Key Terms
monitor
geostationary
climate model
general circulation model (GCM)
forcing agent

monitor to measure conditions systematically and repeatedly in order to track changes

9.2 Monitoring and Modelling Climate Change

Are oceans getting warmer? Are sea levels rising? To answer questions such as these, scientists need to collect accurate data over a long period of time. Making a consistent, long-term series of observations and measurements is known as **monitoring**. Monitoring is the only way to identify climate trends, such as an increase in average global temperature, reliably.

As well as having a long-term set of data, people who monitor climate change also need to know how the data were obtained. The way in which data are collected, and even the type of instruments used, can affect the reliability of the answers derived from the data. One method of obtaining data related to weather and ocean conditions is shown in **Figure 9.9**.

Improving Technology, Improving Data

Measurements of atmospheric temperature, humidity, precipitation, and other weather data have been collected for 200 years or more. These measurements provide a valuable baseline from which to measure changing weather patterns. However, records from meteorological stations may be somewhat misleading when used to study climate change. Most data were collected where such measurements were convenient, and observations may not have been performed or recorded systematically. Our scientific understanding of climate took a huge leap forward with the invention of technologies that can measure atmospheric changes from high above Earth's surface.

Figure 9.9 Scientists use buoys to monitor meteorologic and oceanographic data. A series of buoys collects data from across the oceans and radios information back to a central location for analysis.

Using Radar to Gather Weather and Climate Data

Meteorologists and climate scientists use radar data to forecast the weather and to estimate global average climate factors, such as humidity and precipitation. Radar systems take measurements by emitting short pulses of microwaves. The microwaves are reflected by water droplets and ice crystals in the atmosphere, as shown in **Figure 9.10**. Computers analyze the returning microwaves and generate an image of the clouds or precipitation based on the analysis. Because the microwave pulses spread out as they move away from the radar station, the radar images are more clear and accurate for areas closer to the radar station. Weather radar is used to track storms, because it can measure conditions that might wreck a weather balloon.

Figure 9.10 A radar instrument transmits short pulses of microwaves that move through the air until they strike an object, such as a raindrop or a snowflake. The object reflects some of the waves back to the radar instrument, thus communicating information about conditions in the atmosphere..

Climate Data from Weather Satellites

The ultimate step in monitoring Earth's climate came with the development of satellites that can measure climatic conditions over the entire planet. Records of Earth's temperature were first obtained from satellites in 1978. Today, hundreds of satellites orbiting Earth measure many different components of our climate system with great accuracy.

Two types of satellite are used to monitor climate:

- **Geostationary satellites** These satellites orbit Earth at the same speed as Earth rotates. Because of this similarity of speed, they remain above the same point on Earth at all times, appearing stationary to an observer on the ground. As a result, the satellites constantly monitor changes over one particular area of the planet.
- **Polar orbiting satellites** These satellites move north and south over the poles as Earth turns beneath them. One complete orbit takes just over 2 h. This type of satellite can monitor the entire planet in about 6 h.

geostationary describing a satellite that travels around Earth's equator at a speed that matches the speed of Earth's rotation so that the satellite remains in the same position relative to Earth's surface

Although satellites have been measuring variables related to Earth's atmosphere since the 1970s, most satellites have been designed for weather forecasting. Climate studies need measurements of subtle trends and changes that can take years to appear. This requirement led to the development of a new generation of instruments that are designed to help answer some of the unsolved questions about climate change.

The Earth Observing System (EOS)

In 1997, Canada, the United States, and Japan combined resources to launch the first of a series of satellites intended to make long-term observations of Earth's changing atmosphere, oceans, land, and ecosystems. This monitoring program is known as the Earth Observing System (EOS). By the end of 2008, more than 20 specialized satellites were in orbit as part of this program. Some of these satellites are illustrated in **Figure 9.11** and the functions of four of these satellites are summarized below.

Study Toolkit

Identifying the Main Idea and Details The headings in this section can be used to organize information about weather satellites. Make an outline to organize the main ideas and details about the satellites in the Earth Observing System.

