Chapter 11
Atmospheric Circulation and Climate

Abstract Earth's atmosphere, made up essentially of the gases that surround our planet, consists of circulation patterns that move air from one place to another and from the surface to higher elevations. There are lateral and vertical ways to force air to move and these are explained in this chapter. The Coriolis Effect, as well as its effect on atmospheric circulation, is explained. Trade winds, polar highs, westerlies, easterlies, doldrums, and horse latitudes are explained and illustrated. Air movement over the Western Hemisphere is illustrated. The Intertropical Convergence Zone (ITCZ) and Horse Latitudes as well as Hadley, Polar, and Ferrel cells are explained and illustrated. The dangers of increased energy and uncertainty concerning future weather events are discussed. Some extreme weather events occurring during 2011–2012 are enumerated and explained in the context of changing climatic conditions (i.e., the "new normal").

Keywords Coriolis • Trade • ITCZ • Convergence • Hadley • Ferrel • Cell • Horse • Latitudes • Siberian • Polar • Subtropical • Rotation • Axis • Winter • Insolation • Trade • Winds • PBL • Jet stream • GCMs • Barometric • Extreme • Weather • Flooding • Cyclones

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and each chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_11,

Things to Know	
Hadley Cell	ITCZ
Horse Latitudes	High Pressure Systems
Insolation	Earth's Revolution
Barometric Pressure	Siberian High
Rising Air	Troposphere
Subtropical High	Earth's Rotation
Icelandic Low	Ferrel Cell
Winter Insolation	PBL
Trade Winds	Jet Stream
Subpolar Low	Westerlies
Polar Lows	ITCZ Northern Shift
Bermuda High	SE Trade Winds
Subtropical Jet	Doldrums
Convection Cell	Coriolis Effect
Future Projections for Atmospheric Circulation	Azores High
Extreme Weather Events	The New Normal

11.1 Introduction

Circulation in the atmosphere is controlled by Earth's rotation, barometric pressure, topography, ocean currents, and differences in temperature, salinity, and moisture.

Differences in barometric pressure occur when air flow is slowed causing a mass of air to build up over a particular location thus increasing air pressure. Heating and cooling the air also create variations in air pressure. When air is heated it expands and rises; and if pushed away aloft, surface air pressure decreases. Conversely if air is cooled, it subsides toward the surface causing air pressure to increase. In other words, hot air rises and cold air descends and this movement affects air moving both laterally and vertically.

11.2 Atmospheric Circulation

If Earth had a simplified atmosphere in a non-rotating state, the majority of the Sun's energy would be incident on the Earth at the equator and the Earth would uniformly heat at the equator and be cold at the poles. Convection cells would develop, one in each hemisphere, to transport heat from the equator to the poles in relatively straight paths. But the Earth does rotate from west to east and completes a rotation on its axis approximately every 24 hours (Fig. 11.1) and forces build up in the atmosphere as a result. The main and most recognizable force is the Coriolis force resulting in the Coriolis Effect, the result of which is air masses turning to the right

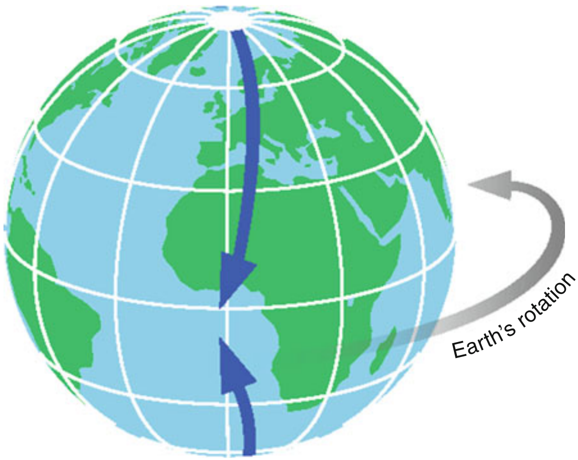

Fig. 11.1 The Coriolis Effect as seen from an oblique view of the Earth. Earth's rotation indicated by the *grey arrow*; the Coriolis Effect represented by the *blue arrows* which shows deflection of moving air masses or objects in both hemispheres, to the *right* in the north and to the *left* in the south (Credit: John Cook)

in the Northern Hemisphere and to the left in the Southern Hemisphere as illustrated by the blue arrows in Fig. 11.1.

