO_2 emissions have grown between 1970 and 2004 by about 80% (28% between 1990 and 2004) and represented 77% of total anthropogenic GHG emissions in 2004.
- The largest growth in global GHG emissions between 1970 and 2004 has come from the energy supply sector (an increase of 145%). The growth in direct emissions[3] from transport in this period was 120%, industry 65% and land use, land use change, and forestry (LULUCF)[4] 40%[5]. Between 1970 and 1990 direct emissions from agriculture grew by 27% and from buildings by 26%, and the latter remained at approximately at 1990 levels thereafter. However, the buildings sector has a high level of electricity use and hence the total of direct and indirect emissions in this sector is much higher (75%) than direct emissions [1.3, 6.1, 11.3, Figures 1.1 and 1.3].
- The effect on global emissions of the decrease in global energy intensity (-33%) during 1970 to 2004 has been smaller than the combined effect of global per capita income growth (77 %) and global population growth (69%); both drivers of increasing energy-related CO_2 emissions (Figure SPM.2). The long-term trend of a declining carbon intensity of energy supply reversed after 2000. Differences in terms of per capita income, per capita emissions, and energy intensity among countries remain significant. (Figure SPM.3). In 2004 UNFCCC Annex I countries held a 20% share in world population, produced 57% of world Gross Domestic Product based on Purchasing Power Parity (GDP_{ppp})[6], and accounted for 46% of global GHG emissions (Figure SPM.3) [1.3].
- The emissions of ozone depleting substances (ODS) controlled under the Montreal Protocol[7], which are also GHGs, have declined significantly since the 1990s. By 2004 the emissions of these gases were about 20% of their 1990 level [1.3].
- A range of policies, including those on climate change, energy security[8], and sustainable development, have been effective in reducing GHG emissions in different sectors and many countries. The scale of such measures, however, has not yet been large enough to counteract the global growth in emissions [1.3, 12.2].

1 Each headline statement has an "agreement/evidence" assessment attached that is supported by the bullets underneath. This does not necessarily mean that this level of "agreement/evidence"applies to each bullet. Endbox 1 provides an explanation of this representation of uncertainty.
2 The definition of carbon dioxide equivalent (CO_2-eq) is the amount of CO2 emission that would cause the same radiative forcing as an emitted amount of a well mixed greenhouse gas or a mixture of well mixed greenhouse gases, all multiplied with their respective GWPs to take into account the differing times they remain in the atmosphere [WGI AR4 Glossary].
3 Direct emissions in each sector do not include emissions from the electricity sector for the electricity consumed in the building, industry and agricultural sectors or of the emissions from refinery operations supplying fuel to the transport sector.
4 The term "land use, land use change and forestry" is used here to describe the aggregated emissions of CO_2, CH_4, N_2O from deforestation, biomass and burning, decay of biomass from logging and deforestation, decay of peat and peat fires [1.3.1]. This is broader than emissions from deforestation, which is included as a subset. The emissions reported here do not include carbon uptake (removals).
5 This trend is for the total LULUCF emissions, of which emissions from deforestation are a subset and, owing to large data uncertainties, is significantly less certain than for other sectors. The rate of deforestation globally was slightly lower in the 2000-2005 period than in the 1990-2000 period [9.2.1].
6 The GDPppp metric is used for illustrative purposes only for this report. For an explanation of PPP and Market Exchange Rate (MER) GDP calculations, see footnote 12.
7 Halons, chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), methyl chloroform (CH_3CCl_3), carbon tetrachloride (CCl_4) and methyl bromide (CH_3Br).
8 Energy security refers to security of energy supply.

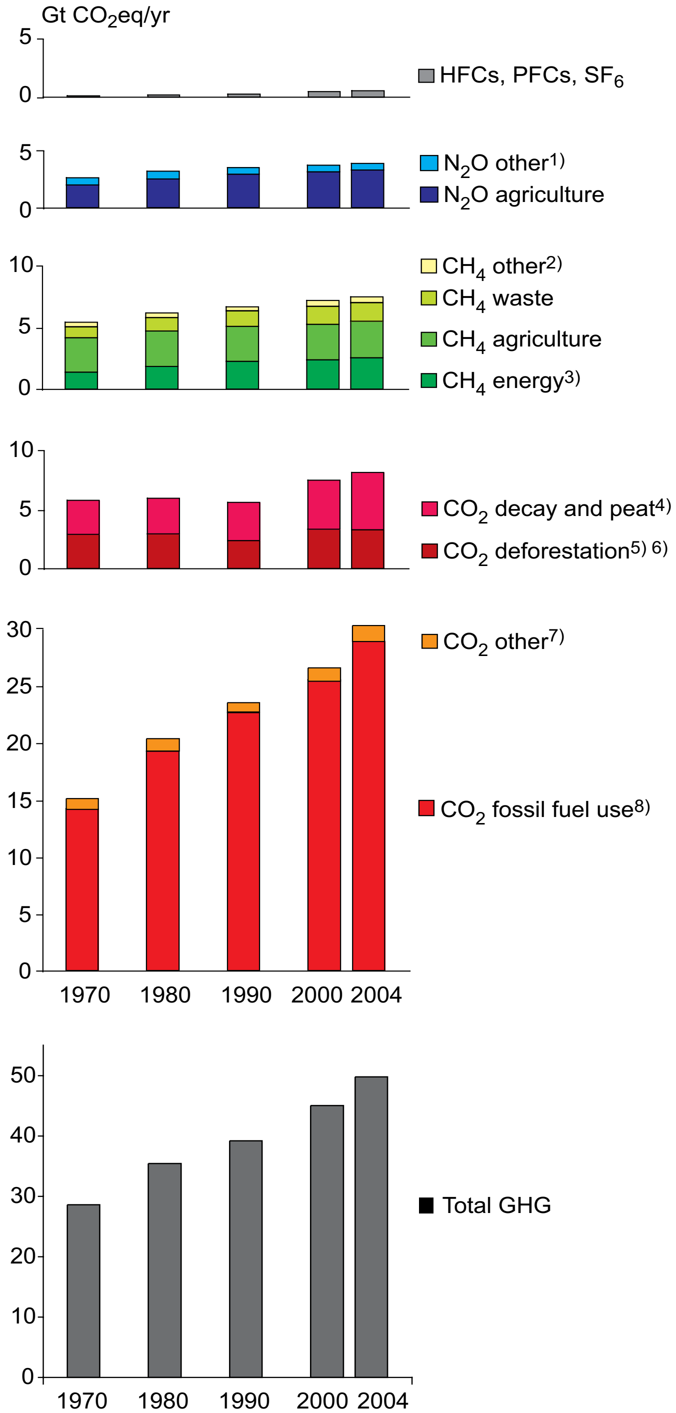


Figure SPM.1: *Global Warming Potential (GWP) weighted global greenhouse gas emissions 1970-2004. 100 year GWPs from IPCC 1996 (SAR) were used to convert emissions to CO_2-eq. (cf. UNFCCC reporting guidelines). CO_2, CH_4, N_2O, HFCs, PFCs and SF_6 from all sources are included.*
The two CO_2 emission categories reflect CO_2 emissions from energy production and use (second from bottom) and from land use changes (third from the bottom) [Figure 1.1a].

Notes:
1. Other N_2O includes industrial processes, deforestation/savannah burning, waste water and waste incineration.
2. Other is CH_4 from industrial processes and savannah burning.
3. Including emissions from bioenergy production and use
4. CO_2 emissions from decay (decomposition) of above ground biomass that remains after logging and deforestation and CO_2 from peat fires and decay of drained peat soils.
5. As well as traditional biomass use at 10% of total, assuming 90% is from sustainable biomass production. Corrected for 10% carbon of biomass that is assumed to remain as charcoal after combustion.
6. For large-scale forest and scrubland biomass burning averaged data for 1997-2002 based on Global Fire Emissions Data base satellite data.
7. Cement production and natural gas flaring.
8. Fossil fuel use includes emissions from feedstocks.

3. **With current climate change mitigation policies and related sustainable development practices, global GHG emissions will continue to grow over the next few decades** *(high agreement, much evidence).*
   - The SRES (non-mitigation) scenarios project an increase of baseline global GHG emissions by a range of 9.7 $GtCO_2$-eq to 36.7 $GtCO_2$-eq (25-90%) between 2000 and 2030[9] (Box SPM.1 and Figure SPM.4). In these scenarios, fossil fuels are projected to maintain their dominant position in the global energy mix to 2030 and beyond. Hence CO_2 emissions between 2000 and 2030 from energy use are projected to grow 40 to 110% over that period. Two thirds to three quarters of this increase in energy CO_2 emissions is projected to come from non-Annex I regions, with their average per capita energy CO_2 emissions being projected to remain substantially lower (2.8-5.1 tCO_2/cap) than those in Annex I regions (9.6-15.1 tCO_2/cap) by 2030. According to SRES scenarios, their economies are projected to have a lower energy use per unit of GDP (6.2 – 9.9 MJ/US\$ GDP) than that of non-Annex I countries (11.0 – 21.6 MJ/US\$ GDP). [1.3, 3.2]

9 The SRES 2000 GHG emissions assumed here are 39.8 GtCO2-eq, i.e. lower than the emissions reported in the EDGAR database for 2000 (45 GtCO2-eq). This is mostly due to differences in LULUCF emissions.

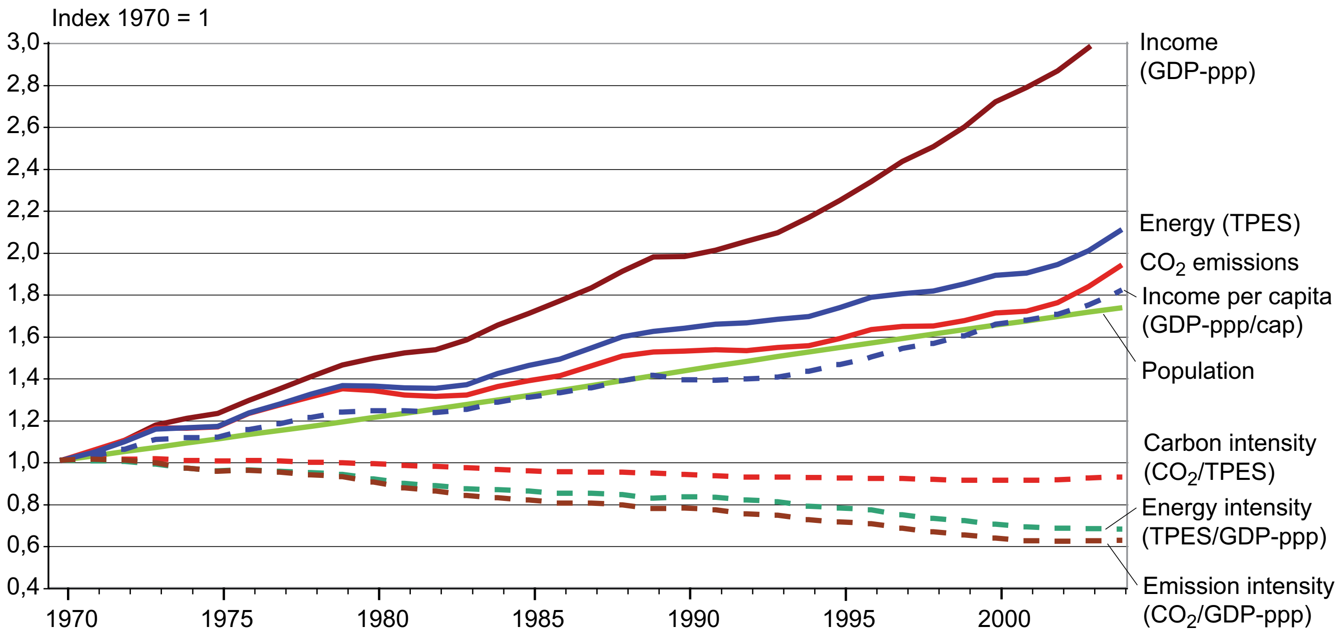


Figure SPM.2: *Relative global development of Gross Domestic Product measured in PPP (GDP_{ppp}), Total Primary Energy Supply (TPES), CO_2 emissions (from fossil fuel burning, gas flaring and cement manufacturing) and Population (Pop). In addition, in dotted lines, the figure shows Income per capita (GDP_{ppp}/Pop), Energy Intensity (TPES/GDP_{ppp}), Carbon Intensity of energy supply (CO_2/TPES), and Emission Intensity of the economic production process (CO_2/GDP_{ppp}) for the period 1970-2004. [Figure 1.5]*

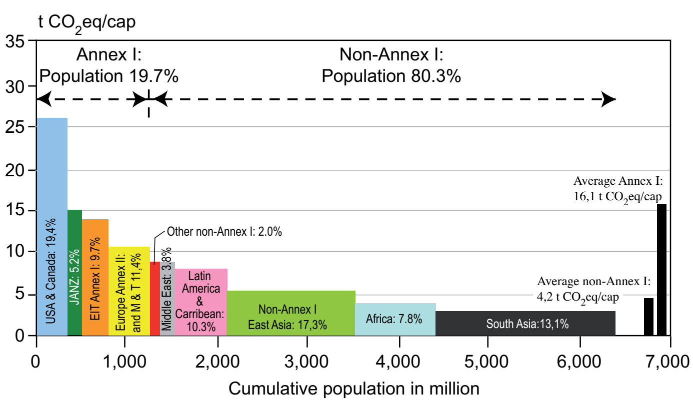


Figure SPM.3a: *Year 2004 distribution of regional per capita GHG emissions (all Kyoto gases, including those from land-use) over the population of different country groupings. The percentages in the bars indicate a regions share in global GHG emissions [Figure 1.4a].*

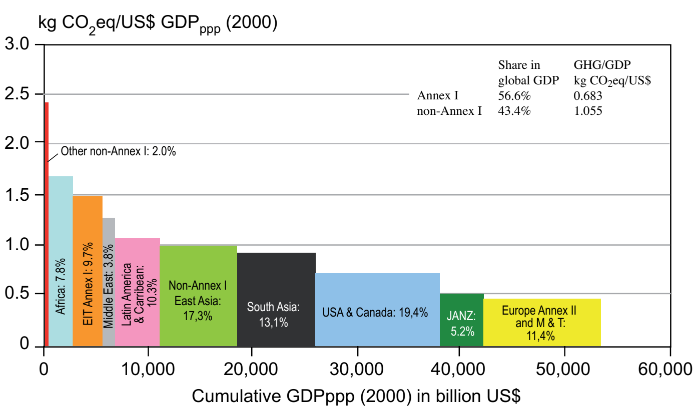


Figure SPM.3b: *Year 2004 distribution of regional GHG emissions (all Kyoto gases, including those from land-use) per US$ of GDP_{ppp} over the GDP_{ppp} of different country groupings. The percentages in the bars indicate a regions share in global GHG emissions [Figure 1.4b].*

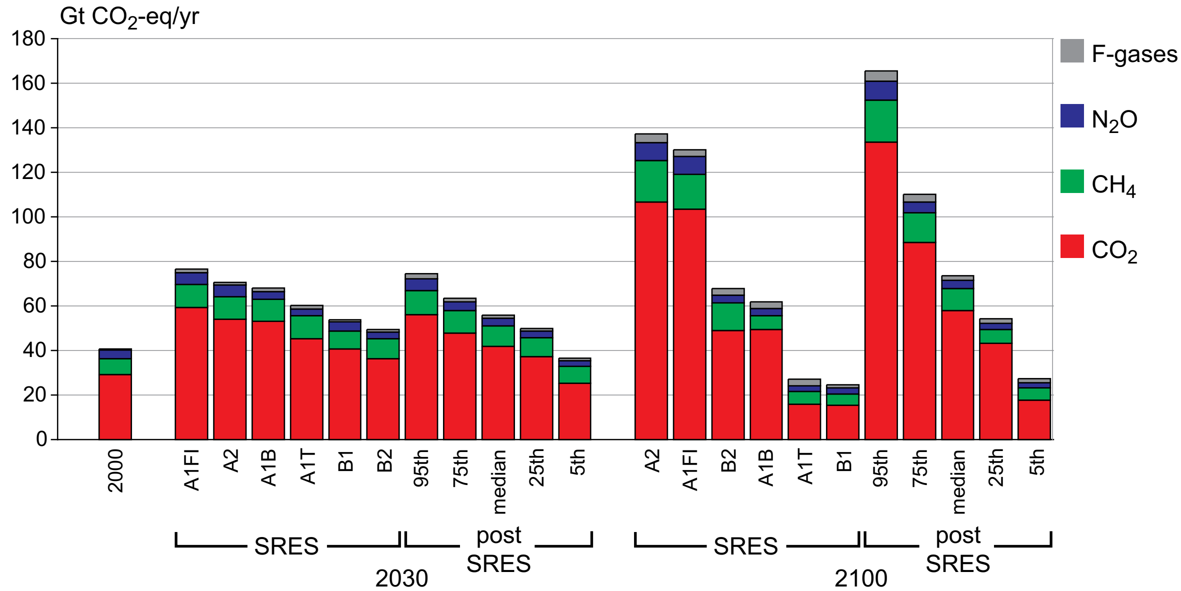


Figure SPM.4: *Global GHG emissions for 2000 and projected baseline emissions[10] for 2030 and 2100 from IPCC SRES and the post-SRES literature. The figure provides the emissions from the six illustrative SRES scenarios. It also provides the frequency distribution of the emissions in the post-SRES scenarios (5th, 25th, median, 75th, 95th percentile), as covered in Chapter 3. F-gases cover HFCs, PFCs and SF_6 [1.3, 3.2, Figure 1.7].*

4. **Baseline emissions scenarios published since SRES[10], are comparable in range to those presented in the IPCC Special Report on Emission Scenarios (SRES) (25- 135 $GtCO_2$-eq/yr in 2100, see Figure SPM.4)** *(high agreement, much evidence)*.
   - Studies since SRES used lower values for some drivers for emissions, notably population projections. However, for those studies incorporating these new population projections, changes in other drivers, such as economic growth, resulted in little change in overall emission levels. Economic growth projections for Africa, Latin America and the Middle East to 2030 in post-SRES baseline scenarios are lower than in SRES, but this has only minor effects on global economic growth and overall emissions [3.2].
   - Representation of aerosol and aerosol precursor emissions, including sulphur dioxide, black carbon, and organic carbon, which have a net cooling effect[11] has improved. Generally, they are projected to be lower than reported in SRES [3.2].
   - Available studies indicate that the choice of exchange rate for GDP (MER or PPP) does not appreciably affect the projected emissions, when used consistently[12]. The differences, if any, are small compared to the uncertainties caused by assumptions on other parameters in the scenarios, e.g. technological change [3.2].

