Weather

10

Water is the driving force of all nature.
Leonardo Da Vinci (1452–1519)

Weather is not very intuitive to most people, but I can assure you that the weather does indeed behave according to the same physical laws that we apply to other phenomena within our Universe. Our weather is primarily caused by chemistry, thermodynamics, and perhaps most of all—by mechanics. These three branches of science are inextricably connected, perhaps never more obviously so than in the weather on our planet.

The Galveston hurricane of 1900 was the worst natural disaster in the recorded history of the United States. About 10,000 lives were lost when the hurricane struck Galveston in early September. Because weather forecasting was in infancy at that time, the U.S. Weather Service did not realize that the storm that struck the Caribbean and Cuba was the same system that struck the coast of Texas a week later. Thus, warnings that could have saved many lives were not issued [100] (Fig. 10.1).

Because it occurred in the United States, the devastation caused by this hurricane was probably the single most important natural disaster that contributed to the rise of modern weather forecasting worldwide. Until that hurricane struck, our ability to predict the weather on this planet was largely forensic in nature, meaning that we simply looked at past events and made statistically supported forecasts based on them. The same approach has until recently been the primary way of practicing medicine on Earth. The field of medicine has seen much greater success via this forensically-based approach because the data set (such as the number of human deaths) is significantly larger than that for hurricanes. Thankfully, both fields of science are now progressing rapidly towards models based on predictive sciences rather than mortality statistics.

Almost all weather on our planet occurs in the Earth's atmosphere. Our planet has had an atmosphere for most of its existence. However, the composition of our atmosphere has changed dramatically over the life of our planet. The atmosphere as we know it today is perhaps only 600 million years old. It is mostly nitrogen (78 %), but there are also oxygen (20 %) and argon (1 %), as well as a number of trace gases. There is also about 0.4 % water vapor in our atmosphere, and as we

D. H. Allen, *How Mechanics Shaped the Modern World*,
DOI: 10.1007/978-3-319-01701-3_10,

Fig. 10.1 Aftermath of the Galveston hurricane of 1900

will see shortly, this is the single most important molecule in our atmosphere with respect to our weather [101, 102].

In my mind, the primary causes of weather on Earth are related to two important inescapable realities. First, the Earth is approximately spherical; and second, water exists in three natural chemical states on our planet.

Let's consider these one at a time. First, the Earth is approximately spherical. This is due to Newton's Gravitational Law (see Chap. 7). As we know from this law, the force exerted by bodies is directly proportional to their mass. All massive solid bodies in the Universe are essentially spherical because their mass is sufficiently large to induce gravitational forces that cause stresses to overcome the fracture toughness of materials near the surface, thus pulling every object on their surface as close as possible to their center of mass.

Where the Earth is not spherical it is because chemical processes inside our planet produce forces that are sufficiently large to overcome the Earth's gravitational force, thus creating for example volcanoes and mountains. But from a distance of one diameter of the Earth, these variations appear small, so that from afar the Earth appears to be approximately spherical.

This is really an exercise in relativity. For example, suppose you could stretch a rope around the circumference of the Earth and pull it tight so that it rests directly on the surface. Now suppose you add 6 m of length to the rope. How high above the Earth's surface would the rope be if it were stretched out equidistant from the surface? The answer is about 1 m! This fact can be verified with some simple trigonometry (see Archimedes in Chap. 2). It seems remarkable, but that is because you the viewer are standing right next to the rope, and you are only around 2 m in height. But if you were standing one Earth radius away from the Earth's surface, you would not even be able to see this 1 m separation between the rope and the surface of the Earth. The viewer's opinion of the significance of the height of the rope above the Earth's surface is relative to the viewer's location with respect to the rope and the Earth's surface.

On the other hand, smaller objects within the Universe are often nowhere close to spherical, and this is due to the fact that the gravitational force of these small bodies, such as asteroids, is not sufficiently large to overcome the fracture toughness of the rocks or ice that they are made of, thereby causing them to remain irregular in shape. Gas giants such as Saturn and Jupiter are quite (oblate) spherical because the surface that we see is not a solid, but is in fact a gas, meaning that there are no molecular (solid) bonds to overcome (via fracture) by the gravitational forces. The surfaces of stars are combinations of liquids and gases, thus meaning that they are also quite spherical for the same reasons that gas giants are spherical. Thus, the Earth is at least approximately spherical, and this is the dominant reason for our global weather.

You may have heard of the First and Second Laws of Thermodynamics. Mechanics is inextricably connected to these two essential scientific principles. These two laws imply that every object will seek thermodynamic equilibrium. Since these are universal laws, the Earth itself behaves according to them. This would imply that every point on the Earth's surface would seek to be at the same temperature. But of course, since the Earth is spherical this is not possible so long as the Sun is out there heating our planet. When in the distant future our Sun burns out, every point on Earth will quickly reach thermodynamic equilibrium (very near to absolute zero!), but until then, we are doomed to have weather on this planet.