Quick Scatterometer (*QuikSCAT*) This satellite measures the speed and direction of winds near the surface of the oceans in all types of weather. Scientists are using *QuikSCAT* to find out how winds and water interact to produce El Niño. The satellite also monitors changes in rainforest vegetation and changes in sea ice cover over the polar regions.

Terra This satellite carries five remote sensors to monitor heat emission and reflection from Earth, cloud cover, and pollution in the troposphere. *Terra* started collecting data in February 2000 and is designed to operate for more than 15 years.

Aura Named for the Latin word for air, *Aura* carries four instruments to monitor atmospheric chemistry and concentrations of greenhouse gases. This satellite, shown in **Figure 9.12**, measures ozone, water vapour, CFCs, methane, carbon monoxide, and nitrogen compounds. One significant indicator of climate change monitored by *Aura* is fluctuations in the size of the Antarctic ozone hole.

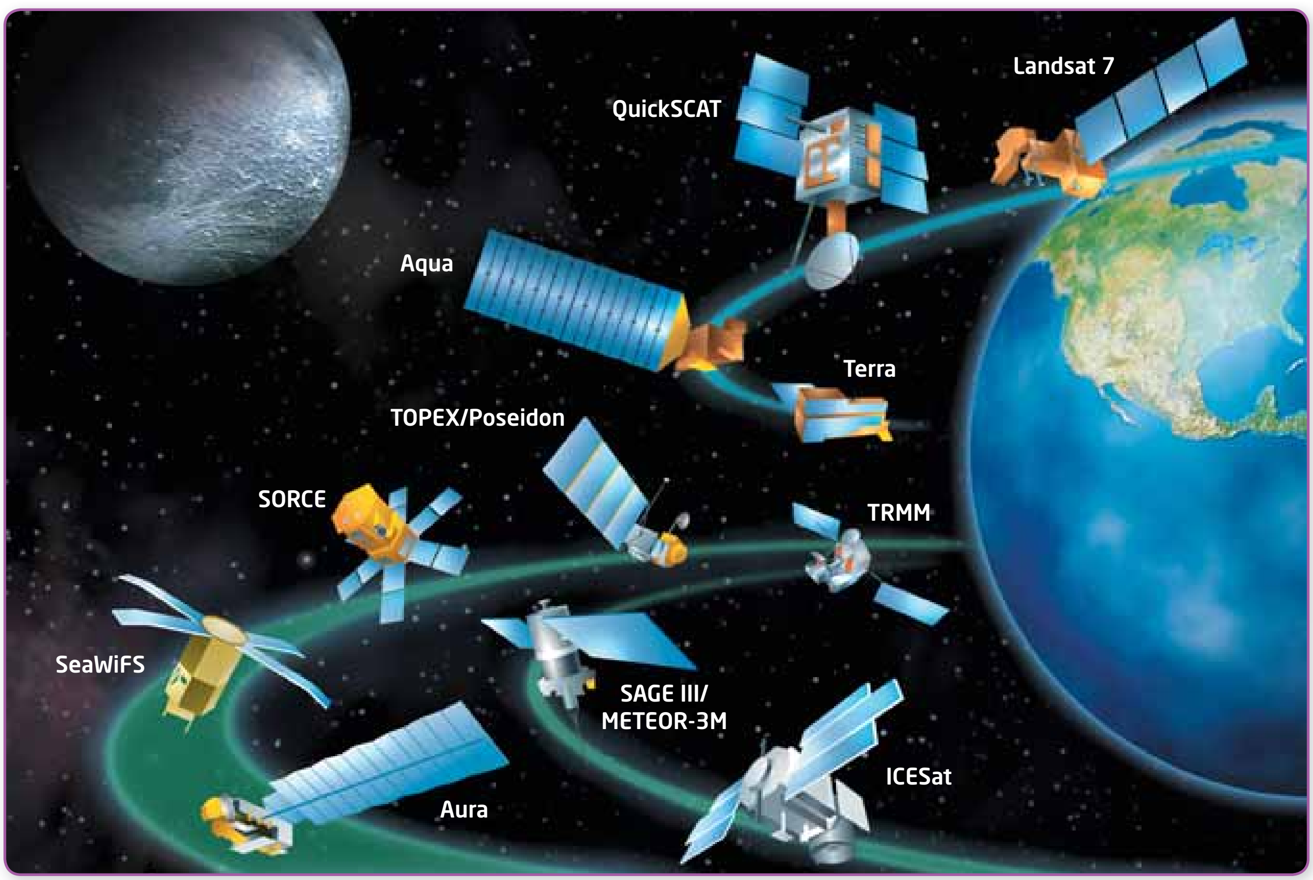


Figure 9.11 As satellite technology improved, older weather and climate satellites were replaced with new satellites that can perform more functions and collect more detailed data compared to older technologies.