10 Baseline scenarios do not include additional climate policy above current ones; more recent studies differ with respect to UNFCCC and Kyoto Protocol inclusion.
11 See AR4 WG I report, Chapter 10.2.
12 Since TAR, there has been a debate on the use of different exchange rates in emission scenarios. Two metrics are used to compare GDP between countries. Use of MER is preferable for analyses involving internationally traded products. Use of PPP, is preferable for analyses involving comparisons of income between countries at very different stages of development. Most of the monetary units in this report are expressed in MER. This reflects the large majority of emissions mitigation literature that is calibrated in MER. When monetary units are expressed in PPP, this is denoted by GDP_{ppp}.

Box SPM.1: The emission scenarios of the IPCC Special Report on Emission Scenarios (SRES)

A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

A2. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

B1. The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

An illustrative scenario was chosen for each of the six scenario groups A1B, A1FI, A1T, A2, B1 and B2. All should be considered equally sound.

The SRES scenarios do not include additional climate initiatives, which means that no scenarios are included that explicitly assume implementation of the United Nations Framework Convention on Climate Change or the emissions targets of the Kyoto Protocol.

This box summarizing the SRES scenarios is taken from the Third Assessment Report and has been subject to prior line by line approval by the Panel.

Box SPM.2: Mitigation potential and analytical approaches

The concept of "mitigation potential" has been developed to assess the scale of GHG reductions that could be made, relative to emission baselines, for a given level of carbon price (expressed in cost per unit of carbon dioxide equivalent emissions avoided or reduced). Mitigation potential is further differentiated in terms of "market potential" and "economic potential".

Market potential is the mitigation potential based on private costs and private discount rates[13], which might be expected to occur under forecast market conditions, including policies and measures currently in place, noting that barriers limit actual uptake [2.4].

13 Private costs and discount rates reflect the perspective of private consumers and companies; see Glossary for a fuller description.

(Box SPM.2 Continued)

Economic potential is the mitigation potential, which takes into account social costs and benefits and social discount rates[14], assuming that market efficiency is improved by policies and measures and barriers are removed [2.4].

Studies of market potential can be used to inform policy makers about mitigation potential with existing policies and barriers, while studies of economic potentials show what might be achieved if appropriate new and additional policies were put into place to remove barriers and include social costs and benefits. The economic potential is therefore generally greater than the market potential.

Mitigation potential is estimated using different types of approaches. There are two broad classes – "bottom-up" and "top-down" approaches, which primarily have been used to assess the economic potential.

Bottom-up studies are based on assessment of mitigation options, emphasizing specific technologies and regulations. They are typically sectoral studies taking the macro-economy as unchanged. Sector estimates have been aggregated, as in the TAR, to provide an estimate of global mitigation potential for this assessment.

Top-down studies assess the economy-wide potential of mitigation options. They use globally consistent frameworks and aggregated information about mitigation options and capture macro-economic and market feedbacks.

Bottom-up and top-down models have become more similar since the TAR as top-down models have incorporated more technological mitigation options and bottom-up models have incorporated more macroeconomic and market feedbacks as well as adopting barrier analysis into their model structures. Bottom-up studies in particular are useful for the assessment of specific policy options at sectoral level, e.g. options for improving energy efficiency, while top-down studies are useful for assessing cross-sectoral and economy-wide climate change policies, such as carbon taxes and stabilization policies. However, current bottom-up and top-down studies of economic potential have limitations in considering life-style choices, and in including all externalities such as local air pollution. They have limited representation of some regions, countries, sectors, gases, and barriers. The projected mitigation costs do not take into account potential benefits of avoided climate change.

Box SPM.3: Assumptions in studies on mitigation portfolios and macro-economic costs

Studies on mitigation portfolios and macro-economic costs assessed in this report are based on top-down modelling. Most models use a global least cost approach to mitigation portfolios and with universal emissions trading, assuming transparent markets, no transaction cost, and thus perfect implementation of mitigation measures throughout the 21st century. Costs are given for a specific point in time.

Global modelled costs will increase if some regions, sectors (e.g. land-use), options or gases are excluded. Global modelled costs will decrease with lower baselines, use of revenues from carbon taxes and auctioned permits, and if induced technological learning is included. These models do not consider climate benefits and generally also co-benefits of mitigation measures, or equity issues.

Box SPM.4: Modelling induced technological change

Relevant literature implies that policies and measures may induce technological change. Remarkable progress has been achieved in applying approaches based on induced technological change to stabilisation studies; however, conceptual issues remain. In the models that adopt these approaches, projected costs for a given stabilization level are reduced; the reductions are greater at lower stabilisation levels.

14 Social costs and discount rates reflect the perspective of society. Social discount rates are lower than those used by private investors; see Glossary for a fuller description.

C. Mitigation in the short and medium term (until 2030)

5. **Both bottom-up and top-down studies indicate that there is substantial economic potential for the mitigation of global GHG emissions over the coming decades, that could offset the projected growth of global emissions or reduce emissions below current levels** *(high agreement, much evidence).*

Uncertainties in the estimates are shown as ranges in the tables below to reflect the ranges of baselines, rates of technological change and other factors that are specific to the different approaches. Furthermore, uncertainties also arise from the limited information for global coverage of countries, sectors and gases.

Bottom-up studies:

- In 2030, the economic potential estimated for this assessment from bottom-up approaches (see Box SPM.2) is presented in Table SPM.1 below and Figure SPM.5A. For reference: emissions in 2000 were equal to 43 $GtCO_2$-eq. [11.3]:
- Studies suggest that mitigation opportunities with net negative costs[15] have the potential to reduce emissions by around 6 $GtCO_2$-eq/yr in 2030. Realizing these requires dealing with implementation barriers [11.3].
- No one sector or technology can address the entire mitigation challenge. All assessed sectors contribute to the total (see Figure SPM.6). The key mitigation technologies and practices for the respective sectors are shown in Table SPM 3 [4.3, 4.4, 5.4, 6.5, 7.5, 8.4, 9.4, 10.4].

Top-down studies:

- Top-down studies calculate an emission reduction for 2030 as presented in Table SPM.2 below and Figure SPM.5B. The global economic potentials found in the top-down studies are in line with bottom-up studies (see Box SPM.2), though there are considerable differences at the sectoral level [3.6].
- The estimates in Table SPM.2 were derived from stabilization scenarios, i.e., runs towards long-run stabilization of atmospheric GHG concentration [3.6].

Table SPM.1: *Global economic mitigation potential in 2030 estimated from bottom-up studies.*

Carbon price ($US\$/tCO_2$-eq)	**Economic potential** ($GtCO_2$-eq/yr)	**Reduction relative to SRES A1 B** (68 $GtCO_2$-eq/yr) (%)	**Reduction relative to SRES B2** (49 $GtCO_2$-eq/yr) (%)
0	5-7	7-10	10-14
20	9-17	14-25	19-35
50	13-26	20-38	27-52
100	16-31	23-46	32-63

Table SPM.2: *Global economic mitigation potential in 2030 estimated from top-down studies.*

Carbon price ($US\$/tCO_2$-eq)	**Economic potential** ($GtCO_2$-eq/yr)	**Reduction relative to SRES A1 B** (68 $GtCO_2$-eq/yr) (%)	**Reduction relative to SRES B2** (49 $GtCO_2$-eq/yr) (%)
20	9-18	13-27	18-37
50	14-23	21-34	29-47
100	17-26	25-38	35-53

15 In this report, as in the SAR and the TAR, options with net negative costs (no regrets opportunities) are defined as those options whose benefits such as reduced energy costs and reduced emissions of local/regional pollutants equal or exceed their costs to society, excluding the benefits of avoided climate change (see Box SPM.1).

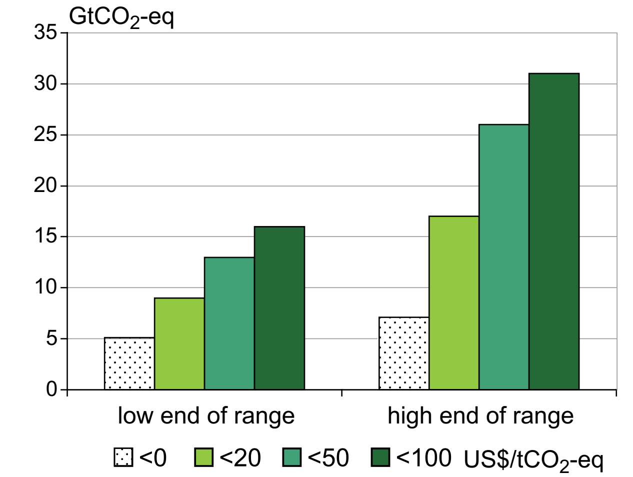


Figure SPM.5A: *Global economic mitigation potential in 2030 estimated from bottom-up studies (data from Table SPM.1)*

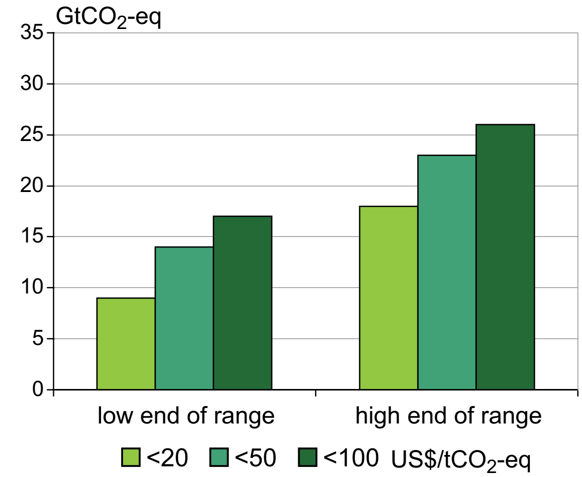
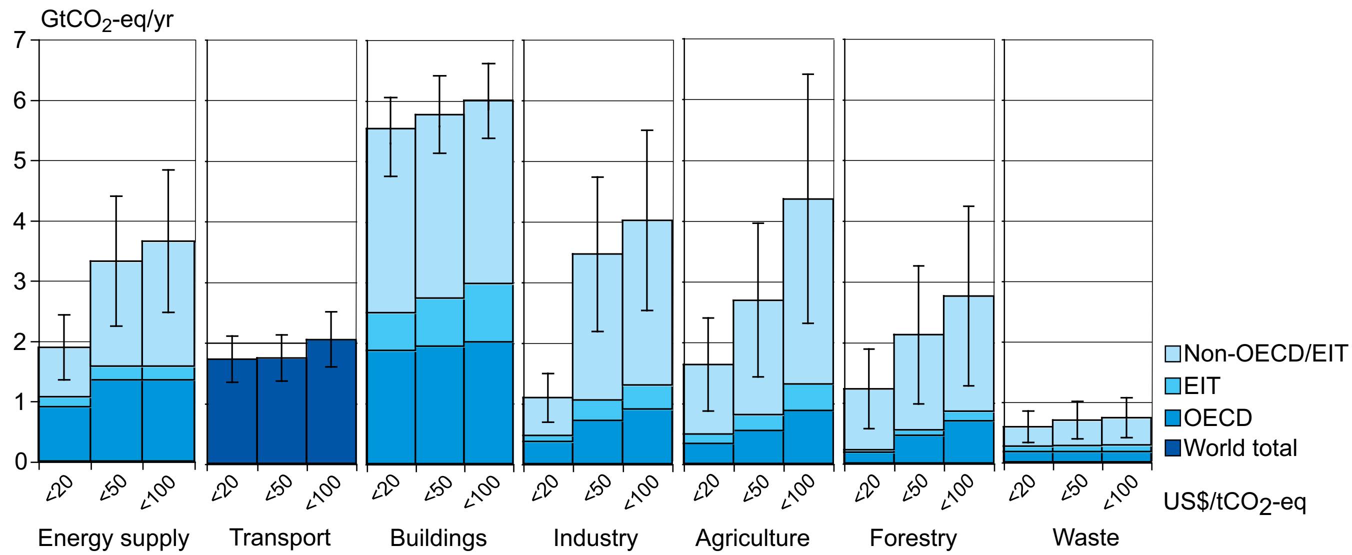


Figure SPM.5B: *Global economic mitigation potential in 2030 estimated from top-down studies (data from Table SPM.2)*

Table SPM.3: *Key mitigation technologies and practices by sector. Sectors and technologies are listed in no particular order. Non-technological practices, such as lifestyle changes, which are cross-cutting, are not included in this table (but are addressed in paragraph 7 in this SPM).*

Sector	**Key mitigation technologies and practices currently commercially available**	**Key mitigation technologies and practices projected to be commercialized before 2030**
Energy supply [4.3, 4.4]	Improved supply and distribution efficiency; fuel switching from coal to gas; nuclear power; renewable heat and power (hydropower, solar, wind, geothermal and bioenergy); combined heat and power; early applications of Carbon Capture and Storage (CCS, e.g. storage of removed CO_2 from natural gas).	CCS for gas, biomass and coal-fired electricity generating facilities; advanced nuclear power; advanced renewable energy, including tidal and waves energy, concentrating solar, and solar PV.
Transport [5.4]	More fuel efficient vehicles; hybrid vehicles; cleaner diesel vehicles; biofuels; modal shifts from road transport to rail and public transport systems; non-motorised transport (cycling, walking); land-use and transport planning.	Second generation biofuels; higher efficiency aircraft; advanced electric and hybrid vehicles with more powerful and reliable batteries.
Buildings [6.5]	Efficient lighting and daylighting; more efficient electrical appliances and heating and cooling devices; improved cook stoves, improved insulation ; passive and active solar design for heating and cooling; alternative refrigeration fluids, recovery and recycle of fluorinated gases.	Integrated design of commercial buildings including technologies, such as intelligent meters that provide feedback and control; solar PV integrated in buildings.
Industry [7.5]	More efficient end-use electrical equipment; heat and power recovery; material recycling and substitution; control of non-CO_2 gas emissions; and a wide array of process-specific technologies.	Advanced energy efficiency; CCS for cement, ammonia, and iron manufacture; inert electrodes for aluminium manufacture.
Agriculture [8.4]	Improved crop and grazing land management to increase soil carbon storage; restoration of cultivated peaty soils and degraded lands; improved rice cultivation techniques and livestock and manure management to reduce CH_4 emissions; improved nitrogen fertilizer application techniques to reduce N_2O emissions; dedicated energy crops to replace fossil fuel use; improved energy efficiency.	Improvements of crops yields.
Forestry/forests [9.4]	Afforestation; reforestation; forest management; reduced deforestation; harvested wood product management; use of forestry products for bioenergy to replace fossil fuel use.	Tree species improvement to increase biomass productivity and carbon sequestration. Improved remote sensing technologies for analysis of vegetation/ soil carbon sequestration potential and mapping land use change.
Waste management [10.4]	Landfill methane recovery; waste incineration with energy recovery; composting of organic waste; controlled waste water treatment; recycling and waste minimization.	Biocovers and biofilters to optimize CH_4 oxidation.