As a result of Earth's rotation atmospheric circulation is more complex than it would be with no rotation.

The illustration below (Fig. 11.2) shows the rotating Earth with three cells developing in each hemisphere. Those nearest the equator are Hadley cells. Going towards the poles, the next cells are the Ferrel cells and the ones at or near the poles are Polar cells.

The Earth doesn't just rotate on a vertical axis; its axis is tilted and as the Earth revolves around the Sun, each hemisphere is alternately bathed in the more direct sunlight. Because of this axial tilt, half the Earth receives more sunlight during the summer and the other half, at the same time, during the winter. In other words, when the Northern Hemisphere is experiencing summer, the Southern Hemisphere is having winter (see Fig. 11.3).

11.3 Insolation

As the Earth rotates on its axis and revolves around the Sun, the amount of sunlight received by different parts of the Earth varies. For example, more sunlight is received by the Northern Hemisphere during the summer months and less during the winter months (Fig. 11.3).

Figure 11.4 below shows movement of air due strictly to Earth's rotation and without the influence of land masses. Land masses divide high and low pressure systems into separate air masses on either side of the continents.

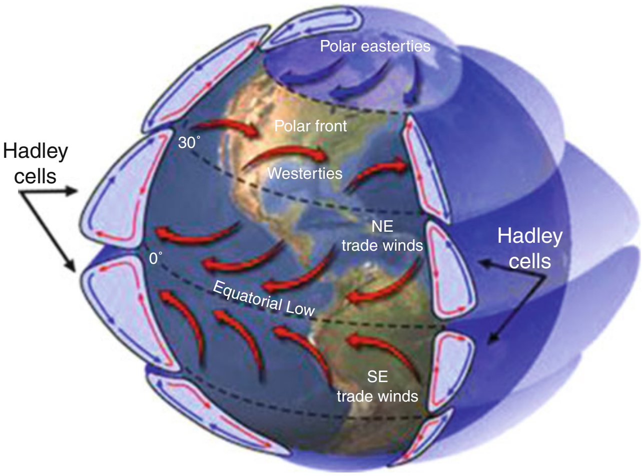

Fig. 11.2 Idealized, three cell atmospheric convection in a rotating Earth. The three cells being either three cells north or south of the equator. The deflections of the winds within each cell is caused by the Coriolis Force (Credit: John Cook)

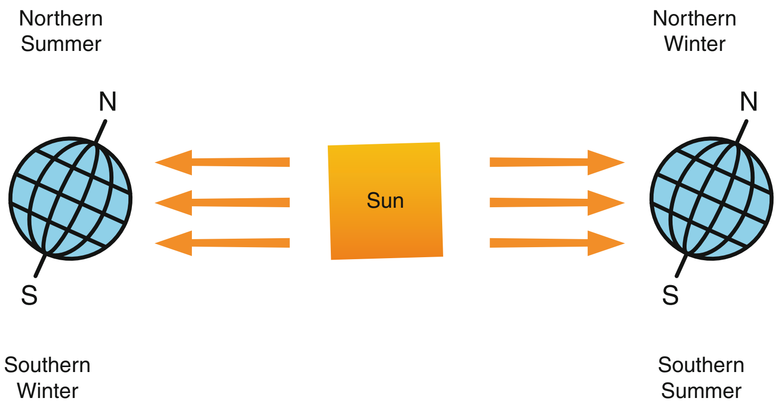

Fig. 11.3 The effect of Earth's obliquity on insolation, the amount of energy received by the Earth at different seasons of the year (summer and winter) (Source: John Cook)

11.4 Air Flow Patterns

Air flows from areas of high pressure to areas of low pressure and moving air is called wind. Wind on the Earth is caused by different atmospheric pressure or by air being moved by convection. Convection moves air vertically and in a circular motion, up and down, as opposed to laterally from equator to pole. The air from