Aqua Named for the Latin word for water, this satellite carries six instruments designed to study precipitation, evaporation, and the cycling of water. *Aqua* is shown in **Figure 9.13**. One of its instruments is the Atmospheric Infrared Sounder, or AIRS. It uses cutting-edge technology to accurately measure the amounts of water vapour and greenhouse gases in the atmosphere.

Measurements taken by AIRS over several years will give scientists their most precise picture to date of how water vapour is distributed over the planet in time and space. This information will help determine if global warming is causing the water cycle to accelerate. If Earth's water is moving through this cycle more quickly, more water vapour and clouds will appear in the atmosphere, and more precipitation will fall from the atmosphere at any particular time. Would an increase in global cloud cover lead to further warming, or to cooling, or to neither? Many unanswered questions can be resolved by analyzing new data from this satellite.

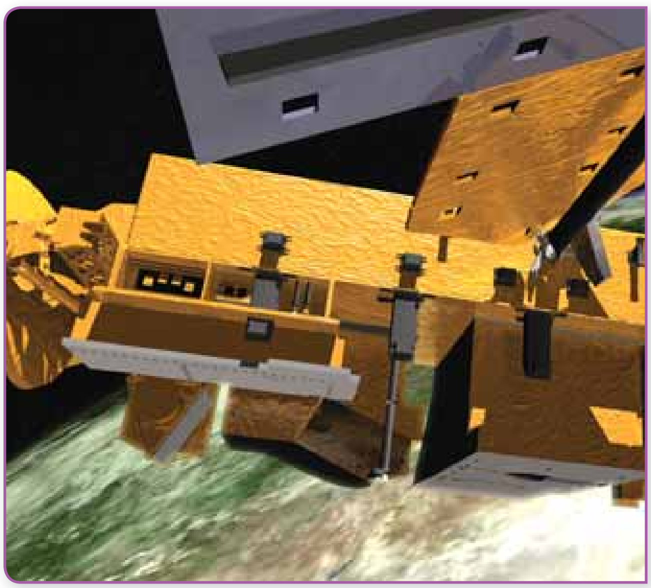


Figure 9.12 The *Aura* spacecraft monitors the Antarctic ozone hole.

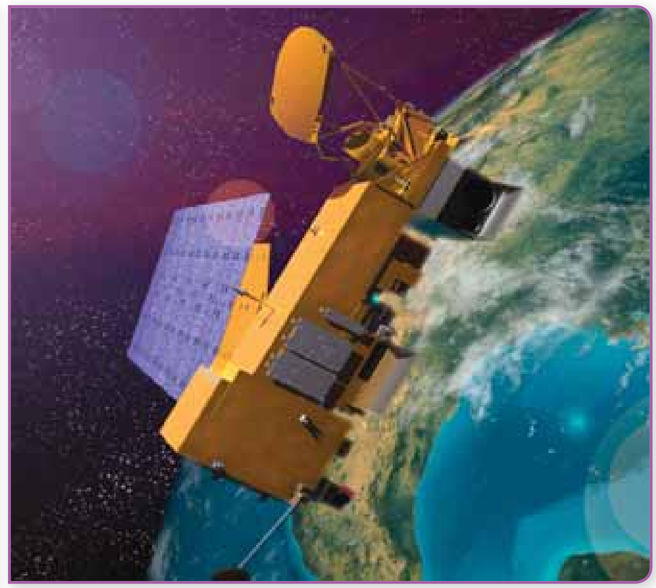


Figure 9.13 Every day, the *Aqua* satellite collects an amount of data equivalent to the data from more than 300 000 weather balloons.