Energy supply	Transport	Buildings	Industry	Agriculture	Forestry	Waste
(potential at <US$100/ tCO_2-eq: 2.4 - 4.7 Gt CO_2-eq/yr)	*(potential at <US$100/ tCO_2-eq: 1.6 - 2.5 Gt CO_2-eq/yr)*	*(potential at <US$100/ tCO_2-eq: 5.3 -6.7 Gt CO_2-eq/yr)*	*(potential at <US$100/ tCO_2-eq: 2.5 - 5.5 Gt CO_2-eq/yr)*	*(potential at <US$100/ tCO_2-eq: 2.3 -6.4 Gt CO_2-eq/yr)*	*(potential at <US$100/ tCO_2-eq: 1.3 - 4.2 Gt CO_2-eq/yr)*	*(potential at <US$100/ tCO_2-eq: 0.4 - 1 Gt CO_2-eq/yr)*

Figure SPM.6: *Estimated sectoral economic potential for global mitigation for different regions as a function of carbon price in 2030 from bottom-up studies, compared to the respective baselines assumed in the sector assessments. A full explanation of the derivation of this figure is found in Section 11.3.*

Notes:

1. The ranges for global economic potentials as assessed in each sector are shown by vertical lines. The ranges are based on end-use allocations of emissions, meaning that emissions of electricity use are counted towards the end-use sectors and not to the energy supply sector.
2. The estimated potentials have been constrained by the availability of studies particularly at high carbon price levels.
3. Sectors used different baselines. For industry the SRES B2 baseline was taken, for energy supply and transport the WEO 2004 baseline was used; the building sector is based on a baseline in between SRES B2 and A1B; for waste, SRES A1B driving forces were used to construct a waste specific baseline, agriculture and forestry used baselines that mostly used B2 driving forces.
4. Only global totals for transport are shown because international aviation is included [5.4].
5. Categories excluded are: non-CO_2 emissions in buildings and transport, part of material efficiency options, heat production and cogeneration in energy supply, heavy duty vehicles, shipping and high-occupancy passenger transport, most high-cost options for buildings, wastewater treatment, emission reduction from coal mines and gas pipelines, fluorinated gases from energy supply and transport. The underestimation of the total economic potential from these emissions is of the order of 10-15%.

6. **In 2030 macro-economic costs for multi-gas mitigation, consistent with emissions trajectories towards stabilization between 445 and 710 ppm CO_2-eq, are estimated at between a 3% decrease of global GDP and a small increase, compared to the baseline (see Table SPM.4). However, regional costs may differ significantly from global averages** (*high agreement, medium evidence)* **(see Box SPM.3 for the methodologies and assumptions of these results).**
    - The majority of studies conclude that reduction of GDP relative to the GDP baseline increases with the stringency of the stabilization target.
    - Depending on the existing tax system and spending of the revenues, modelling studies indicate that costs may be substantially lower under the assumption that revenues from carbon taxes or auctioned permits under an emission trading system are used to promote low-carbon technologies or reform of existing taxes [11.4].
    - Studies that assume the possibility that climate change policy induces enhanced technological change also give lower costs. However, this may require higher upfront investment in order to achieve costs reductions thereafter (see Box SPM.4) [3.3, 3.4, 11.4, 11.5, 11.6].
    - Although most models show GDP losses, some show GDP gains because they assume that baselines are non-optimal and mitigation policies improve market efficiencies, or they assume that more technological change may be induced by mitigation policies. Examples of market inefficiencies include unemployed resources, distortionary taxes and/or subsidies [3.3, 11.4].
    - A multi-gas approach and inclusion of carbon sinks generally reduces costs substantially compared to CO_2 emission abatement only [3.3].
    - Regional costs are largely dependent on the assumed stabilization level and baseline scenario. The allocation regime is also important, but for most countries to a lesser extent than the stabilization level [11.4, 13.3].

Table SPM.4: *Estimated global macro-economic costs in 2030[a] for least-cost trajectories towards different long-term stabilization levels.[b), c)]*

Stabilization levels (ppm CO_2-eq)	**Median GDP reduction[d)]** (%)	**Range of GDP reduction[d), e)]** (%)	**Reduction of average annual GDP growth rates[d), f)]** (percentage points)
590-710	0.2	-0.6-1.2	<0.06
535-590	0.6	0.2-2.5	<0.1
445-535[g)]	not available	<3	<0.12

Notes:
a) For a given stabilization level, GDP reduction would increase over time in most models after 2030. Long-term costs also become more uncertain. [Figure 3.25]
b) Results based on studies using various baselines.
c) Studies vary in terms of the point in time stabilization is achieved; generally this is in 2100 or later.
d) This is global GDP based market exchange rates.
e) The median and the 10th and 90th percentile range of the analyzed data are given.
f) The calculation of the reduction of the annual growth rate is based on the average reduction during the period till 2030 that would result in the indicated GDP decrease in 2030.
g) The number of studies that report GDP results is relatively small and they generally use low baselines.

7. **Changes in lifestyle and behaviour patterns can contribute to climate change mitigation across all sectors. Management practices can also have a positive role** *(high agreement, medium evidence).*
   - Lifestyle changes can reduce GHG emissions. Changes in lifestyles and consumption patterns that emphasize resource conservation can contribute to developing a low-carbon economy that is both equitable and sustainable [4.1, 6.7].
   - Education and training programmes can help overcome barriers to the market acceptance of energy efficiency, particularly in combination with other measures [Table 6.6].
   - Changes in occupant behaviour, cultural patterns and consumer choice and use of technologies can result in considerable reduction in CO_2 emissions related to energy use in buildings [6.7].
   - Transport Demand Management, which includes urban planning (that can reduce the demand for travel) and provision of information and educational techniques (that can reduce car usage and lead to an efficient driving style) can support GHG mitigation [5.1].
   - In industry, management tools that include staff training, reward systems, regular feedback, documentation of existing practices can help overcome industrial organization barriers, reduce energy use, and GHG emissions [7.3].

8. **While studies use different methodologies, in all analyzed world regions near-term health co-benefits from reduced air pollution as a result of actions to reduce GHG emissions can be substantial and may offset a substantial fraction of mitigation costs** *(high agreement, much evidence).*
   - Including co-benefits other than health, such as increased energy security, and increased agricultural production and reduced pressure on natural ecosystems, due to decreased tropospheric ozone concentrations, would further enhance cost savings [11.8].
   - Integrating air pollution abatement and climate change mitigation policies offers potentially large cost reductions compared to treating those policies in isolation [11.8].

9. **Literature since TAR confirms that there may be effects from Annex I countries' action on the global economy and global emissions, although the scale of carbon leakage remains uncertain** *(high agreement, medium evidence).*
   - Fossil fuel exporting nations (in both Annex I and non-Annex I countries) may expect, as indicated in TAR[16], lower demand and prices and lower GDP growth due to mitigation policies. The extent of this spill over[17] depends strongly on assumptions related to policy decisions and oil market conditions [11.7].
   - Critical uncertainties remain in the assessment of carbon leakage[18]. Most equilibrium modelling support the conclusion in the TAR of economy-wide leakage from Kyoto action in the order of 5-20%, which would be less if competitive low-emissions technologies were effectively diffused [11.7] .

10. **New energy infrastructure investments in developing countries, upgrades of energy infrastructure in industrialized countries, and policies that promote energy security, can, in many cases, create opportunities to achieve GHG emission reductions[19] compared to baseline scenarios. Additional co-benefits are country-**

16 See TAR WG III (2001) SPM paragraph 16.
17 Spill over effects of mitigation in a cross-sectoral perspective are the effects of mitigation policies and measures in one country or group of countries on sectors in other countries.
18 Carbon leakage is defined as the increase in CO_2 emissions outside the countries taking domestic mitigation action divided by the reduction in the emissions of these countries.
19 See table SPM.1 and Figure SPM.6

specific but often include air pollution abatement, balance of trade improvement, provision of modern energy services to rural areas and employment *(high agreement, much evidence).*

- Future energy infrastructure investment decisions, expected to total over 20 trillion US$[20] between now and 2030, will have long term impacts on GHG emissions, because of the long life-times of energy plants and other infrastructure capital stock. The widespread diffusion of low-carbon technologies may take many decades, even if early investments in these technologies are made attractive. Initial estimates show that returning global energy-related CO_2 emissions to 2005 levels by 2030 would require a large shift in the pattern of investment, although the net additional investment required ranges from negligible to 5-10% [4.1, 4.4, 11.6].
- It is often more cost-effective to invest in end-use energy efficiency improvement than in increasing energy supply to satisfy demand for energy services. Efficiency improvement has a positive effect on energy security, local and regional air pollution abatement, and employment [4.2, 4.3, 6.5, 7.7, 11.3, 11.8].
- Renewable energy generally has a positive effect on energy security, employment and on air quality. Given costs relative to other supply options, renewable electricity, which accounted for 18% of the electricity supply in 2005, can have a 30-35% share of the total electricity supply in 2030 at carbon prices up to 50 US$/t$CO_2$-eq [4.3, 4.4, 11.3, 11.6, 11.8].
- The higher the market prices of fossil fuels, the more low-carbon alternatives will be competitive, although price volatility will be a disincentive for investors. Higher priced conventional oil resources, on the other hand, may be replaced by high carbon alternatives such as from oil sands, oil shales, heavy oils, and synthetic fuels from coal and gas, leading to increasing GHG emissions, unless production plants are equipped with CCS [4.2, 4.3, 4.4, 4.5].
- Given costs relative to other supply options, nuclear power, which accounted for 16% of the electricity supply in 2005, can have an 18% share of the total electricity supply in 2030 at carbon prices up to 50 US$/t$CO_2$-eq, but safety, weapons proliferation and waste remain as constraints [4.2, 4.3, 4.4][21].
- CCS in underground geological formations is a new technology with the potential to make an important contribution to mitigation by 2030. Technical, economic and regulatory developments will affect the actual contribution [4.3, 4.4, 7.3].

11. **There are multiple mitigation options in the transport sector[19], but their effect may be counteracted by growth in the sector. Mitigation options are faced with many barriers, such as consumer preferences and lack of policy frameworks** *(medium agreement, medium evidence).*
    - Improved vehicle efficiency measures, leading to fuel savings, in many cases have net benefits (at least for light-duty vehicles), but the market potential is much lower than the economic potential due to the influence of other consumer considerations, such as performance and size. There is not enough information to assess the mitigation potential for heavy-duty vehicles. Market forces alone, including rising fuel costs, are therefore not expected to lead to significant emission reductions [5.3, 5.4].
    - Biofuels might play an important role in addressing GHG emissions in the transport sector, depending on their production pathway. Biofuels used as gasoline and diesel fuel additives/substitutes are projected to grow to 3% of total transport energy demand in the baseline in 2030. This could increase to about 5-10%, depending on future oil and carbon prices, improvements in vehicle efficiency and the success of technologies to utilise cellulose biomass [5.3, 5.4].
    - Modal shifts from road to rail and to inland and coastal shipping and from low-occupancy to high-occupancy passenger transportation[22], as well as land-use, urban planning and non-motorized transport offer opportunities for GHG mitigation, depending on local conditions and policies [5.3, 5.5].
    - Medium term mitigation potential for CO_2 emissions from the aviation sector can come from improved fuel efficiency, which can be achieved through a variety of means, including technology, operations and air traffic management. However, such improvements are expected to only partially offset the growth of aviation emissions. Total mitigation potential in the sector would also need to account for non-CO_2 climate impacts of aviation emissions [5.3, 5.4].
    - Realizing emissions reductions in the transport sector is often a co-benefit of addressing traffic congestion, air quality and energy security [5.5].

12. **Energy efficiency options[19] for new and existing buildings could considerably reduce CO_2 emissions with net economic benefit. Many barriers exist against tapping this potential, but there are also large co-benefits** *(high agreement, much evidence).*
    - By 2030, about 30% of the projected GHG emissions in the building sector can be avoided with net economic benefit [6.4, 6.5].

20 20 trillion = 20000 billion= $20*10^{12}$.
21 Austria could not agree with this statement.
22 Including rail, road and marine mass transit and carpooling.

- Energy efficient buildings, while limiting the growth of CO_2 emissions, can also improve indoor and outdoor air quality, improve social welfare and enhance energy security [6.6, 6.7].
- Opportunities for realising GHG reductions in the building sector exist worldwide. However, multiple barriers make it difficult to realise this potential. These barriers include availability of technology, financing, poverty, higher costs of reliable information, limitations inherent in building designs and an appropriate portfolio of policies and programs [6.7, 6.8].
- The magnitude of the above barriers is higher in the developing countries and this makes it more difficult for them to achieve the GHG reduction potential of the building sector [6.7].

13. **The economic potential in the industrial sector[19] is predominantly located in energy intensive industries. Full use of available mitigation options is not being made in either industrialized or developing nations** (*high agreement, much evidence*).
    - Many industrial facilities in developing countries are new and include the latest technology with the lowest specific emissions. However, many older, inefficient facilities remain in both industrialized and developing countries. Upgrading these facilities can deliver significant emission reductions [7.1, 7.3, 7.4].
    - The slow rate of capital stock turnover, lack of financial and technical resources, and limitations in the ability of firms, particularly small and medium-sized enterprises, to access and absorb technological information are key barriers to full use of available mitigation options [7.6].

14. **Agricultural practices collectively can make a significant contribution at low cost[19] to increasing soil carbon sinks, to GHG emission reductions, and by contributing biomass feedstocks for energy use** *(medium agreement, medium evidence)***.**
    - A large proportion of the mitigation potential of agriculture (excluding bioenergy) arises from soil carbon sequestration, which has strong synergies with sustainable agriculture and generally reduces vulnerability to climate change [8.4, 8.5, 8.8].
    - Stored soil carbon may be vulnerable to loss through both land management change and climate change [8.10].
    - Considerable mitigation potential is also available from reductions in methane and nitrous oxide emissions in some agricultural systems [8.4, 8.5].
    - There is no universally applicable list of mitigation practices; practices need to be evaluated for individual agricultural systems and settings [8.4].
    - Biomass from agricultural residues and dedicated energy crops can be an important bioenergy feedstock, but its contribution to mitigation depends on demand for bioenergy from transport and energy supply, on water availability, and on requirements of land for food and fibre production. Widespread use of agricultural land for biomass production for energy may compete with other land uses and can have positive and negative environmental impacts and implications for food security [8.4, 8.8].

15. **Forest-related mitigation activities can considerably reduce emissions from sources and increase CO_2 removals by sinks at low costs[19], and can be designed to create synergies with adaptation and sustainable development** *(high agreement, much evidence)[23].*
    - About 65% of the total mitigation potential (up to 100 US\$/tCO_2-eq) is located in the tropics and about 50% of the total could be achieved by reducing emissions from deforestation [9.4].
    - Climate change can affect the mitigation potential of the forest sector (i.e., native and planted forests) and is expected to be different for different regions and sub-regions, both in magnitude and direction [9.5].
    - Forest-related mitigation options can be designed and implemented to be compatible with adaptation, and can have substantial co-benefits in terms of employment, income generation, biodiversity and watershed conservation, renewable energy supply and poverty alleviation [9.5, 9.6, 9.7].

16. **Post-consumer waste[24] is a small contributor to global GHG emissions[25] (<5%), but the waste sector can positively contribute to GHG mitigation at low cost[19] and promote sustainable development** *(high agreement, much evidence).*
    - Existing waste management practices can provide effective mitigation of GHG emissions from this sector: a wide range of mature, environmentally effective technologies are commercially available to mitigate emissions and provide co-benefits for improved public health and safety, soil protection and pollution prevention, and local energy supply [10.3, 10.4, 10.5].
    - Waste minimization and recycling provide important indirect mitigation benefits through the conservation of energy and materials [10.4].

23 Tuvalu noted difficulties with the reference to "low costs" as Chapter 9, page 15 of the WG III report states that: "the cost of forest mitigation projects rise significantly when opportunity costs of land are taken into account".
24 Industrial waste is covered in the industry sector.
25 GHGs from waste include landfill and wastewater methane, wastewater N_2O, and CO_2 from incineration of fossil carbon.

- Lack of local capital is a key constraint for waste and wastewater management in developing countries and countries with economies in transition. Lack of expertise on sustainable technology is also an important barrier [10.6].

17. **Geo-engineering options, such as ocean fertilization to remove CO_2 directly from the atmosphere, or blocking sunlight by bringing material into the upper atmosphere, remain largely speculative and unproven, and with the risk of unknown side-effects. Reliable cost estimates for these options have not been published** *(medium agreement, limited evidence)* [11.2].

D. Mitigation in the long term (after 2030)

18. **In order to stabilize the concentration of GHGs in the atmosphere, emissions would need to peak and decline thereafter. The lower the stabilization level, the more quickly this peak and decline would need to occur. Mitigation efforts over the next two to three decades will have a large impact on opportunities to achieve lower stabilization levels (see Table SPM.5, and Figure SPM. 8)[26]** (*high agreement, much evidence*).

- Recent studies using multi-gas reduction have explored lower stabilization levels than reported in TAR [3.3].
- Assessed studies contain a range of emissions profiles for achieving stabilization of GHG concentrations[27]. Most of these studies used a least cost approach and include both early and delayed emission reductions (Figure SPM.7) [Box SPM.2]. Table SPM.5 summarizes the required emissions levels for different groups of stabilization concentrations and the associated equilibrium global mean temperature increase[28], using the 'best estimate' of climate sensitivity (see also Figure SPM.8 for the likely range of uncertainty)[29]. Stabilization at lower concentration and related equilibrium temperature levels advances the date when emissions need to peak, and requires greater emissions reductions by 2050 [3.3].