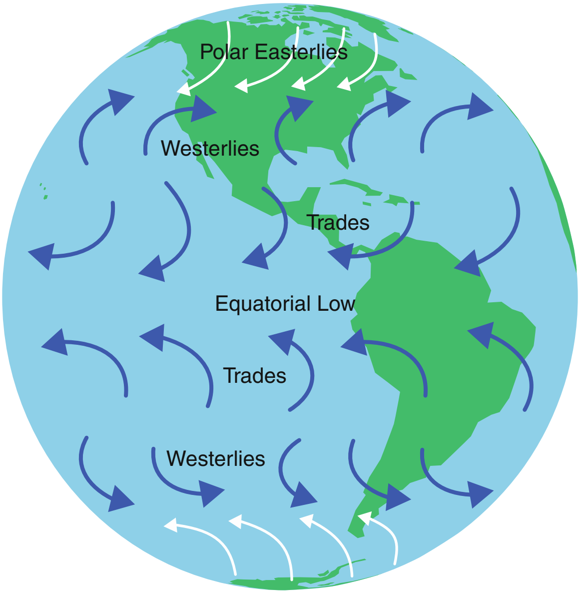

Fig. 11.4 Idealized winds generated by Coriolis force (Credit: John Cook)

equator to poles moves mainly by the Hadley, Ferrel, and Polar cells and from high pressure areas to those of low atmospheric pressure.

The lower part of the atmosphere is sometimes referred to as the planetary boundary layer (PBL) where it is influenced by its contact with the Earth's surface. It is in this layer that most turbulence occurs and vertical mixing is great. Above the PBL, the wind is approximately parallel to the isobars of a weather or barometric map and the winds are said to be geostrophic. Within the PBL the wind is affected by surface drag and flows across the isobars, which are lines of equal barometric pressure.

Air moves from high pressure areas to low pressure areas. Barometric pressure is the weight of a column of air, or atmospheric pressure. On weather maps, high and low pressure areas are marked H and L respectively and contour lines connecting points of equal barometric pressure (isobars) are drawn. If these isobars are close together, wind is stronger; further apart, the wind is not as strong. The analogy with topographic contour lines is that when contour lines are closer together the slope is steeper; when they are further apart the slope is more gradual.

The Sun heats the ground or ocean surface most intensely in tropical areas. The heated air rises and as it rises it cools and loses its moisture as rain or snow, depending on the temperature. This belt of converging air masses, called the doldrums due to low air and water circulation sometimes causing sailing ships to struggle to escape the region, includes some of the rainiest areas on Earth. The cooled, now drier air is forced by continuously rising air to move out of the way, and so it moves towards the temperate latitudes. Air moves by convection from tropical to temperate to Polar Regions. Air also moves laterally by differences in pressure.

Such air from the tropics meets air moving down from the poles at about 30° N and S, called the horse latitudes, where it settles. Here the sinking air compresses, warms, and absorbs moisture from the surface. This is why desert belts lie in the horse latitudes. This warm, dry air is displaced by more sinking air and so some of it returns back to the equatorial zone, and some returns to the poles. Such cycling air between low and mid-latitudes defines a Hadley Cell (see Fig. 11.2).

A similar cell forms between the horse latitudes and the stormy polar fronts at 60° N and 60° S, where warm temperate air moving toward the poles meets very cold air rolling down from the poles. The lighter warm air is forced to rise over the denser cold air, which chills it and forces precipitation. From this polar front, air returns both toward the Equator and toward the poles. Air immediately over the pole sinks. While it is not warm, it is extremely dry (only centimeters of snow every year). From the poles, air within the polar cap streams back towards the polar front.

Thus, six belt-like cells circulate air from pole to pole and establish patterns of climate over the planet. The cells are also characterized by specific patterns of wind flow, a function of the Coriolis force generated by the spin of the Earth (Fig. 11.1). In the temperate zone between the horse latitudes and the polar front, the prevailing westerlies dominate air circulation. In the tropics, the easterly trade winds dominate. Winds around the poles are also easterly. Winds are named from the directions from which they come; therefore, easterlies come from the east, westerlies from the west.

The Ferrel Cell is a secondary circulation feature, dependent for its existence upon the Hadley cell and the Polar cell. The Ferrel Cell behaves much as an atmospheric conduit between the Hadley cell and the Polar cell, and comes about as a result of the eddy circulations (the high and low pressure areas) of the mid-latitudes. For this reason it is sometimes known as the "zone of mixing". At its southern extent (in the Northern Hemisphere), it overrides the Hadley cell, and at its northern extent, it overrides the Polar cell. Just as the Trade Winds are to be found below the Hadley cell, the Westerlies can be found beneath the Ferrel cell. Thus, strong high pressure areas which divert the prevailing westerlies, such as a Siberian high (which could be considered an extension of the Arctic high), could be said to override the Ferrel cell, making it discontinuous.