Learning Check

1. Why is monitoring weather important in understanding climate change?
2. Use the illustration in **Figure 9.10** to create a flowchart that explains how radar is used to monitor weather and climate.
3. What major benefit results from monitoring weather by using satellites?
4. How is the mission of the *Terra* satellite different from the mission of the *Aqua* satellite?

Modelling Climates and Climate Change

Gathering accurate data is only the first step in understanding climate change. Equally important is the way in which the data are interpreted. To analyze and interpret data, scientists commonly use models, or representations of objects or systems. Examples of models include maps, miniatures, mathematical formulas, and computer programs.

Because of the size and complexity of Earth's climate system, scientists are unable to construct a physical model planet in their lab that would act like Earth. Therefore, scientists have to use observations of past climates and input the data into computers. Then, they use this information to see which climate features the model predicts well and which ones it does not.

Climate models are computer programs designed to analyze climate data and project how climate may change in the future. Data entered into a model include basic measurements such as global temperatures, polar ice cover, and carbon dioxide concentrations in the atmosphere. Mathematical formulas are applied to these figures based on studies of how different parts of the climate system interact.

Climate models used today link data about the atmosphere and oceans together into **general circulation models (GCMs)**, which are also known as global climate models. An example of a GCM is shown in **Figure 9.14**. These three-dimensional models represent how currents of water and air interact and move around the planet over specified periods of time.

climate model a mathematical or computer program that describes, simulates, and predicts the interactions of the atmosphere, oceans, land surface, and ice of Earth to simulate past, present, and future climate conditions

general circulation model (GCM) a complex computer program that uses mathematical equations to describe the physical processes of the atmosphere and to manipulate the variables that affect how the natural climate system works