Table SPM.5: *Characteristics of post-TAR stabilization scenarios [Table TS 2, 3.10][a)]*

Category	Radiative forcing (W/m²)	CO_2 concentration[c)] (ppm)	CO_2-eq concentration[c)] (ppm)	Global mean temperature increase above pre-industrial at equilibrium, using "best estimate" climate sensitivity[b), c)] (ºC)	Peaking year for CO_2 emissions[d)]	Change in global CO_2 emissions in 2050 (% of 2000 emissions)[d)]	No. of assessed scenarios
I	2.5-3.0	350-400	445-490	2.0-2.4	2000-2015	-85 to -50	6
II	3.0-3.5	400-440	490-535	2.4-2.8	2000-2020	-60 to -30	18
III	3.5-4.0	440-485	535-590	2.8-3.2	2010-2030	-30 to +5	21
IV	4.0-5.0	485-570	590-710	3.2-4.0	2020-2060	+10 to +60	118
V	5.0-6.0	570-660	710-855	4.0-4.9	2050-2080	+25 to +85	9
VI	6.0-7.5	660-790	855-1130	4.9-6.1	2060-2090	+90 to +140	5
						Total	177

a) The understanding of the climate system response to radiative forcing as well as feedbacks is assessed in detail in the AR4 WGI Report. Feedbacks between the carbon cycle and climate change affect the required mitigation for a particular stabilization level of atmospheric carbon dioxide concentration. These feedbacks are expected to increase the fraction of anthropogenic emissions that remains in the atmosphere as the climate system warms. Therefore, the emission reductions to meet a particular stabilization level reported in the mitigation studies assessed here might be underestimated.
b) The best estimate of climate sensitivity is 3ºC [WG 1 SPM].
c) Note that global mean temperature at equilibrium is different from expected global mean temperature at the time of stabilization of GHG concentrations due to the inertia of the climate system. For the majority of scenarios assessed, stabilisation of GHG concentrations occurs between 2100 and 2150.
d) Ranges correspond to the 15th to 85th percentile of the post-TAR scenario distribution. CO_2 emissions are shown so multi-gas scenarios can be compared with CO_2-only scenarios.

26 Paragraph 2 addresses historical GHG emissions since pre-industrial times.
27 Studies vary in terms of the point in time stabilization is achieved; generally this is around 2100 or later.
28 The information on global mean temperature is taken from the AR4 WGI report, chapter 10.8. These temperatures are reached well after concentrations are stabilized.
29 The equilibrium climate sensitivity is a measure of the climate system response to sustained radiative forcing. It is not a projection but is defined as the global average surface warming following a doubling of carbon dioxide concentrations [AR4 WGI SPM].

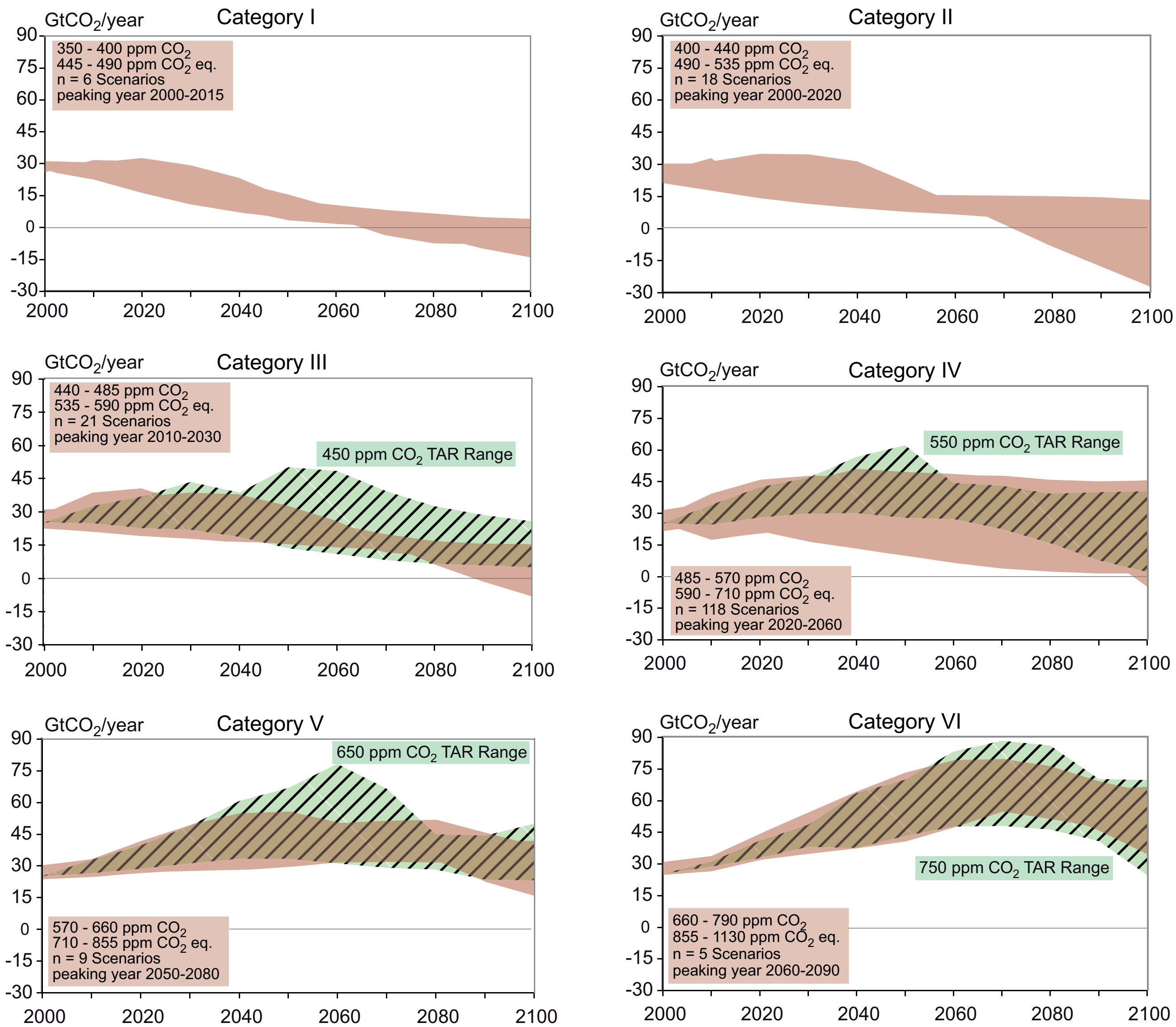


Figure SPM.7: *Emissions pathways of mitigation scenarios for alternative categories of stabilization levels (Category I to VI as defined in the box in each panel). The pathways are for CO_2 emissions only. Light brown shaded areas give the CO_2 emissions for the post-TAR emissions scenarios. Green shaded and hatched areas depict the range of more than 80 TAR stabilization scenarios. Base year emissions may differ between models due to differences in sector and industry coverage. To reach the lower stabilization levels some scenarios deploy removal of CO_2 from the atmosphere (negative emissions) using technologies such as biomass energy production utilizing carbon capture and storage. [Figure 3.17]*

19. **The range of stabilization levels assessed can be achieved by deployment of a portfolio of technologies that are currently available and those that are expected to be commercialised in coming decades. This assumes that appropriate and effective incentives are in place for development, acquisition, deployment and diffusion of technologies and for addressing related barriers** *(high agreement, much evidence).*

- The contribution of different technologies to emission reductions required for stabilization will vary over time, region and stabilization level.
  - o Energy efficiency plays a key role across many scenarios for most regions and timescales.
  - o For lower stabilization levels, scenarios put more emphasis on the use of low-carbon energy sources, such as renewable energy and nuclear power, and the use of CO_2 capture and storage (CCS). In these scenarios improvements of carbon intensity of energy supply and the whole economy need to be much faster than in the past.
  - o Including non-CO_2 and CO_2 land-use and forestry mitigation options provides greater flexibility and cost-effectiveness for achieving stabilization. Modern bioenergy could contribute substantially to the share of renewable energy in the mitigation portfolio.

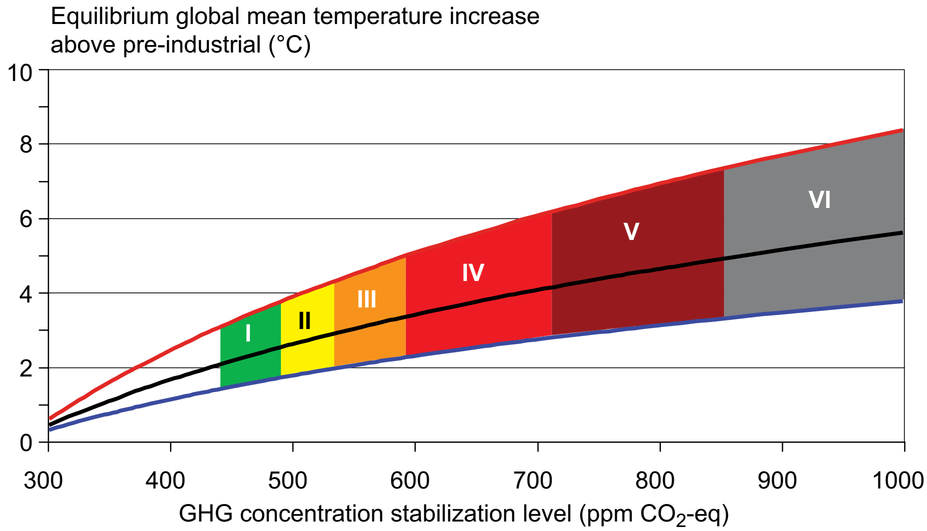


Figure SPM.8: *Stabilization scenario categories as reported in Figure SPM.7 (coloured bands) and their relationship to equilibrium global mean temperature change above pre-industrial, using (i) "best estimate" climate sensitivity of 3°C (black line in middle of shaded area), (ii) upper bound of likely range of climate sensitivity of 4.5°C (red line at top of shaded area) (iii) lower bound of likely range of climate sensitivity of 2°C (blue line at bottom of shaded area). Coloured shading shows the concentration bands for stabilization of greenhouse gases in the atmosphere corresponding to the stabilization scenario categories I to VI as indicated in Figure SPM.7. The data are drawn from AR4 WGI, Chapter 10.8.*

- o For illustrative examples of portfolios of mitigation options, see figure SPM.9 [3.3, 3.4].

- Investments in and world-wide deployment of low-GHG emission technologies as well as technology improvements through public and private Research, Development & Demonstration (RD&D) would be required for achieving stabilization targets as well as cost reduction. The lower the stabilization levels, especially those of 550 ppm CO_2-eq or lower, the greater the need for more efficient RD&D efforts and investment in new

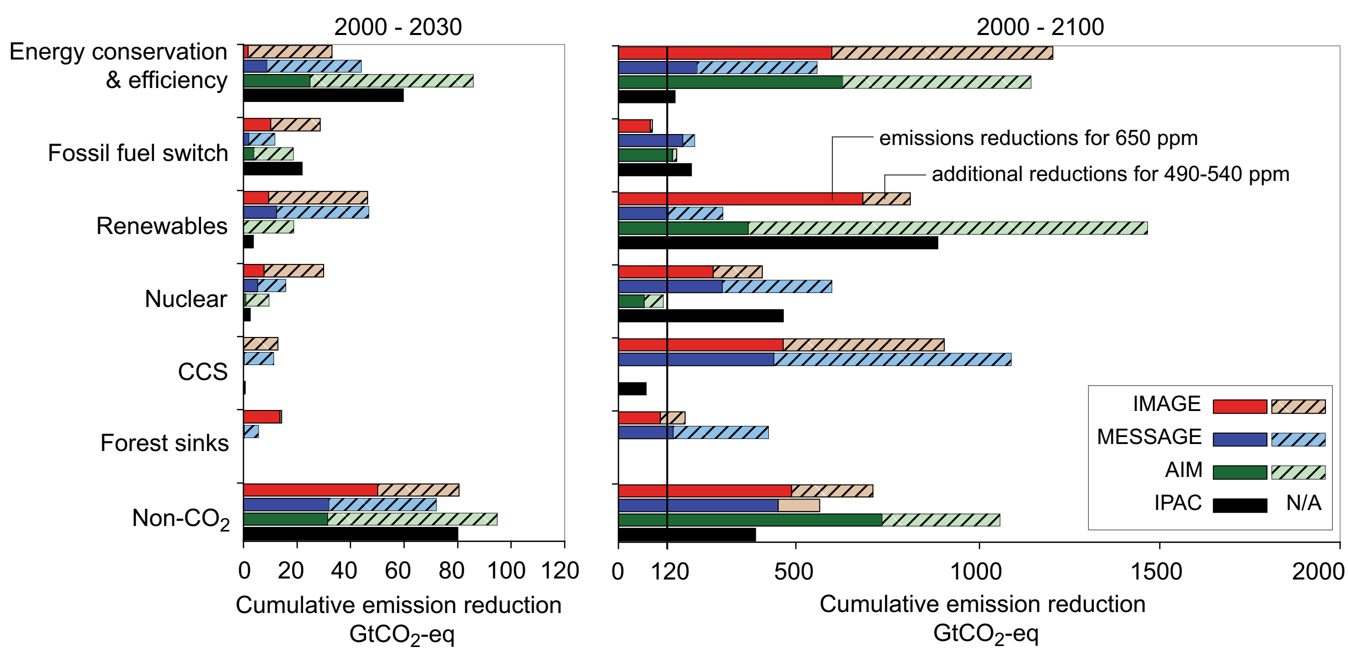


Figure SPM.9: *Cumulative emissions reductions for alternative mitigation measures for 2000 to 2030 (left-hand panel) and for 2000-2100 (right-hand panel). The figure shows illustrative scenarios from four models (AIM, IMAGE, IPAC and MESSAGE) aiming at the stabilization at 490-540 ppm CO_2-eq and levels of 650 ppm CO_2-eq, respectively. Dark bars denote reductions for a target of 650 ppm CO_2-eq and light bars the additional reductions to achieve 490-540 ppm CO_2-eq. Note that some models do not consider mitigation through forest sink enhancement (AIM and IPAC) or CCS (AIM) and that the share of low-carbon energy options in total energy supply is also determined by inclusion of these options in the baseline. CCS includes carbon capture and storage from biomass. Forest sinks include reducing emissions from deforestation. [Figure 3.23]*

technologies during the next few decades. This requires that barriers to development, acquisition, deployment and diffusion of technologies are effectively addressed.
- Appropriate incentives could address these barriers and help realize the goals across a wide portfolio of technologies. [2.7, 3.3, 3.4, 3.6, 4.3, 4.4, 4.6].

20. In 2050[30] global average macro-economic costs for multi-gas mitigation towards stabilization between 710 and 445 ppm CO_2-eq, are between a 1% gain to a 5.5% decrease of global GDP (see Table SPM.6). For specific countries and sectors, costs vary considerably from the global average. (See Box SPM.3 and SPM.4 for the methodologies and assumptions and paragraph 5 for explanation of negative costs) *(high agreement, medium evidence)*.

21. Decision-making about the appropriate level of global mitigation over time involves an iterative risk management process that includes mitigation and adaptation, taking into account actual and avoided climate change damages, co-benefits, sustainability, equity, and attitudes to risk. Choices about the scale and timing of GHG mitigation involve balancing the economic costs of more rapid emission reductions now against the corresponding medium-term and long-term climate risks of delay *[high agreement, much evidence]*.
- Limited and early analytical results from integrated analyses of the costs and benefits of mitigation indicate that these are broadly comparable in magnitude, but do not as yet permit an unambiguous determination of an emissions pathway or stabilization level where benefits exceed costs [3.5].
- Integrated assessment of the economic costs and benefits of different mitigation pathways shows that the economically optimal timing and level of mitigation depends upon the uncertain shape and character of the assumed climate change damage cost curve. To illustrate this dependency:

  o if the climate change damage cost curve grows slowly and regularly, and there is good foresight (which increases the potential for timely adaptation), later and less stringent mitigation is economically justified;

  o alternatively if the damage cost curve increases steeply, or contains non-linearities (e.g. vulnerability thresholds or even small probabilities of catastrophic events), earlier and more stringent mitigation is economically justified [3.6].
- Climate sensitivity is a key uncertainty for mitigation scenarios that aim to meet a specific temperature level. Studies show that if climate sensitivity is high then the timing and level of mitigation is earlier and more stringent than when it is low [3.5, 3.6].
- Delayed emission reductions lead to investments that lock in more emission-intensive infrastructure and development pathways. This significantly constrains the opportunities to achieve lower stabilization levels (as shown in Table SPM.5) and increases the risk of more severe climate change impacts [3.4, 3.1, 3.5, 3.6]

Table SPM.6: *Estimated global macro-economic costs in 2050 relative to the baseline for least-cost trajectories towards different long-term stabilization targets[a)] [3.3, 13.3]*

Stabilization levels (ppm CO_2-eq)	**Median GDP reduction[b)]** (%)	**Range of GDP reduction[b), c)]** (%)	**Reduction of average annual GDP growth rates[b), d)]** (percentage points)
590-710	0.5	-1 - 2	<0.05
535-590	1.3	slightly negative - 4	<0.1
445-535[e)]	not available	<5.5	<0.12

Notes:
a) This corresponds to the full literature across all baselines and mitigation scenarios that provide GDP numbers.
b) This is global GDP based market exchange rates.
c) The median and the 10th and 90th percentile range of the analyzed data are given.
d) The calculation of the reduction of the annual growth rate is based on the average reduction during the period until 2050 that would result in the indicated GDP decrease in 2050.
e) The number of studies is relatively small and they generally use low baselines. High emissions baselines generally lead to higher costs.