The illustration below (Fig. 11.5) shows the high and low pressure systems in January. The ITCZ is the Intertropical Convergence Zone where the Trade Winds converge. The ITCZ shifts to the north in summer. The red arrows in Fig. 11.5 indicate wind directions.

A major atmospheric current that affects weather and climate in the Northern Hemisphere continents of North America and Europe, including the British Isles, is the Jet Stream, sometimes a single current, sometimes multiple currents as shown below (Figs. 11.6, 11.7, and 11.8). The Jet Stream is a strong current or currents of air somewhere between 10 and 15 km (6–9 miles) above the earth's surface near the boundary of the troposphere and the stratosphere. The position of this upper-level Jet Stream denotes the location of the strongest surface temperature contrast between cold air to the north and warm air to the south and shows a stronger demarcation during the winter months.

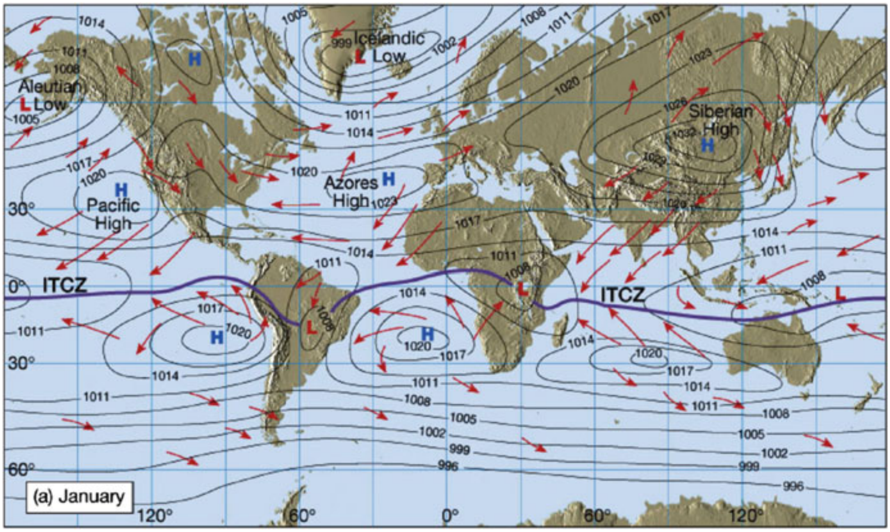

Fig. 11.5 Atmospheric circulation in January showing the southern shift of ITCZ in January

11.5 Climate Change Effects on Atmospheric Circulations

As Earth and its atmosphere continue to warm, atmospheric circulation will drastically change with major changes being increased moisture in some areas, drought in others, and increased weather uncertainty across the Earth's surface. This changing weather uncertainty has already begun. If atmospheric circulation changes, oceanic circulation will eventually also change.

Global warming will alter atmospheric currents in unpredictable ways in many areas. The warming is expected to be greatest over land and in high latitudes. The effects are projected to be greater over the Northern Hemisphere than the Southern Hemisphere as the former is warming more rapidly than the latter at present.

It is very likely that hot extremes, heat waves and heavy precipitation events will become more frequent. The heavy precipitation events will be due to the increased moisture in the atmosphere. 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 and may increase in number and intensity with even greater warming in the future. If more energy continues to be added to the atmosphere as heat, more unusual weather events can be expected.