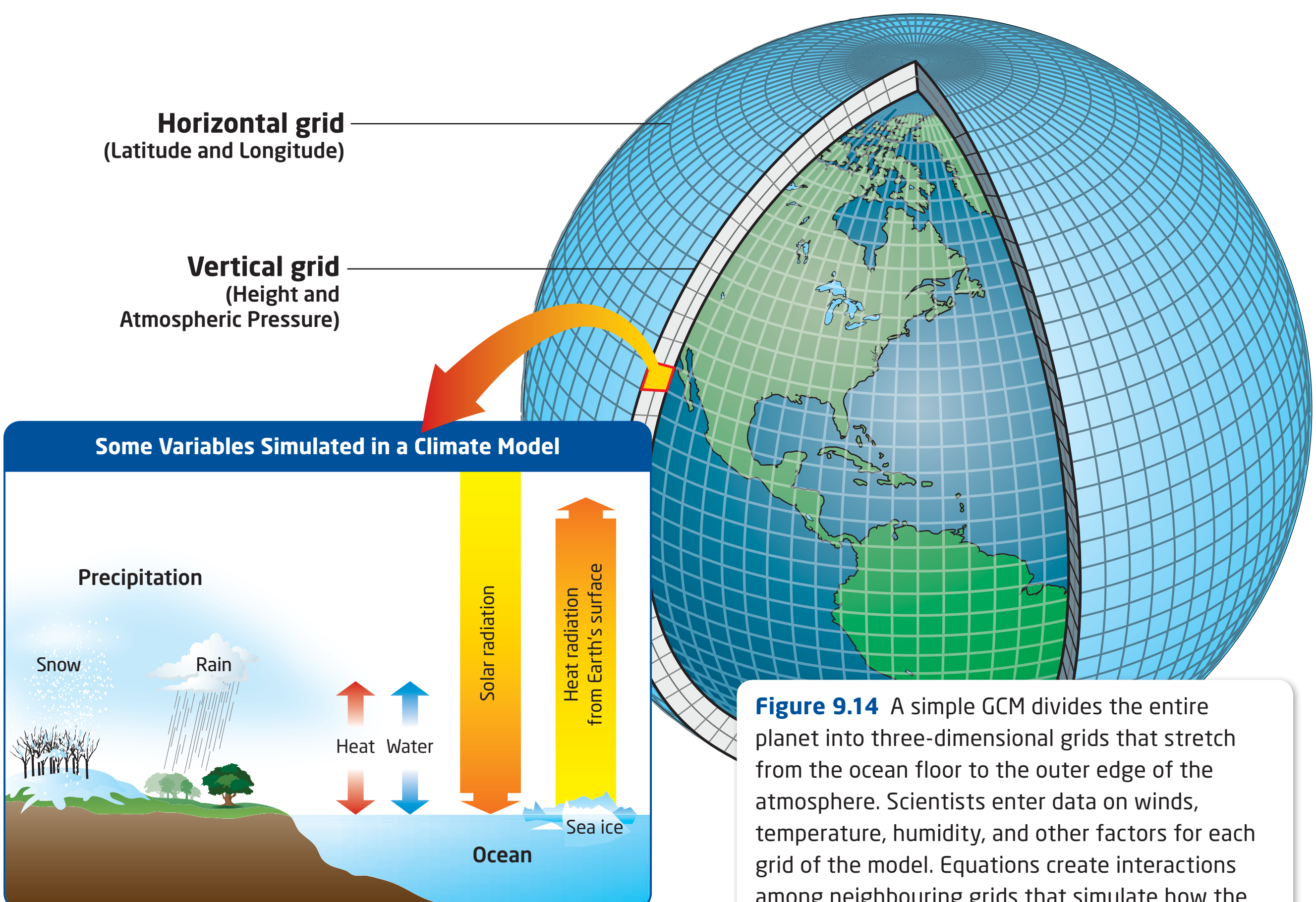


Figure 9.14 A simple GCM divides the entire planet into three-dimensional grids that stretch from the ocean floor to the outer edge of the atmosphere. Scientists enter data on winds, temperature, humidity, and other factors for each grid of the model. Equations create interactions among neighbouring grids that simulate how the natural climate system operates.

Activity 9-3

Pennies from Heaven

How does a computer model simulate interactions between the components of the climate system? In this activity, you will simulate a simple system by using pennies and a couple of rules for how they interact.

Materials

- about 200 pennies or other small markers
- large surface, such as a table

Procedure

1. On a piece of paper, create a square grid that has five rows and five columns.
2. Place a stack of three to eight pennies on each square in the grid. The pennies simulate water vapour, and the model shows how water enters and exits Earth's atmosphere.
3. Make a note of how many pennies are in each square of your grid. Label this diagram "Initial Conditions."
4. Move the pennies according to the rules on the right. After each round, record how many pennies are in each place in the grid. Repeat this step three times.

Rules

1. If a square has three or fewer pennies on it, remove a penny from each adjacent square.
2. If a square has four pennies on it, remove a penny from any adjacent square that has five or more pennies.
3. If a square has five pennies on it and the top one is tails up, do not remove any pennies except for those called for by the other rules. If a square has five pennies on it and the top one is heads up, move the top penny to an adjacent square.
4. If a square has six pennies on it, move one penny to an adjacent square that has four or fewer pennies on it.
5. If a square has seven or more pennies on it, move a penny to each adjacent square.

Questions

1. In which cells of your grid was water vapour content highest and lowest? Explain your answer.
2. How would you change this model to better simulate the movement of water vapour in the atmosphere?

Limitations and Sources of Uncertainty in Climate Models

In December 1961, a scientist named Edward Lorenz ran a weather and climate simulation on his computer. He then input the same data into another computer and got completely different results. He discovered the difference was that one computer carried calculations to six decimal places, while the other one carried them to only three decimal places. The differences in rounding were significant when solving some equations.

Improved accuracy in data and in models has produced "virtual climates" that closely match observations of climate in the real world. Despite scientists' growing understanding of the climate system, however, uncertainties remain. Uncertainties can result from several sources. The precision of the measurements taken of the variables in the system is one source. Three other sources of uncertainty in climate models include:

1. sophistication of the model
2. quality and quantity of the data, and
3. complexity of the variables.

Each of these sources of uncertainty is discussed on the next page.

Figure 9.15 Clouds are a challenge for scientists who develop climate models. Clouds can cool the planet by preventing solar radiation from reaching Earth's surface. They also prevent the escape of thermal energy radiated by Earth's surface, which heats the planet.