30 Cost estimates for 2030 are presented in paragraph 5.

E. Policies, measures and instruments to mitigate climate change

22. **A wide variety of national policies and instruments are available to governments to create the incentives for mitigation action. Their applicability depends on national circumstances and an understanding of their interactions, but experience from implementation in various countries and sectors shows there are advantages and disadvantages for any given instrument** *(high agreement, much evidence).*
    - Four main criteria are used to evaluate policies and instruments: environmental effectiveness, cost effectiveness, distributional effects, including equity, and institutional feasibility [13.2].
    - All instruments can be designed well or poorly, and be stringent or lax. In addition, monitoring to improve implementation is an important issue for all instruments. General findings about the performance of policies are: [7.9, 12.2,13.2]
        - o *Integrating climate policies in broader development policies* makes implementation and overcoming barriers easier.
        - o *Regulations and standards* generally provide some certainty about emission levels. They may be preferable to other instruments when information or other barriers prevent producers and consumers from responding to price signals. However, they may not induce innovations and more advanced technologies.
        - o *Taxes and charges* can set a price for carbon, but cannot guarantee a particular level of emissions. Literature identifies taxes as an efficient way of internalizing costs of GHG emissions.
        - o *Tradable permits* will establish a carbon price. The volume of allowed emissions determines their environmental effectiveness, while the allocation of permits has distributional consequences. Fluctuation in the price of carbon makes it difficult to estimate the total cost of complying with emission permits.
        - o *Financial incentives* (subsidies and tax credits) are frequently used by governments to stimulate the development and diffusion of new technologies. While economic costs are generally higher than for the instruments listed above, they are often critical to overcome barriers.
        - o *Voluntary agreements* between industry and governments are politically attractive, raise awareness among stakeholders, and have played a role in the evolution of many national policies. The majority of agreements has not achieved significant emissions reductions beyond business as usual. However, some recent agreements, in a few countries, have accelerated the application of best available technology and led to measurable emission reductions.
        - o *Information instruments* (e.g. awareness campaigns) may positively affect environmental quality by promoting informed choices and possibly contributing to behavioural change, however, their impact on emissions has not been measured yet.
        - o *RD&D* can stimulate technological advances, reduce costs, and enable progress toward stabilization.
    - Some corporations, local and regional authorities, NGOs and civil groups are adopting a wide variety of voluntary actions. These voluntary actions may limit GHG emissions, stimulate innovative policies, and encourage the deployment of new technologies. On their own, they generally have limited impact on the national or regional level emissions [13.4].
    - Lessons learned from specific sector application of national policies and instruments are shown in Table SPM.7.

23. **Policies that provide a real or implicit price of carbon could create incentives for producers and consumers to significantly invest in low-GHG products, technologies and processes. Such policies could include economic instruments, government funding and regulation** (*high agreement, much evidence*).
    - An effective carbon-price signal could realize significant mitigation potential in all sectors [11.3, 13.2].
    - Modelling studies, consistent with stabilization at around 550 ppm CO_2-eq by 2100 (see Box SPM.3), show carbon prices rising to 20 to 80 US$/t$CO_2$-eq by 2030 and 30 to 155 US$/t$CO_2$-eq by 2050. For the same stabilization level, studies since TAR that take into account induced technological change lower these price ranges to 5 to 65 US$/t$CO_2$-eq in 2030 and 15 to 130 US$/t$CO_2$-eq in 2050 [3.3, 11.4, 11.5].
    - Most top-down, as well as some 2050 bottom-up assessments, suggest that real or implicit carbon prices of 20 to 50 US$/t$CO_2$-eq, sustained or increased over decades, could lead to a power generation sector with low-GHG emissions by 2050 and make many mitigation options in the end-use sectors economically attractive. [4.4,11.6]
    - Barriers to the implementation of mitigation options are manifold and vary by country and sector. They can be related to financial, technological, institutional, informational and behavioural aspects [4.5, 5.5, 6.7, 7.6, 8.6, 9.6, 10.5].

Table SPM.7: *Selected sectoral policies, measures and instruments that have shown to be environmentally effective in the respective sector in at least a number of national cases.*

Sector	Policies[a)], measures and instruments shown to be environmentally effective	Key constraints or opportunities
Energy supply [4.5]	Reduction of fossil fuel subsidies Taxes or carbon charges on fossil fuels	Resistance by vested interests may make them difficult to implement
	Feed-in tariffs for renewable energy technologies Renewable energy obligations Producer subsidies	May be appropriate to create markets for low emissions technologies
Transport [5.5]	Mandatory fuel economy, biofuel blending and CO_2 standards for road transport	Partial coverage of vehicle fleet may limit effectiveness
	Taxes on vehicle purchase, registration, use and motor fuels, road and parking pricing	Effectiveness may drop with higher incomes
	Influence mobility needs through land use regulations, and infrastructure planning Investment in attractive public transport facilities and non-motorised forms of transport	Particularly appropriate for countries that are building up their transportation systems
Buildings [6.8]	Appliance standards and labelling Building codes and certification Demand-side management programmes Public sector leadership programmes, including procurement Incentives for energy service companies (ESCOs)	Periodic revision of standards needed Attractive for new buildings. Enforcement can be difficult Need for regulations so that utilities may profit Government purchasing can expand demand for energy-efficient products Success factor: Access to third party financing
Industry [7.9]	Provision of benchmark information Performance standards Subsidies, tax credits	May be appropriate to stimulate technology uptake. Stability of national policy important in view of international competitiveness
	Tradable permits	Predictable allocation mechanisms and stable price signals important for investments
	Voluntary agreements	Success factors include: clear targets, a baseline scenario, third party involvement in design and review and formal provisions of monitoring, close cooperation between government and industry
Agriculture [8.6, 8.7, 8.8]	Financial incentives and regulations for improved land management, maintaining soil carbon content, efficient use of fertilizers and irrigation	May encourage synergy with sustainable development and with reducing vulnerability to climate change, thereby overcoming barriers to implementation
Forestry/ forests [9.6]	Financial incentives (national and international) to increase forest area, to reduce deforestation, and to maintain and manage forests	Constraints include lack of investment capital and land tenure issues. Can help poverty alleviation
	Land use regulation and enforcement	
Waste management [10.5]	Financial incentives for improved waste and wastewater management	May stimulate technology diffusion
	Renewable energy incentives or obligations	Local availability of low-cost fuel
	Waste management regulations	Most effectively applied at national level with enforcement strategies

Note:
a) Public RD & D investment in low emissions technologies have proven to be effective in all sectors

24. Government support through financial contributions, tax credits, standard setting and market creation is important for effective technology development, innovation and deployment. Transfer of technology to developing countries depends on enabling conditions and financing *(high agreement, much evidence)*.

- Public benefits of RD&D investments are bigger than the benefits captured by the private sector, justifying government support of RD&D.
- Government funding in real absolute terms for most energy research programmes has been flat or declining for nearly two decades (even after the UNFCCC came into force) and is now about half of the 1980 level [2.7, 3.4, 4.5, 11.5, 13.2].

- Governments have a crucial supportive role in providing appropriate enabling environment, such as, institutional, policy, legal and regulatory frameworks[31], to sustain investment flows and for effective technology transfer – without which it may be difficult to achieve emission reductions at a significant scale. Mobilizing financing of incremental costs of low-carbon technologies is important. International technology agreements could strengthen the knowledge infrastructure [13.3].
- The potential beneficial effect of technology transfer to developing countries brought about by Annex I countries action may be substantial, but no reliable estimates are available [11.7].
- Financial flows to developing countries through Clean Development Mechanism (CDM) projects have the potential to reach levels of the order of several billions US$ per year[32], which is higher than the flows through the Global Environment Facility (GEF), comparable to the energy oriented development assistance flows, but at least an order of magnitude lower than total foreign direct investment flows. The financial flows through CDM, GEF and development assistance for technology transfer have so far been limited and geographically unequally distributed [12.3, 13.3].

25. Notable achievements of the UNFCCC and its Kyoto Protocol are the establishment of a global response to the climate problem, stimulation of an array of national policies, the creation of an international carbon market and the establishment of new institutional mechanisms that may provide the foundation for future mitigation efforts *(high agreement, much evidence).*

- The impact of the Protocol's first commitment period relative to global emissions is projected to be limited. Its economic impacts on participating Annex-B countries are projected to be smaller than presented in TAR, that showed 0.2-2% lower GDP in 2012 without emissions trading, and 0.1-1.1% lower GDP with emissions trading among Annex-B countries [1.4, 11.4, 13.3].

26. The literature identifies many options for achieving reductions of global GHG emissions at the international level through cooperation. It also suggests that successful agreements are environmentally effective, cost-effective, incorporate distributional considerations and equity, and are institutionally feasible *(high agreement, much evidence).*

- Greater cooperative efforts to reduce emissions will help to reduce global costs for achieving a given level of mitigation, or will improve environmental effectiveness [13.3].
- Improving, and expanding the scope of, market mechanisms (such as emission trading, Joint Implementation and CDM) could reduce overall mitigation costs [13.3].
- Efforts to address climate change can include diverse elements such as emissions targets; sectoral, local, sub-national and regional actions; RD&D programmes; adopting common policies; implementing development oriented actions; or expanding financing instruments. These elements can be implemented in an integrated fashion, but comparing the efforts made by different countries quantitatively would be complex and resource intensive [13.3].
- Actions that could be taken by participating countries can be differentiated both in terms of when such action is undertaken, who participates and what the action will be. Actions can be binding or non-binding, include fixed or dynamic targets, and participation can be static or vary over time [13.3].

F. Sustainable development and climate change mitigation

27. Making development more sustainable by changing development paths can make a major contribution to climate change mitigation, but implementation may require resources to overcome multiple barriers. There is a growing understanding of the possibilities to choose and implement mitigation options in several sectors to realize synergies and avoid conflicts with other dimensions of sustainable development *(high agreement, much evidence).*

- Irrespective of the scale of mitigation measures, adaptation measures are necessary [1.2].
- Addressing climate change can be considered an integral element of sustainable development policies. National circumstances and the strengths of institutions determine how development policies impact GHG emissions. Changes in development paths emerge from the interactions of public and private decision processes involving government, business and civil society, many of which are not traditionally considered as climate policy. This process is most effective when actors participate equitably and decentralized decision making processes are coordinated [2.2, 3.3, 12.2].
- Climate change and other sustainable development policies are often but not always synergistic. There is growing evidence that decisions about macroeconomic policy, agricultural policy, multilateral development bank lending, insurance practices, electricity market reform, energy security and forest conservation, for example, which are often treated as being apart from

31 See the IPCC Special Report on Methodological and Technological Issues in Technology Transfer.

32 Depends strongly on the market price that has fluctuated between 4 and 26 US$/tCO2-eq and based on approximately 1000 CDM proposed plus registered projects likely to generate more than 1.3 billion emission reduction credits before 2012.

climate policy, can significantly reduce emissions. On the other hand, decisions about improving rural access to modern energy sources for example may not have much influence on global GHG emissions [12.2].

- Climate change policies related to energy efficiency and renewable energy are often economically beneficial, improve energy security and reduce local pollutant emissions. Other energy supply mitigation options can be designed to also achieve sustainable development benefits such as avoided displacement of local populations, job creation, and health benefits [4.5,12.3].
- Reducing both loss of natural habitat and deforestation can have significant biodiversity, soil and water conservation benefits, and can be implemented in a socially and economically sustainable manner. Forestation and bioenergy plantations can lead to restoration of degraded land, manage water runoff, retain soil carbon and benefit rural economies, but could compete with land for food production and may be negative for biodiversity, if not properly designed [9.7, 12.3].
- There are also good possibilities for reinforcing sustainable development through mitigation actions in the waste management, transportation and buildings sectors [5.4, 6.6, 10.5, 12.3].
- Making development more sustainable can enhance both mitigative and adaptive capacity, and reduce emissions and vulnerability to climate change. Synergies between mitigation and adaptation can exist, for example properly designed biomass production, formation of protected areas, land management, energy use in buildings and forestry. In other situations, there may be trade-offs, such as increased GHG emissions due to increased consumption of energy related to adaptive responses [2.5, 3.5, 4.5, 6.9, 7.8, 8.5, 9.5, 11.9, 12.1].

G. Gaps in knowledge

28. There are still relevant gaps in currently available knowledge regarding some aspects of mitigation of climate change, especially in developing countries. Additional research addressing those gaps would further reduce uncertainties and thus facilitate decision-making related to mitigation of climate change [TS.14].

Endbox 1: Uncertainty representation

Uncertainty is an inherent feature of any assessment. The fourth assessment report clarifies the uncertainties associated with essential statements.

Fundamental differences between the underlying disciplinary sciences of the three Working Group reports make a common approach impractical. The “likelihood” approach applied in “Climate change 2007, the physical science basis” and the “confidence” and “likelihood” approaches used in “Climate change 2007, impacts, adaptation, and vulnerability” were judged to be inadequate to deal with the specific uncertainties involved in this mitigation report, as here human choices are considered.

In this report a two-dimensional scale is used for the treatment of uncertainty. The scale is based on the expert judgment of the authors of WGIII on the level of concurrence in the literature on a particular finding (level of agreement), and the number and quality of independent sources qualifying under the IPCC rules upon which the finding is based (amount of evidence[1]) (see Table SPM.E.1). This is not a quantitative approach, from which probabilities relating to uncertainty can be derived.

Table SPM.E.1: *Qualitative definition of uncertainty*

Level of agreement (on a particular finding) ↑			
	High agreement, limited evidence	**High agreement, medium evidence**	**High agreement, much evidence**
	Medium agreement, limited evidence	**Medium agreement, medium evidence**	**Medium agreement, much evidence**
	Low agreement, limited evidence	**Low agreement, medium evidence**	**Low agreement, much evidence**

Amount of evidence[33] (number and quality of independent sources) →

Because the future is inherently uncertain, scenarios i.e. internally consistent images of different futures - not predictions of the future - have been used extensively in this report.

33 “Evidence” in this report is defined as: Information or signs indicating whether a belief or proposition is true or valid. See Glossary.