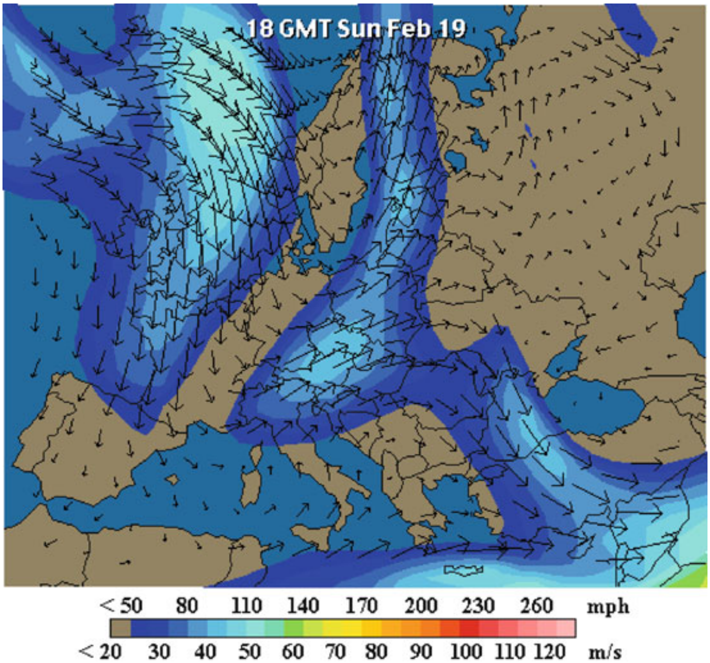

Fig. 11.6 Atmospheric circulation over the European continent showing Jet Streams in February 2012 (From http://www.wunderground.com/global/EU_2xJT_Index.html)

Fig. 11.7 An unusual region of atmospheric pressure over the Arctic has kept the polar jet stream (*green*) locked up at far northern latitudes, causing a warm, dry U.S. winter (Image: Courtesy of NOAA, Public Domain)

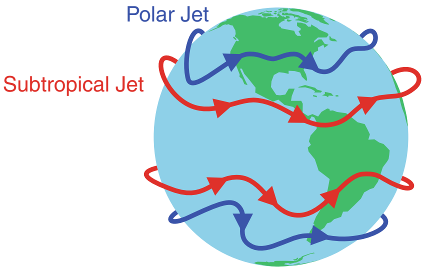

Fig. 11.8 Polar and subtropical jet streams in both hemispheres (Credit: John Cook)

Extra-tropical 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.

There is an improving understanding of projected patterns of precipitation as the result of more sophisticated computer models. 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%), continuing observed patterns in recent trends.

Glaciers will continue to melt and sea level will continue to rise. Regions of the Earth where populations depend on glacial melt water will have to find new water sources or migrate to areas where there are more water resources. The increased sea level rise will also displace billions of people that will have to move inland.

A changed climate and atmospheric circulation will have a profound impact on agriculture and thus on food supplies. Growing seasons will be affected and agriculture will have to migrate to higher elevations and latitudes. Some of this migration can be seen today with plants and animals. Certain plants are also germinating earlier each year and the life cycles of some insects are being effected by earlier springs and later fall seasons.

As sea level rises, inland seas will develop over current land areas and will result in moderating the climate extremes but this will happen over hundreds of thousands of years as it has in the geologic past. However, it may happen more suddenly if the Greenland and Antarctic ice sheets collapse, as is an eventual certainty with increased warming, and the accompanying sea-level rise will displace millions of people living in low-lying areas today.

11.6 Extreme Weather Events

Climate change scientists and meteorologists are calling 2011 one of the worst years on record for climate extremes and 2012 may be worse. Already in June of 2012, over 3,000 heat records have been broken in the U.S. alone. From torrential, flooding downpours to record heat and cold, the events have been spread out from coast-to-coast and border-to-border in the United States. In September 2011 the following events took place in the United States:

11.6.1 Washington, D.C. Metro Rainfall

An incredible 7.03″ of rain fell in 3 h on September 8, 2011 to the south of D.C. in Ft. Belvoir, VA. According to the National Weather Service in Baltimore/Washington, this has a less than 0.1% chance of happening in a given year, making it a 1,000-year rainfall event.

To the west of D.C. in Reston, VA, 6.57″ of rain fell in 6 h on September 8, 2011. According to the National Weather Service in Baltimore/Washington, this has a 0.2% chance of happening in a given year, making it a 500-year rain event. The same is true for Franconia in Fairfax County, VA where 5.47″ fell in 3 h.

11.6.2 Binghamton, N.Y. – Rainfall

7.49″ of rain on September 7 was the wettest day in history. The old record of 4.24″ on September 30, 2010 was crushed. September 2011 will also go down as the wettest month in history.

11.6.3 Allentown, PA. – Rainfall

With almost 13″ of rain, September 2011 is the wettest September on record. Amazingly, August was the wettest month on record (13.47″). Records date back to 1922.

11.6.4 Harrisburg, PA – Rainfall

With more than 18″ of rain, September 2011 is the wettest September on record. The rains this month also pushed the Pennsylvania State Capitol to its wettest year on record, beating out 1972.

11.6.5 Cincinnati, Ohio – Rainfall

3.76″ of rain on September 26, 2011 was the wettest September day in history. Records date back to 1871.

11.6.6 Dayton, Ohio – Rainfall

September 2011 is the wettest September on record with more than 10″ of rain.