1. Sophistication of the Model Computers can simulate solutions to the equations that define the model, but the solutions are only approximations. As you can see in the GCM in **Figure 9.14**, each cell of the grid is very large. Neither the weather nor the climate in one of these cells is the same everywhere in that cell. In typical grids, cells can be more than 100 km along each edge. Therefore, any interactions that might affect the climate, such as places where carbon dioxide is added or stored, have to be approximated inside each cell. Every interaction in that 10 000 km^2 area has to be reduced to a single average value, which is assumed to be true throughout that cell.

2. Quality and Quantity of Data A computer model is only as good as the data entered into it. The quality and quantity of data vary for different components of Earth's climate system. For example, direct measurements of carbon dioxide in the atmosphere began about the middle of the 20th century. Reliable records of other greenhouse gases were not collected until later in the 20^{th} century, and accurate measurements of solar radiation have been recorded only since the 1980s. As you learned at the beginning of this section, developments in technology have improved the quality of data, but some factors in the climate system are more difficult to measure than others are.

Study Toolkit

Identifying Cause and Effect General circulation models use equations to simulate cause-and-effect relationships in the climate system. Use a cause-and-effect map to describe how the quality and quantity of data affect a climate model.

3. Complexity of Variables Another area of uncertainty concerns how sensitive the climate system is to different factors. For example, we know that greenhouse gases affect temperature, but scientists disagree over how much and how quickly different greenhouse gases may raise global temperature. Scientists also debate the overall effect of complex factors, such as clouds. Clouds, such as the ones in **Figure 9.15**, reflect sunlight back into space and help cool the planet. On the other hand, they also increase the amount of infrared radiation emitted from the atmosphere to Earth's surface, which helps warm the planet. Changes in cloud cover are one of the main uncertainties in predicting future climate change.

Comparing the Accuracy of Climate Models

Suppose you have two models that give different predictions of how climate may change in the future. How can you decide which model is more accurate? One way is to test whether the models can accurately "predict" changes that have already occurred. For example, you can enter climate data from 400 000 to 100 000 years ago, based on ice cores and other evidence. Then, have each model analyze these data and project the climate from 100 000 years ago to the present. The more closely the computer prediction matches the actual measurements from the past 100 000 years, the more confidence you can have in the accuracy of the computer model.

Climate Models Indicate Probabilities, Not Certainty

Another way to assess the reliability of a climate model is to give several different models the same test and then compare the results. For example, **Figure 9.16** shows the results of a test of 19 different climate models. Each model was used to predict the increase in global temperature that would occur if carbon dioxide concentrations increased by 1 percent per year over 80 years. Notice how there is less agreement among the predictions as they move further into the future.

Tests like this one remind us that science cannot make predictions about the future with absolute certainty. Climate models provide probabilities based on our current state of knowledge. All of the model results in **Figure 9.16** agree that temperature will increase. However, they differ about the amount of the increase over time. As models and measurements improve, uncertainties can be reduced and disagreements among scientists may be resolved.