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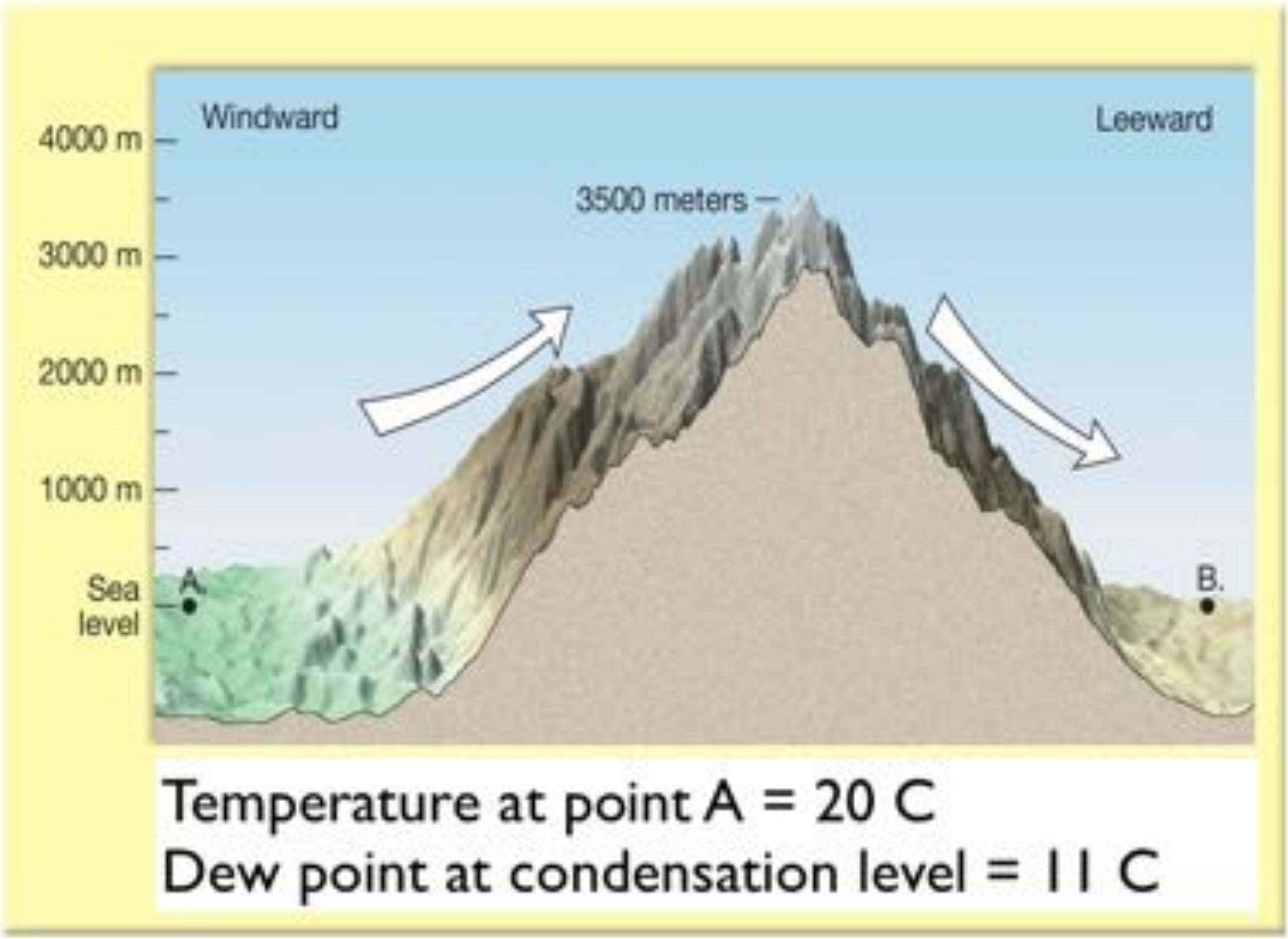
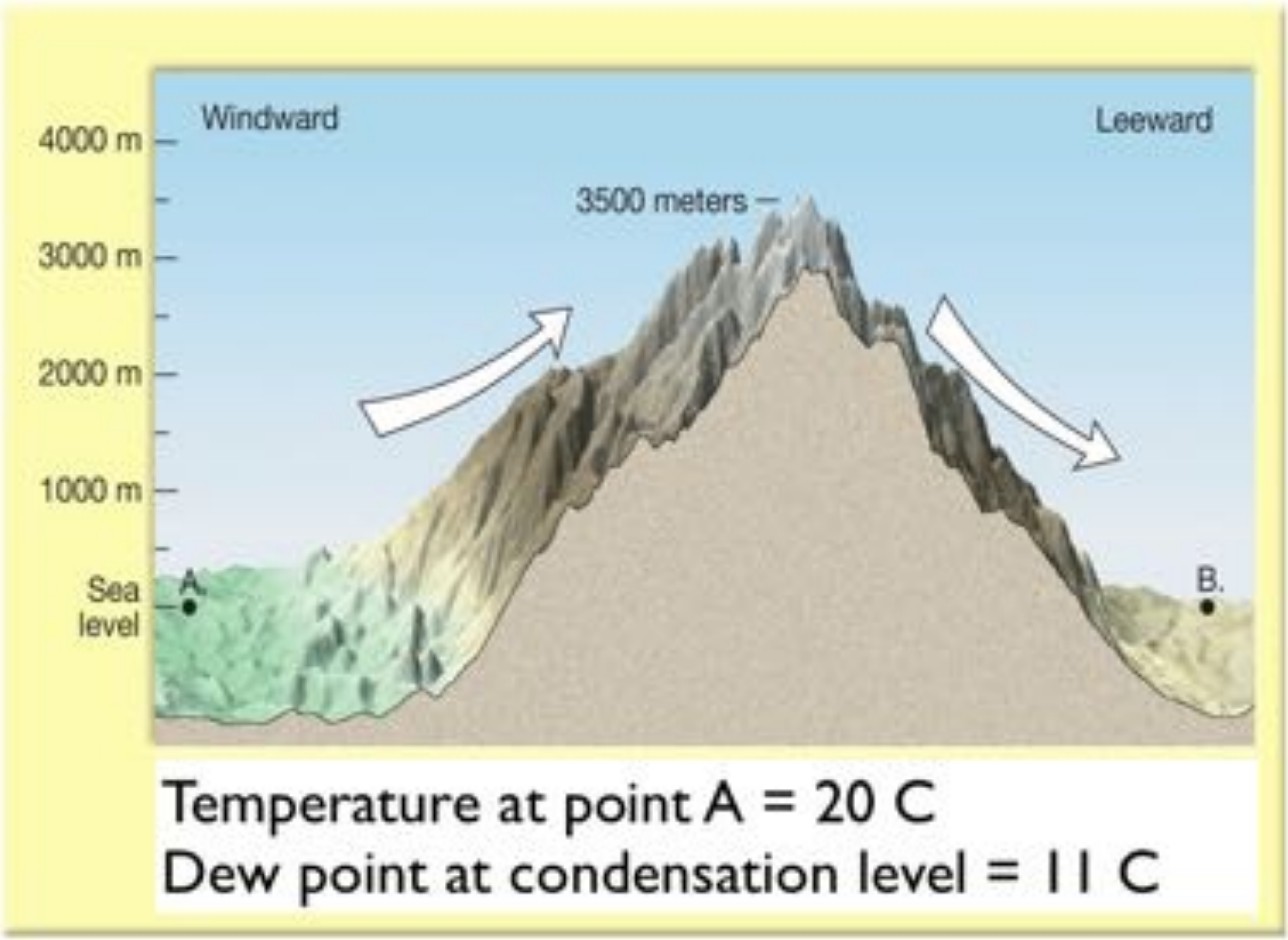
1. The BEST definition of the term climate is:

- ✔ a comprehensive statistical analysis of aggregate weather conditions in a specific place or region.
- average weather over a long period of time.
- identical to the definition of meteorology.
- the weather occurring in the atmosphere at a specific place and time.



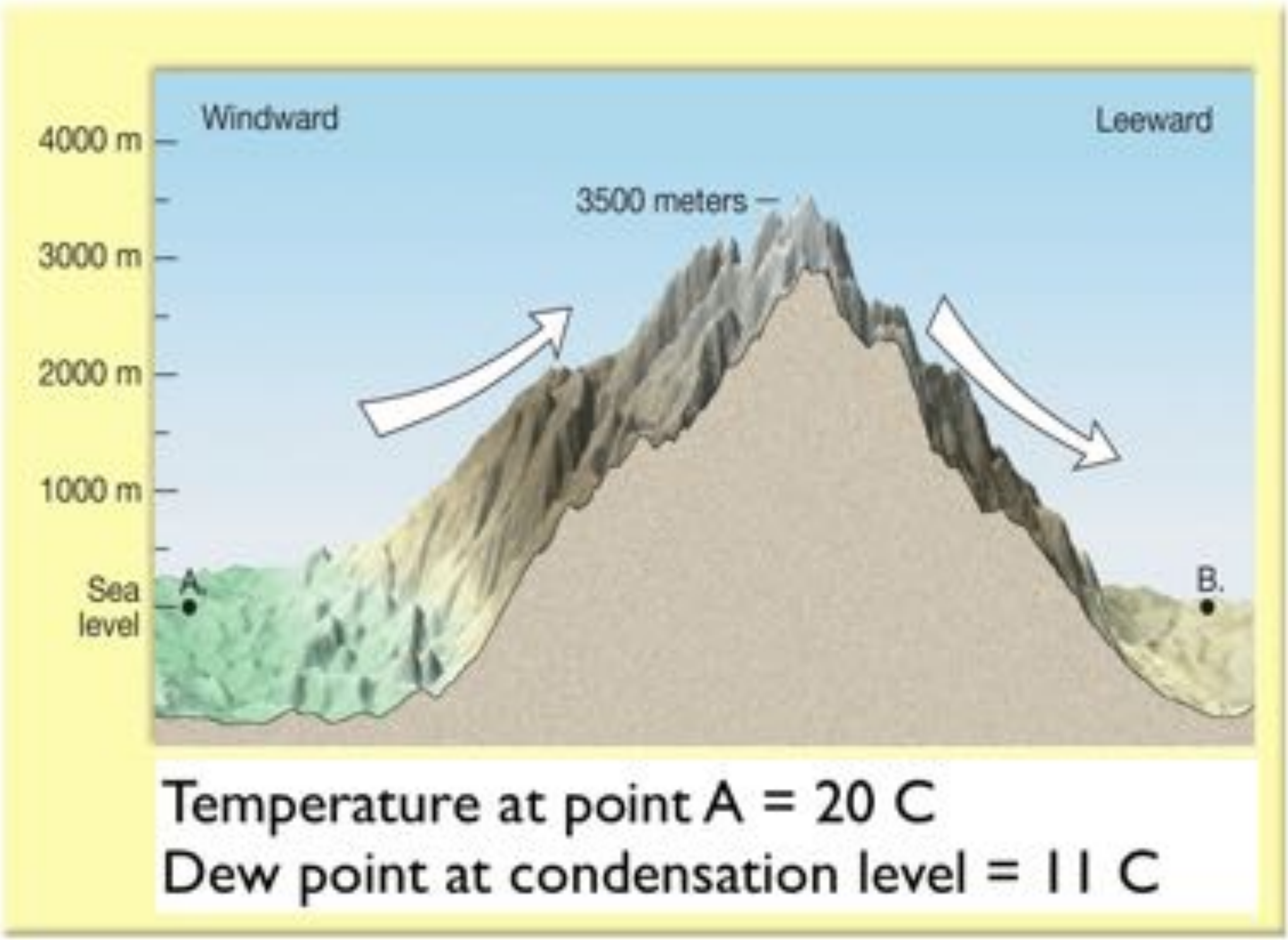
2. Using the figure above, answer the following question: At what elevation do clouds form? Assume that the dry adiabatic lapse rate is 10 degrees/1000 m and the wet adiabatic lapse rate is 5 degrees/1000 m.

- 800 m
- ✔ 900 m
- 1000 m
- 1100 m



3. Using the figure above, answer the following question: What is the temperature at the top of the mountain? Assume that the dry adiabatic lapse rate is 10 degrees/1000 m and the wet adiabatic lapse rate is 5 degrees/1000 m.

- ○ 1 C
- ○ 0 C
- ○ -1 C
- ○ ✔ -2 C



4. Using the figure above, answer the following question: Assuming all the water condenses out of the atmosphere on the windward side, what is the temperature at point B? Assume that the dry adiabatic lapse rate is 10 degrees/1000 m and the wet adiabatic lapse rate is 5 degrees/1000 m.

- 31 C
- 32 C
- ✔ 33 C
- 34 C

5. On the average, for every 1 km increase in altitude in the troposphere the air temperature:

- rises by day and drops by night.
- ✔ drops about 6.5 degrees Celsius.
- rises about 6.5 degrees Celsius.
- remains unchanged for the first 500 m and then drops.

6. Which two gases make up a combined total of 99% of clean, dry air in the homosphere?

- oxygen and carbon dioxide
- ✔ nitrogen and oxygen
- nitrogen and argon
- carbon dioxide and water vapor

7. The four thermal layers of the atmosphere in order beginning from the surface are:

- ✔ troposphere, stratosphere, mesosphere, thermosphere.
- thermosphere, stratosphere, mesosphere, troposphere.
- mesosphere, stratosphere, thermosphere, troposphere.
- stratosphere, troposphere, mesosphere, thermosphere.

8. Which of these is NOT a significant factor in the role played by particles or dust in the atmosphere?

- cloud formation
- ✔ ozone production
- reflection of sunlight
- absorption of sunlight

9. Suppose the albedo of a planet is measured to be 40 percent. This means that

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- 40 percent of the Sun's energy is absorbed.
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- changes the wavelength of light.
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- winter solstice
- summer solstice
- perihelion
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- emit only shortwave radiation.
- ✔ emit more shortwave radiation than cooler objects do.
- emit most of their energy in the form of longwave energy.
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14. Which of the following describes the role played by the water cycle in determining the Earth's heat budget?

- has no significant role
- transfers heat from atmosphere to space
- transfers heat from atmosphere to surface
- ✔ transfers heat from surface to atmosphere

15. Atmosphere is strongly ________ with respect to terrestrial radiation.

- ○ ✔ absorptive
- ○ reflective
- ○ transparent
- ○ conductive

16. The atmosphere is nearly ________ with respect to solar radiation.

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- ○ conductive

17. If the maximum temperature for a particular day is 26 degrees C and the minimum temperature is 14 degrees C, the daily mean would be:

- ○ ✔ 20 degrees C.
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- ○ the difference between maximum and minimum temperatures during the period of one month.
- ○ the sum of the average temperatures for each month of the year.
- ○ ✔ the difference between the average temperatures of the warmest and coldest months.
- ○ the difference between maximum and minimum temperatures over a period of one year.

19. An isotherm on a map:

- ○ ✔ connects points of equal temperature.
- ○ represents the coldest place on the map.
- ○ represents the warmest place on the map.
- ○ identifies all places that have the same annual mean temperature.

20. A place located along a windward coast:

- ○ will probably have summer temperatures that are very similar to an inland place at the same latitude.
- ○ will probably have warmer summer temperatures than an inland place at the same latitude.
- ○ ✔ will probably have cooler summer temperatures than an inland place at the same latitude.

21. Two cities are located at the same latitude (40 degrees). City A is in the Southern Hemisphere and City B is in the Northern Hemisphere. Assume the two cities reflect the general characteristics of the hemispheres where they are located. Which city should have the warmer winter temperatures?

- ○ ✔ City A
- ○ City B
- ○ Both cities should have nearly identical winter temperatures.

22. The amount of heat needed to raise the temperature of 1 gram of a substance by 1 degree C is called:

- ○ latent heat.
- ○ ✔ specific heat.
- ○ kinetic heat.
- ○ conductive heat.

23. The city with the highest annual heating degree-days is

- ✔ International Falls, MN.
- Salt Lake City, UT.
- Atlanta, GA.
- Chicago, IL.
- Cleveland, OH.

24. On a particular day a place accumulates 15 heating degree days. What was the daily mean temperature on that day?

- 80 degrees F
- 40 degrees F
- 65 degrees F
- 15 degrees F
- ✔ 50 degrees F

25. The annual temperature range at most latitudes in the Southern Hemisphere is much smaller than that in the Northern Hemisphere. The reason for this is that:

- less area is covered by desert in the Southern Hemisphere.
- ✔ there is a greater percentage of water surface in the Southern Hemisphere.
- a greater proportion of the land surface is mountainous in the Southern Hemisphere.
- rainfall and cloudiness are greater in the Southern Hemisphere.
- the Earth is closest to the Sun during the Southern Hemisphere summer.

26. The specific heat of water is high; what does this mean?

- Water will always be warmer than other materials for the same energy gain or loss.
- Water has a high density.
- ✔ Water must gain or lose large amounts of energy when its temperature changes.
- Water can always serve as a source of heat.

27. A large temperature lapse rate would occur in a layer with

- uniformly cold temperatures throughout.
- ✔ cold air above, warm air below.
- warm air above, cold air below.
- uniformly warm temperatures throughout.

28. Which of the following processes requires the highest RELEASE of energy from the water molecules?

- melting
- freezing
- condensation
- ✔ deposition

29. An inversion represents an extremely stable atmosphere because a parcel of air that rises into an inversion will eventually become ________ and ________ dense than the air surrounding it.

- colder, less
- ✔ colder, more
- warmer, less
- warmer, more

30. These two conditions, working together, will make the atmosphere the most unstable.

- ○ warm the surface and warm the air aloft
- ○ ✔ warm the surface and cool the air aloft
- ○ cool the surface and warm the air aloft
- ○ cool the surface and cool the air aloft

31. Adiabatic processes are only important for air

- ○ masses which remain near the Earth's surface.
- ○ that is saturated.
- ○ that is polluted.
- ○ that is stagnant.
- ○ ✔ which is rising or sinking.

32. Assume that the actual vapor content of the air remains constant over the course of a day. How does the relative humidity at 2:00 p.m. probably compare to the relative humidity at 5:00 a.m.?

- ○ The relative humidity at 2:00 p.m. is higher.
- ○ ✔ The relative humidity at 2:00 p.m. is lower.
- ○ The relative humidity is the same at 2:00 p.m. as at 5:00 a.m.

33. Saturation is best defined as:

- ○ a mixing ratio of at least 100 g/kg.
- ○ ✔ equal numbers of water molecules evaporating from and condensing into a water surface.
- ○ the point when water molecules completely stop evaporating from a water surface.
- ○ a vapor pressure greater than 1000 mb.

34. The air in Great Falls, Montana has a temperature of 5°C and a relative humidity of 50 percent. On the same afternoon, the air in Palm Springs, California has a temperature of 25°C and a relative humidity of 50 percent. What can be said about the amount of vapor in the air at these two cities?

- ○ Great Falls will have a higher vapor content than Palm Springs.
- ○ ✔ Palm Springs will have a higher vapor content than Great Falls.
- ○ Great Falls and Palm Springs will have the same vapor content.

35. Which type of lifting mechanism results from warm air lifting over cold air?

- ○ orographic lifting
- ○ convective lifting
- ○ convergence
- ○ ✔ frontal wedging

36. At sea level, on the windward side of a mountain range, the temperature is 25 C and the dew point is 5 C. As the air rises over the mountains, the elevation of the cloud base would be

- ○ 1000 m
- ○ ✔ 2000 m
- ○ 2500 m
- ○ 3000 m

37. You are flying in an airplane at 36,000 feet above sea level. You see lightning outside your plane window. The cloud that is close by is

- ○ cirrus.
- ○ cumulus.
- ○ stratus.
- ○ ✔ cumulonimbus.
- ○ altocumulus.

38. The most important process for cloud formation in the atmosphere is

- ○ cooling by loss of latent heat.
- ○ cooling by compression of the air.
- ○ radiational cooling.
- ○ cooling by contact with the cold ground.
- ○ ✔ cooling by expansion of the air.

GEO 1130 Armstrong Exam 2 Spring 2014

1. The pressure gradient force is directed from higher to lower pressure
- only in the Northern Hemisphere.
- only at the poles.
- everywhere except the equator.
- only at the equator.
- ✔ everywhere.

2. Divergence in the atmosphere is best defined as:
- ✔ air moving out of an area.
- air piling up in one area.
- warm air moving away from cold air.
- clouds separating and dissipating.

3. Horizontal variations in air pressure cause a force which makes the wind blow. These pressure variations are caused by
- warm temperatures in the stratosphere.
- greenhouse effect.
- non-circular shape of Earth.
- Earth's rotation.
- ✔ uneven heating of the Earth's surface.

4. The wind speed normally increases with height in the layer of air next to the ground. This illustrates the fact that
- ✔ friction is present only close to the ground.
- the lowest part of the atmosphere is turbulent.
- temperature decreases with height.
- pressure decreases with height.
- density decreases with height.