11.6.7 Colorado Springs, Colorado – Rainfall

4.50″ of rain on September 14, 2011 was the wettest day in history. Records date back to 1894. The 2-day total (September 14–15 of 2011) of 5.36″ is the wettest 2-day period on record.

11.6.8 Tucson, Arizona – Rainfall

As of September 28, 2011 the southeast Arizona city has seen 5.60″ of rain. This makes September 2011 the wettest on record.

Propelling them to this record was 2.84″ on September 15. This was the 5th wettest day on record.

11.7 Record Heat

11.7.1 Houston, Texas

Hit 102° on September 13, 2011. This was the hottest day ever recorded so late in the year.

11.7.2 Dallas, Texas

Temperatures soared to 107 degrees on September 13, 2011. This was the hottest day ever recorded so late in the year.

11.7.3 Phoenix, Arizona

Low temperature of 91° on September 5, 2011 was the hottest low temperature ever recorded in September.

11.7.4 Seattle, Washington

Recorded 8 straight days with 80+ degree days temperatures from September 3 through September 11, 2011. This is the most consecutive 80-degree days ever recorded in September.

11.7.5 Corpus Christi, Texas

One hundred and three degrees on September 25, 2011 was the hottest temperature ever recorded so late in the season. Records date back to 1887.

11.8 Record Cold

11.8.1 International Falls, Minnesota

The nation's icebox lived up to its reputation in September 2011. The low temperature of 19° on September 15, 2011 was the coldest temperature so early in the season and also the first time temperatures have fallen into the teens during September. Later in the month, a daily record high of 82° was set on September 28, 2011.

11.9 Record River Flooding

Heavy rains from the remnants of Tropical Storm Lee caused record river flooding in many locations in New York and Pennsylvania on September 8 and 9, 2011.

This included the Susquehanna River at Binghamton, N.Y., Wilkes-Barre, PA and Meshoppen, PA. The Swatara Creek in Hershey, PA beat the previous record level by 10 ft!

11.10 Tropical Storm Lee's Tornadoes

According to at least one severe weather expert, the preliminary tornado count from Tropical Storm Lee and its remnants is 38. This is the second most tornadoes on record from a tropical storm that did not reach hurricane strength.

The events described above are based on a report by Chris Dolce, a meteorologist with the Weather Channel. And these weather events are only for 1 month in 1 year in one country, the United States in 2011.

11.11 Other Meteorological Events

The World Meteorological Organization reported on Friday, March 23, 2012 that last year (2011) was the eleventh hottest year on record for Earth.

Extreme weather events were devastating in their impacts and affected nearly all regions of the globe over the past decade. They included severe floods and record hot summers in Europe; a record number of tropical storms and hurricanes in the Atlantic in 2005; the hottest Russian summer since 1,500 in 2010 and the worst flooding in Pakistan's history.

Last year alone (2011), the United States suffered 14 weather events which caused losses of over $1 billion each.

On March 13 and 19 of 2012, historical heat records were exceeded in over 1,000 places in North America.

Scientists believe these extreme weather events are being caused by man-made global warming. In this year alone (2012) massive blizzards have struck the U.S. Northeast, tornadoes have ripped through the nation, mighty rivers like the Mississippi and Missouri have flowed over their banks, and floodwaters have covered huge swaths of Australia as well as displaced more than five million people in China and devastated Colombia. And this year's natural disasters follow on the heels of a staggering litany of extreme weather in 2010, from record floods in Nashville, Tenn., and Pakistan, to Russia's brutal heat wave.

The WMO Commission for climatology provides more information about Global Weather and Climate Extremes at: http://wmo.asu.edu/

Additional Readings

Emanuel, K. A. (2005). Increasing destructiveness of tropical cyclones over the past 30 years. *Nature, 436*(4), 686–688. August 2005, doi:10.1038/nature03906.

Intergovernmental Panel on Climate Change (IPCC). (2007). AR4, 2007, Section 2.7. *Has climate variability, or have climate extremes, changed?*. Cambridge/New York: Cambridge University Press.

Mogil, M. H. (2007). *Extreme weather* (pp. 210–211). New York: Black Dog & Leventhal, Publisher. ISBN 978-1-57912-743-5.

Persson, A. (2006). Hadley's principle: Understanding and misunderstanding the trade winds. *History of Meteorology, 3*, 17–42.