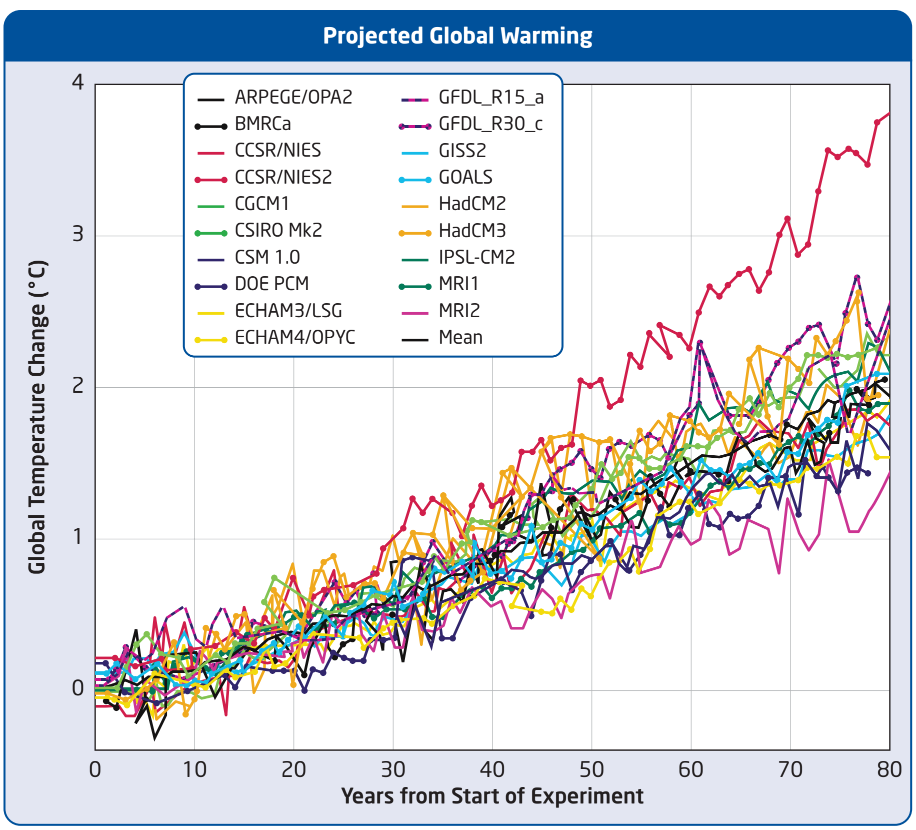


Figure 9.16 This graph shows the responses of 19 different climate models to the same test of climate change. Each acronym in the key represents a different computer model. The models predict how temperature will increase after 80 years of increasing carbon dioxide levels.

Climate Forcing Agents

forcing agent any substance or process that alters the global energy balance and causes climate to change

Anything that alters Earth's energy balance and "forces" the climate to change is known as a **forcing agent**. Different agents have been responsible for climate change at different times throughout Earth's history.

A continuing debate about climate change involves how much of the change being observed today is due to natural causes and how much is anthropogenic. **Figure 9.17** shows how several different forcing agents have contributed to climate change since the 1700s. Although many factors affect the climate in different ways, this model indicates that an increase in greenhouse gases has had a greater impact on current global warming than any other single forcing agent.

Simulating Multiple Factors to Improve Computer Models

Another factor in evaluating models is determining whether all possible answers to the question have been explored. For example, global sea level is rising by about 3 mm each year. Part of this increase comes from the melting of glaciers and polar icecaps, and part comes from the expansion of ocean water through warming. But calculations showed that one third of the measured increase cannot be explained by these two factors alone.

Dr. Richard Peltier, of the University of Toronto's Centre for Global Change Science, suggested that the extra water may result from the drying out of continents or from a higher rate of melting ice in Antarctica than scientists had previously measured. In addition, the melting of ice sheets after the last glacial maximum resulted in uplift of land that was once weighed down by the heavy ice. When all of these additional factors were simulated in a computer model, most of Dr. Peltier's predictions were supported. The better scientists' predictions are, the better recommendations they can make to help reduce the effects of human activities on the climate system.