5. If "fair" weather is approaching, the pressure tendency would probably be:
- falling.
- steady.
- ✔ rising.
- Pressure tendency has nothing to do with forecasting good or bad weather.

6. The term "Hadley cell" applies to
- ✔ 0 degrees to 30 degrees latitude.
- the whole atmosphere.
- 30 degrees to 60 degrees latitude.
- 60 degrees to 90 degrees latitude.
- the poles and the equator.

7. Jet streams
- are usually about ten miles wide.
- ✔ occur at 25,000 to 40,000 feet in middle latitudes.
- were first detected by George Hadley.
- reverse direction 180 degrees in summer.
- do not go below 50 degrees latitude.

8. The large rainfall totals associated with the Indian monsoon occur when:
- ○ the winds shift to the north, blowing off of the Eurasian subcontinent.
- ○ ✔ the ITCZ shifts to the north, near the Himalaya Mountains.
- ○ high pressure develops over the Indian subcontinent.
- ○ the ITCZ shifts south towards the Tropic of Capricorn.

9. The major features of precipitation distribution patterns are determined by
- ○ ✔ general circulation and pressure patterns.
- ○ solar radiation available.
- ○ temperature lapse rates.
- ○ ocean water temperature.
- ○ annual temperature range.

10. Most of the Earth's deserts are located in the
- ○ boundary between liquid and frozen oceans.
- ○ trade wind belt.
- ○ ✔ subsidence areas of subtropical highs.
- ○ areas along the polar front.
- ○ doldrum belt.

11. The usual size of an air mass is:
- ○ at most a few kilometers across.
- ○ between 100 and 200 km across.
- ○ around 1000 km across.
- ○ ✔ at least 1600 km across.

12. Air masses are identified by a pair of letters, one lowercase and one uppercase. The uppercase letter (P, A, or T. refers to:
- ○ average air pressure within the air mass.
- ○ ✔ the approximate latitude of the air mass source region.
- ○ the humidity levels within the air mass.
- ○ the elevation of the air mass source region.

13. A cT air mass is:
- ○ warm and humid.
- ○ cold and dry.
- ○ ✔ warm and dry.
- ○ cold and humid.

14. An mP air mass is:
- ○ ✔ humid and cold.
- ○ humid and warm.
- ○ dry and warm.
- ○ dry and cold.

15. The two most important properties that should be relatively homogeneous at the same altitude in an air mass are
- ○ temperature and carbon dioxide concentration.
- ○ vapor pressure and latitude.
- ○ ✔ moisture content and temperature.
- ○ relative humidity and radiation.

16. In the United States, lake-effect snows occur over which area?

- ○ the eastern side of the Cascade Mountains
- ○ the windward side of the Mississippi River
- ○ ✔ the leeward shores of the Great Lakes
- ○ Lake Champlain

17. The general term applied to warm air moving up over a colder air mass is:

- ○ ✔ overrunning.
- ○ warm front.
- ○ cold front.
- ○ orographic lifting.

18. Middle-latitude anticyclones in the Northern Hemisphere

- ○ ✔ rotate clockwise.
- ○ travel from east to west.
- ○ have cold fronts but not warm fronts.
- ○ are large low-pressure systems.

19. The cloud type most frequently associated with a cold front is:

- ○ cirrus.
- ○ ✔ cumulonimbus.
- ○ altocumulus.
- ○ status.
- ○ cirrocumulus.

20. A dryline causes uplift to occur because:

- ○ the intruding air mass is colder and more humid than the lifted air mass.
- ○ ✔ the lifted air mass is moister than the intruding air mass.
- ○ the lifted air mass is dryer than the intruding air mass.
- ○ the intruding air mass has the same low humidity as the lifted air mass.

21. Why does occlusion lead to the demise of a mid-latitude cyclone?

- ○ ✔ All warm air is displaced aloft, so the surface temperature gradient has been equalized.
- ○ The cold front stops progressing during occlusion.
- ○ The cold cP air mass driving the cyclone has warmed intensely.
- ○ Occlusion stops all precipitation from occurring within the cyclone.

22. Rain long foretold, long last; short notice, soon past. The FIRST FIVE words of this weather proverb:

- ○ ✔ refer to a warm front.
- ○ refer to an anticyclone.
- ○ refer to the formation of cumulonimbus clouds.
- ○ have no basis in fact.
- ○ refer to a cold front.

23. The more violent nature of weather produced by a cold front can be attributed to which two factors?

- ○ the gradual slope and fast forward motion of the front
- ○ ✔ the steep slope and fast forward motion of the front
- ○ the gradual slope and slow forward motion of the front
- ○ the steep slope and slow forward motion of the front

24. Some of the most dangerous weather is produced by a type of thunderstorm called a(n.:

- ○ gust front.
- ○ updraft.
- ○ roll cloud.
- ○ ✔ supercell.

25. Infrared images provide a way to determine which clouds are more likely to produce what?

- ○ humidity
- ○ drought
- ○ ✔ precipitation
- ○ wind

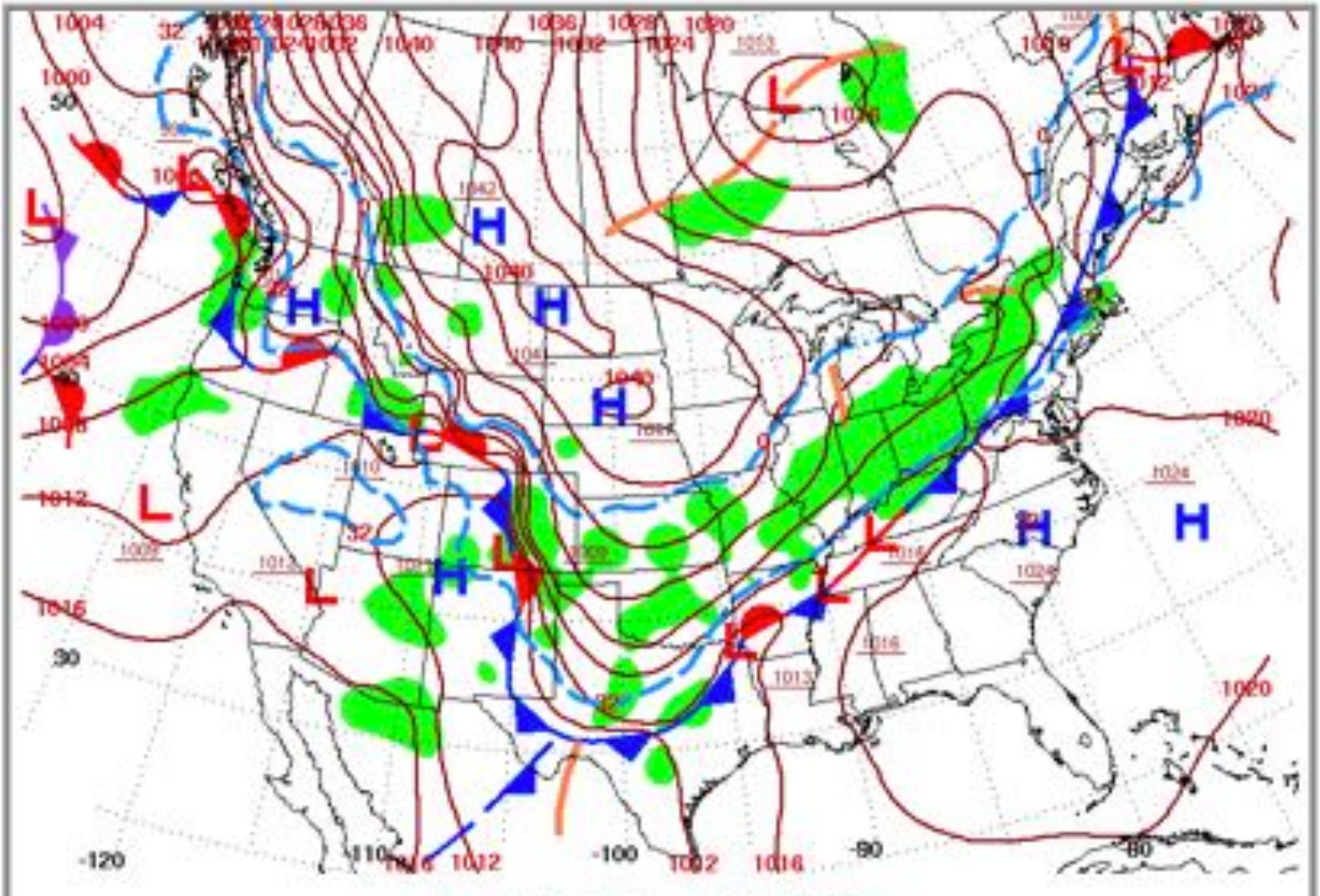
26. These types of images are views of the Earth the way an astronaut would see our planet from space.

- ○ infrared images
- ○ ✔ visible images
- ○ Moon images
- ○ water vapor images

27. Long range forecasts (monthly or seasonal. include predictions of

- ○ pressure.
- ○ wind.
- ○ temperature.
- ○ precipitation.
- ○ ✔ temperature and precipitation.

28. Write a paragraph describing the major weather events affecting the nation in this weather map.

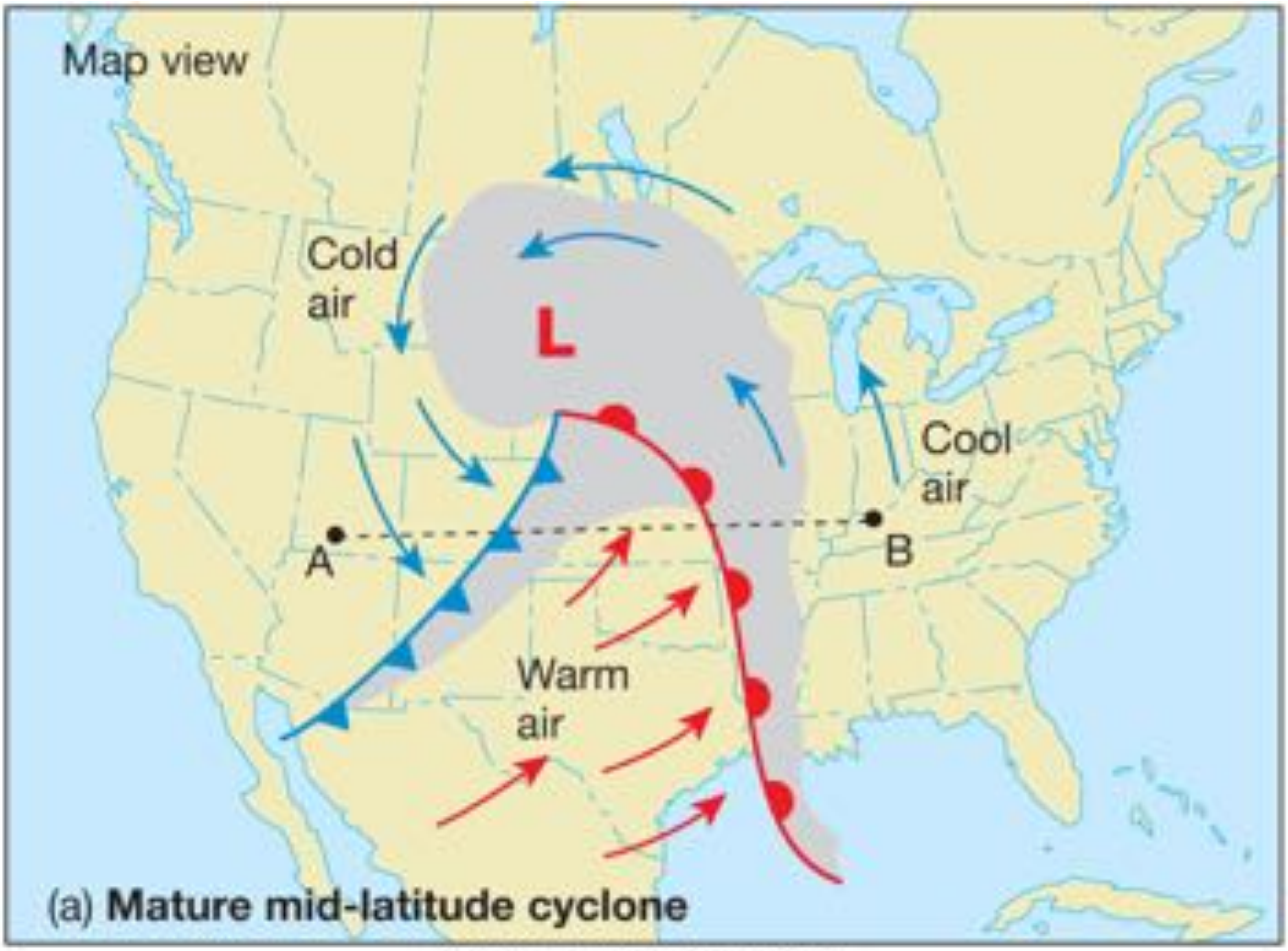


Surface Weather Map at 7:00 A.M. E.S.T.

Click in the box below and type in your response

29. What are the primary difference between surface winds and winds aloft (at, say, 500 mbars)? Cast your answer in terms of the forces involved.

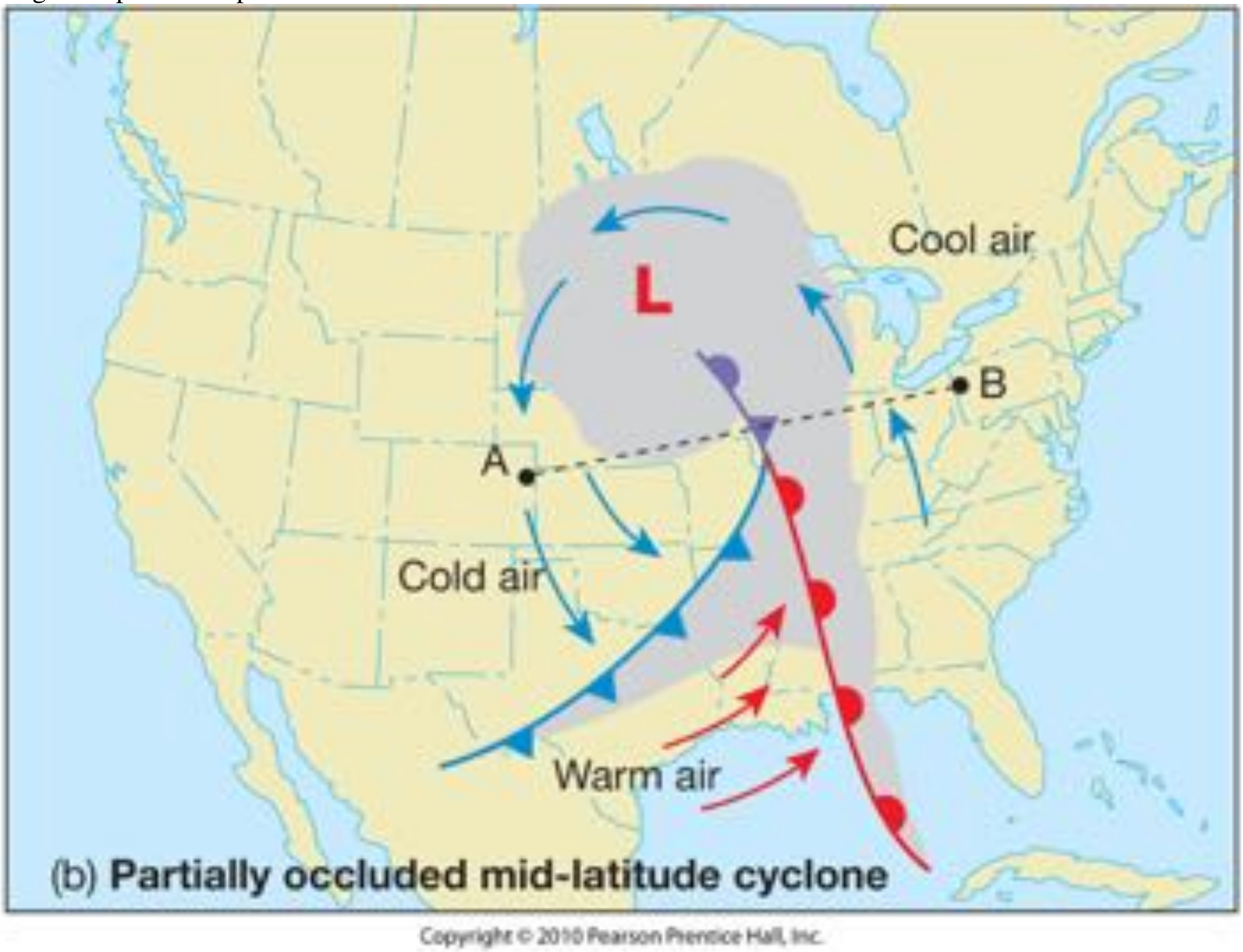
Click in the box below and type in your response



30.

Click in the box below and type in your response

31. Describe the sequence of weather events - in terms of cloud types, temperature, and preciptation, that you would experience driving from point A to point



B.

Click in the box below and type in your response

GEO 1130 Armstrong Exam 3 Spring 2014

1. Which of the following is a greenhouse gas?
- carbon
- carbon monoxide
- oxygen
- ✔ nitrous oxide
- hydrogen peroxide

2. Which of the following is NOT a greenhouse gas?
- methane
- CFCs
- water vapor
- ✔ argon
- carbon dioxide

3. Which of these is the most important cause of the increase in atmospheric CO2?
- decaying vegetation
- ✔ burning of coal and petroleum
- wetlands and swamps
- cattle
- deforestation

4. Astronomical causes of climate change occur with cycles of
- 1 - 5 million yrs.
- 20,000 yrs.
- 450,000 yrs.
- 100 million yrs.
- ✔ 26,000 - 100,000 yrs.

5. Compared to climate changes due to plate tectonics and astronomical causes, the changes due to volcanic eruptions are
- ✔ very short.
- much larger.
- longer.
- of equal duration.

6. Past climate data measured with instruments extends back about

- ○ 30 yrs.
- ○ ✔ 200 yrs.
- ○ 100 yrs.
- ○ 500 yrs.

7. Which of the following is NOT a source of proxy data?

- ○ ✔ the ASOS network
- ○ seafloor sediments
- ○ Antarctic ice cores
- ○ fossilized pollen

8. What are proxy data?

- ○ data that are provided by instruments directly measuring the elements of weather
- ○ averages of climate data compiled by the ASOS network
- ○ ✔ indirect evidence that is used to estimate climate when no direct instrument record is available
- ○ the most reliable data available to forecast future climate change in the United States

9. Oxygen-isotope analysis:

- ○ has been shown to be of little or no use in the study of past climatic changes.
- ○ makes use of the fact that as temperatures decreases, the amount of 18O found in precipitation increases.
- ○ ✔ relies on the fact that 16O evaporates from the ocean more readily than 18O.
- ○ is very simple.

10. Which of the following is NOT associated with the astronomical theory of climate change?

- ○ precession
- ○ eccentricity
- ○ obliquity
- ○ ✔ lunar phases

11. The Milankovitch cycles cannot entirely explain recent global warming trends because:

- ○ ✔ they operate on a very long time scale and cannot address shorter term cycles.
- ○ they were disproved in the 1980s.
- ○ they address cycles in precipitation only.
- ○ no data have been found to support their influence on Earth's climate.

12. Which of the following are possible consequences of a CO2-induced climate change?

- ○ shorter growing season at higher latitudes
- ○ less rainfall in some regions
- ○ ✔ higher evaporation rates and decreased rainfall in some areas
- ○ less vegetation

13. The atmosphere's CO2 content is rising. Which one of the following is a significant contributor to this increase?

- ○ refrigerant leakage
- ○ rice paddies
- ○ ✔ deforestation
- ○ aerosol spray cans

14. Which of the following gases may be contributing to a greenhouse warming?

- ○ hydrogen
- ○ ✔ methane
- ○ nitrogen
- ○ oxygen
- ○ carbon monoxide

15. The combustion of coal and oil is a major source of which greenhouse gas?

- ○ ozone
- ○ ✔ carbon dioxide
- ○ CFCs
- ○ methane

16. Which of the following is a possible consequence of a greenhouse warming?

- ○ ✔ sea-level rise
- ○ increase in sea ice
- ○ a decrease in global mean precipitation
- ○ lower frequency of hurricanes

17. Which of the following is a possible consequence of a greenhouse warming?

- ○ ✔ shifts in the paths of large-scale cyclonic storms
- ○ fewer heat waves and droughts
- ○ a reduction in coastal erosion
- ○ colder winters in polar regions

18. Studies have shown that the sea level

- ○ has lowered about 10 centimeters over the last 100 years.
- ○ should drop over the next 100 years.
- ○ should not change significantly over the next 100 years.
- ○ ✔ has risen at least 10 centimeters over the last 100 years.
- ○ has not changed measurably over the last 100 years.

19. Which of the following is NOT a part of the climate system?

- ○ hydrosphere
- ○ lithosphere
- ○ biosphere
- ○ atmosphere
- ○ ✔ climosphere

20. Sunspot activity tends to follow a cycle of roughly:

- ○ 500 years.
- ○ 100 years.
- ○ 30 years.
- ○ ✔ 11 years.
- ○ 26,000 years.

21. Why are the climate forecasts of GCMs not to be fully trusted?

- ○ The physics involved are still not fully understood.
- ○ ✔ Underlying assumptions influence the outcome and may not be totally accurate.
- ○ Researchers often tweak the outcome to match political agendas.
- ○ They are still not capable of simulating anything but air temperature.

22. According to the IPCC, what is the likelihood that human activities are responsible for global temperature increases since 1950?

- ○ very unlikely (1-10 percent probability)
- ○ somewhat likely
- ○ likely
- ○ ✔ very likely (90 -99 percent probability)

23. The BEST definition of the term climate is:

- ○ ✔ a comprehensive statistical analysis of aggregate weather conditions in a specific place or region.
- ○ average weather over a long period of time.
- ○ identical to the definition of meteorology.
- ○ the weather occurring in the atmosphere at a specific place and time.

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26. Which of these is NOT a significant factor in the role played by particles or dust in the atmosphere?

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- ○ absorption of sunlight

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- ✔ emit more shortwave radiation than cooler objects do.
- emit most of their energy in the form of longwave energy.
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- ○ will probably have summer temperatures that are very similar to an inland place at the same latitude.
- ○ will probably have warmer summer temperatures than an inland place at the same latitude.
- ○ ✔ will probably have cooler summer temperatures than an inland place at the same latitude.

39. Two cities are located at the same latitude (40 degrees). City A is in the Southern Hemisphere and City B is in the Northern Hemisphere. Assume the two cities reflect the general characteristics of the hemispheres where they are located. Which city should have the warmer winter temperatures?

- ○ ✔ City A
- ○ City B
- ○ Both cities should have nearly identical winter temperatures.

40. The amount of heat needed to raise the temperature of 1 gram of a substance by 1 degree C is called:

- ○ latent heat.
- ○ ✔ specific heat.
- ○ kinetic heat.
- ○ conductive heat.

41. The city with the highest annual heating degree-days is

- ○ ✔ International Falls, MN.
- ○ Salt Lake City, UT.
- ○ Atlanta, GA.
- ○ Chicago, IL.
- ○ Cleveland, OH.

42. On a particular day a place accumulates 15 heating degree days. What was the daily mean temperature on that day?

- 80 degrees F
- 40 degrees F
- 65 degrees F
- 15 degrees F
- ✔ 50 degrees F

43. The annual temperature range at most latitudes in the Southern Hemisphere is much smaller than that in the Northern Hemisphere. The reason for this is that:

- less area is covered by desert in the Southern Hemisphere.
- ✔ there is a greater percentage of water surface in the Southern Hemisphere.
- a greater proportion of the land surface is mountainous in the Southern Hemisphere.
- rainfall and cloudiness are greater in the Southern Hemisphere.
- the Earth is closest to the Sun during the Southern Hemisphere summer.

44. The specific heat of water is high; what does this mean?

- Water will always be warmer than other materials for the same energy gain or loss.
- Water has a high density.
- ✔ Water must gain or lose large amounts of energy when its temperature changes.
- Water can always serve as a source of heat.

45. A large temperature lapse rate would occur in a layer with

- uniformly cold temperatures throughout.
- ✔ cold air above, warm air below.
- warm air above, cold air below.
- uniformly warm temperatures throughout.

46. Which of the following processes requires the highest RELEASE of energy from the water molecules?

- melting
- freezing
- condensation
- ✔ deposition

47. An inversion represents an extremely stable atmosphere because a parcel of air that rises into an inversion will eventually become ________ and ________ dense than the air surrounding it.

- colder, less
- ✔ colder, more
- warmer, less
- warmer, more

48. These two conditions, working together, will make the atmosphere the most unstable.

- ○ warm the surface and warm the air aloft
- ○ ✔ warm the surface and cool the air aloft
- ○ cool the surface and warm the air aloft
- ○ cool the surface and cool the air aloft

49. Adiabatic processes are only important for air

- ○ masses which remain near the Earth's surface.
- ○ that is saturated.
- ○ that is polluted.
- ○ that is stagnant.
- ○ ✔ which is rising or sinking.

50. Assume that the actual vapor content of the air remains constant over the course of a day. How does the relative humidity at 2:00 p.m. probably compare to the relative humidity at 5:00 a.m.?

- ○ The relative humidity at 2:00 p.m. is higher.
- ○ ✔ The relative humidity at 2:00 p.m. is lower.
- ○ The relative humidity is the same at 2:00 p.m. as at 5:00 a.m.

51. Saturation is best defined as:

- ○ a mixing ratio of at least 100 g/kg.
- ○ ✔ equal numbers of water molecules evaporating from and condensing into a water surface.
- ○ the point when water molecules completely stop evaporating from a water surface.
- ○ a vapor pressure greater than 1000 mb.

52. Which type of lifting mechanism results from warm air lifting over cold air?

- ○ orographic lifting
- ○ convective lifting
- ○ convergence
- ○ ✔ frontal wedging

53. At sea level, on the windward side of a mountain range, the temperature is 25 C and the dew point is 5 C. As the air rises over the mountains, the elevation of the cloud base would be

- ○ 1000 m
- ○ ✔ 2000 m
- ○ 2500 m
- ○ 3000 m

54. You are flying in an airplane at 36,000 feet above sea level. You see lightning outside your plane window. The cloud that is close by is

- ○ cirrus.
- ○ cumulus.
- ○ stratus.
- ○ ✔ cumulonimbus.
- ○ altocumulus.

55. The most important process for cloud formation in the atmosphere is

- ○ cooling by loss of latent heat.
- ○ cooling by compression of the air.
- ○ radiational cooling.
- ○ cooling by contact with the cold ground.
- ○ ✔ cooling by expansion of the air.

56. The pressure gradient force is directed from higher to lower pressure

- ○ only in the Northern Hemisphere.
- ○ only at the poles.
- ○ everywhere except the equator.
- ○ only at the equator.
- ○ ✔ everywhere.

57. Divergence in the atmosphere is best defined as:

- ○ ✔ air moving out of an area.
- ○ air piling up in one area.
- ○ warm air moving away from cold air.
- ○ clouds separating and dissipating.

58. Horizontal variations in air pressure cause a force which makes the wind blow. These pressure variations are caused by

- ○ warm temperatures in the stratosphere.
- ○ greenhouse effect.
- ○ non-circular shape of Earth.
- ○ Earth's rotation.
- ○ ✔ uneven heating of the Earth's surface.

59. The wind speed normally increases with height in the layer of air next to the ground. This illustrates the fact that

- ○ ✔ friction is present only close to the ground.
- ○ the lowest part of the atmosphere is turbulent.
- ○ temperature decreases with height.
- ○ pressure decreases with height.
- ○ density decreases with height.

60. If "fair" weather is approaching, the pressure tendency would probably be:

- ○ falling.
- ○ steady.
- ○ ✔ rising.
- ○ Pressure tendency has nothing to do with forecasting good or bad weather.

61. The term "Hadley cell" applies to

- ○ ✔ 0 degrees to 30 degrees latitude.
- ○ the whole atmosphere.
- ○ 30 degrees to 60 degrees latitude.
- ○ 60 degrees to 90 degrees latitude.
- ○ the poles and the equator.

62. Jet streams

- ○ are usually about ten miles wide.
- ○ ✔ occur at 25,000 to 40,000 feet in middle latitudes.
- ○ were first detected by George Hadley.
- ○ reverse direction 180 degrees in summer.
- ○ do not go below 50 degrees latitude.

63. The large rainfall totals associated with the Indian monsoon occur when:

- ○ the winds shift to the north, blowing off of the Eurasian subcontinent.
- ○ ✔ the ITCZ shifts to the north, near the Himalaya Mountains.
- ○ high pressure develops over the Indian subcontinent.
- ○ the ITCZ shifts south towards the Tropic of Capricorn.

64. The major features of precipitation distribution patterns are determined by

- ○ ✔ general circulation and pressure patterns.
- ○ solar radiation available.
- ○ temperature lapse rates.
- ○ ocean water temperature.
- ○ annual temperature range.

65. Most of the Earth's deserts are located in the

- ○ boundary between liquid and frozen oceans.
- ○ trade wind belt.
- ○ ✔ subsidence areas of subtropical highs.
- ○ areas along the polar front.
- ○ doldrum belt.

66. The usual size of an air mass is:

- ○ at most a few kilometers across.
- ○ between 100 and 200 km across.
- ○ around 1000 km across.
- ○ ✔ at least 1600 km across.

67. Air masses are identified by a pair of letters, one lowercase and one uppercase. The uppercase letter (P, A, or T) refers to:

- ○ average air pressure within the air mass.
- ○ ✔ the approximate latitude of the air mass source region.
- ○ the humidity levels within the air mass.
- ○ the elevation of the air mass source region.

68. A cT air mass is:

- ○ warm and humid.
- ○ cold and dry.
- ○ ✔ warm and dry.
- ○ cold and humid.

69. An mP air mass is:

- ○ ✔ humid and cold.
- ○ humid and warm.
- ○ dry and warm.
- ○ dry and cold.

70. The two most important properties that should be relatively homogeneous at the same altitude in an air mass are

- ○ temperature and carbon dioxide concentration.
- ○ vapor pressure and latitude.
- ○ ✔ moisture content and temperature.
- ○ relative humidity and radiation.

71. In the United States, lake-effect snows occur over which area?

- ○ the eastern side of the Cascade Mountains
- ○ the windward side of the Mississippi River
- ○ ✔ the leeward shores of the Great Lakes
- ○ Lake Champlain

72. The general term applied to warm air moving up over a colder air mass is:

- ○ ✔ overrunning.
- ○ warm front.
- ○ cold front.
- ○ orographic lifting.

73. Middle-latitude anticyclones in the Northern Hemisphere

- ○ ✔ rotate clockwise.
- ○ travel from east to west.
- ○ have cold fronts but not warm fronts.
- ○ are large low-pressure systems.

74. The cloud type most frequently associated with a cold front is:

- ○ cirrus.
- ○ ✔ cumulonimbus.
- ○ altocumulus.
- ○ status.
- ○ cirrocumulus.

75. A dryline causes uplift to occur because:

- ○ the intruding air mass is colder and more humid than the lifted air mass.
- ○ ✔ the lifted air mass is moister than the intruding air mass.
- ○ the lifted air mass is dryer than the intruding air mass.
- ○ the intruding air mass has the same low humidity as the lifted air mass.

76. Why does occlusion lead to the demise of a mid-latitude cyclone?

- ○ ✔ All warm air is displaced aloft, so the surface temperature gradient has been equalized.
- ○ The cold front stops progressing during occlusion.
- ○ The cold cP air mass driving the cyclone has warmed intensely.
- ○ Occlusion stops all precipitation from occurring within the cyclone.

77. The more violent nature of weather produced by a cold front can be attributed to which two factors?

- ○ the gradual slope and fast forward motion of the front
- ○ ✔ the steep slope and fast forward motion of the front
- ○ the gradual slope and slow forward motion of the front
- ○ the steep slope and slow forward motion of the front

78. Generally there are three stages involved in the development of thunderstorms. They are:

- ○ ✔ cumulus stage, mature stage, and dissipating stage.
- ○ cumulus stage, mature stage, and deconstructing stage.
- ○ cumulus stage, adolescent stage, and dissipating stage.
- ○ cumulus stage, dissipating stage, and deconstructing stage.

79. Some of the most dangerous weather is produced by a type of thunderstorm called a(n):

- ○ gust front.
- ○ updraft.
- ○ roll cloud.
- ○ ✔ supercell.

80. Thunderstorms and large cumulus clouds are characteristic of

- ○ all polar air masses.
- ○ isothermal lapse rates.
- ○ all warm fronts.
- ○ ✔ unstable air.
- ○ stable air.

81. Tornadoes and mid-latitude cyclones are similar in that:

- ○ ✔ both are areas of low pressure.
- ○ both are most common and well-developed in the winter season.
- ○ both have conspicuous surface fronts.
- ○ both form in the trade-wind belt.

82. An explosion of concentrated, straight-line winds associated with strong downdrafts in a thunderstorm is called:

- ○ a gust front.
- ○ a storm surge.
- ○ ✔ a microburst.
- ○ a roll cloud.

83. Infrared images provide a way to determine which clouds are more likely to produce what?

- humidity
- drought
- ✔ precipitation
- wind

84. These types of images are views of the Earth the way an astronaut would see our planet from space.

- infrared images
- ✔ visible images
- Moon images
- water vapor images

85. These satellites circle the Earth in a north-to-south direction, and obtain images of the entire Earth twice a day by drifting about 15 degrees westward over the Earth's surface during each orbit.

- Automated Surface Observing Systems
- ✔ polar satellites
- geostationary satellites
- Doppler satellites

86. Long range forecasts (monthly or seasonal) include predictions of

- pressure.
- wind.
- temperature.
- precipitation.
- ✔ temperature and precipitation.

87. This source of primary pollutants accounts for nearly half of our pollution.

- solid waste disposal
- ✔ transportation
- industrial processes
- stationary source fuel combustion

88. Particulate matter is categorized according to:

- ✔ its size.
- its source.
- its chemical components.
- its toxicity.

89. Inversions represent a hazardous meteorological condition with respect to air pollution because they always bring

- ○ turbulent motion.
- ○ strong winds.
- ○ reduced oxygen content.
- ○ ✔ a near total lack of mixing.
- ○ cold temperatures.