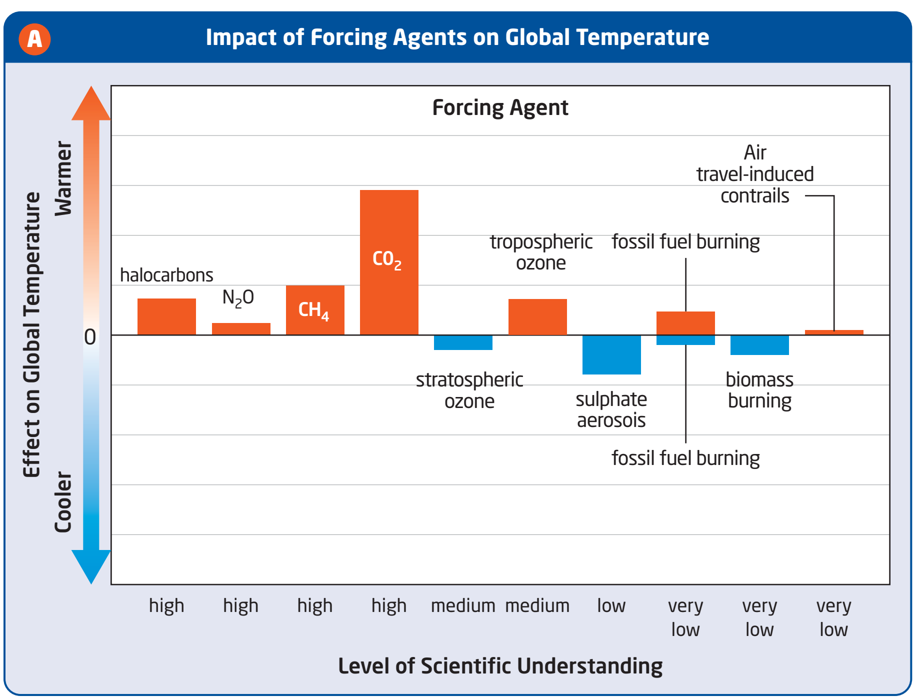


Figure 9.17 The graph in **A** estimates how various forcing agents, such as contrails, have affected global climate from 1750 to the present. Contrails, **B**, are condensed water trails left by airplanes. Bars above the line indicate agents that produce warming. Bars below the line show agents that produce cooling. The height of each bar indicates how much impact each agent has on average global temperature. The bottom of the graph explains how well scientists understand the effects of each forcing agent.

Section 9.2 Review

Section Summary

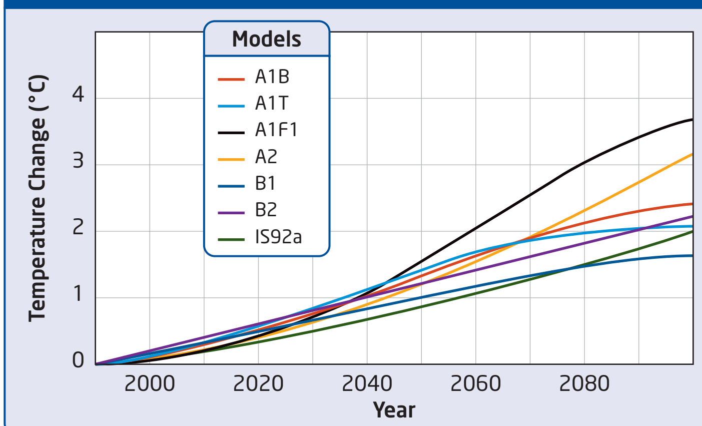
- Dozens of satellites monitor Earth's climate, to provide scientists with data to analyze changes in the Earth system and to project changes in climate. Each satellite focuses on a different aspect of climate and weather.
- Scientists predict future climates by using computer simulations of Earth.
- General circulation models (GCMs) are three-dimensional models that represent how currents of water and air interact and move around the planet over specified periods of time.
- The predictions of climate models are not 100 percent accurate because of imprecision in the data and difficulties in the calculations.
- The major climate models agree on approximately how much some factors such as greenhouse gases contribute to climate change. However, the effects of other factors, such as clouds, are not as well understood.

Review Questions

K/U **1.** What weather features does radar measure?

A **2.** The graph on the right shows projected temperature changes made by several computer models. What are the largest and smallest temperature changes predicted by these models? Why might the models have such widely differing projections?

Projected Global Warming Scenarios for Seven Computer Models



C **3.** What are four sources of uncertainty in climate models today? Organize the four sources of uncertainty by using a graphic organizer of your choice. Study Toolkit 4, on pages 565–566, contains instructions for using graphic organizers.

K/U **4.** Describe two tests that can be used to determine the reliability of computer models.

T/I **5.** Look at **Figure 9.17A**. How does burning fossil fuels cause both warming and cooling of average global temperature?

T/I **6.** Given that scientists do not completely understand all of the complexities of climate change, how can they make inferences about what the future climate of Earth will be like?

T/I **7.** Why can no climate model ever be 100 percent accurate in predicting the future?

K/U **8.** Explain how Dr. Richard Peltier's work shows the importance of analyzing several forcing agents when determining cause and effect in climate change.