From Fig. 10.2 we can see that because the Sun is pretty far from Earth compared to the Earth's radius (about 24,000 Earth radii!), the radiation energy that comes to the Earth from the Sun appears to be planar from the perspective of Earth.

Thus, as we can see, because the equatorial regions of the Earth are nearly perpendicular to the Sun's rays, these regions must always receive more solar radiation than do the polar regions simply because the polar regions are quite oblique to the Sun's rays. Furthermore, because only one side of the Earth is visible to the Sun at any point in time, one side of the Earth is always receiving energy, while the other side is not, and the period of this difference is one day,

Fig. 10.2 Solar radiation intensity on Earth

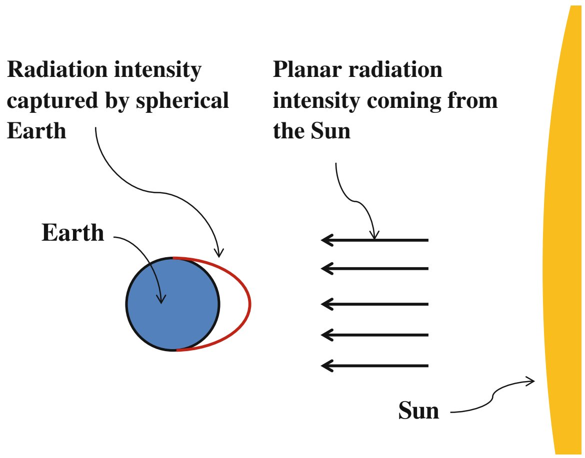

Fig. 10.3 Artist's depiction of the impact of an Asteroid with the Earth that caused the Moon

which is determined by the rate of spin of the Earth. Both the shape and the spin of the Earth are due to mechanics.

Scientists think that the Earth's spin rate was determined primarily by the impact with another body about 2.5 billion years ago, and that impact produced our Moon. The date for this impact has been estimated by using mechanics. When the first astronauts landed on the Moon in 1969, they placed a mirror on its surface, and ever since then we have been measuring the time of flight of a reflected beam of light between the Earth and the Moon. From that measurement we have been able to calculate the rate at which the Moon is moving away from the Earth—about 3.8 cm per year. Thus, we can extrapolate backwards in time using Newton's second law of motion and estimate when the impact occurred (Fig. 10.3).

There is another effect of the impact that produced our Moon. When the two bodies collided, the Earth's axis of spin was tilted, so that this axis is now about 23.5° away from the perpendicular to the plane of the ecliptic, which is the plane that our solar system lies within. This tilt of the Earth's axis of spin is the primary cause for our seasons on Earth, and it is all due to mechanics.

Let's suppose that you live in St. Paul, Minnesota, which lies at a latitude of about 45°. On the day of the summer solstice (June 22), the Sun is at its maximum angle of $45° + 23.5° = 68.5°$ at high noon, whereas on the day of the winter solstice, the Sun is at its maximum angle at high noon of $45° - 23.5° = 21.5°$. Thus, St. Paul receives a maximum radiation rate from the Sun in winter of only about $\sin 21.5°/\sin 68.5° = 39.4\ \%$ of its maximum heating rate in summer. Connect that with the fact that the length of the day on December 22 in St. Paul is only 8 h long, whereas it is 16 h long on June 22, and the difference is staggering. St. Paul only receives about 20 % as much of the Sun's energy on December 22 as it does on June 22 (Fig. 10.4)!

Of course, the amount of solar radiation that the Earth receives at any particular location is a function of four physical variables, as shown in Fig. 10.5: the Sun's

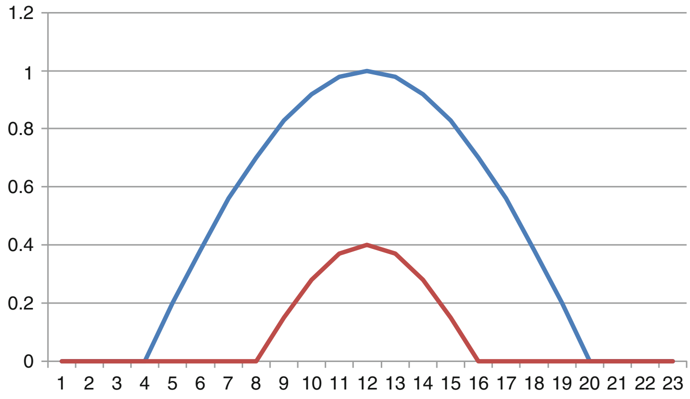

Fig. 10.4 Solar heating as a percent of maximum (*vertical axis*) versus time of day (*horizontal axis*) on June 22 (*blue line*) and December 22 (*red line*) in St. Paul, Minnesota

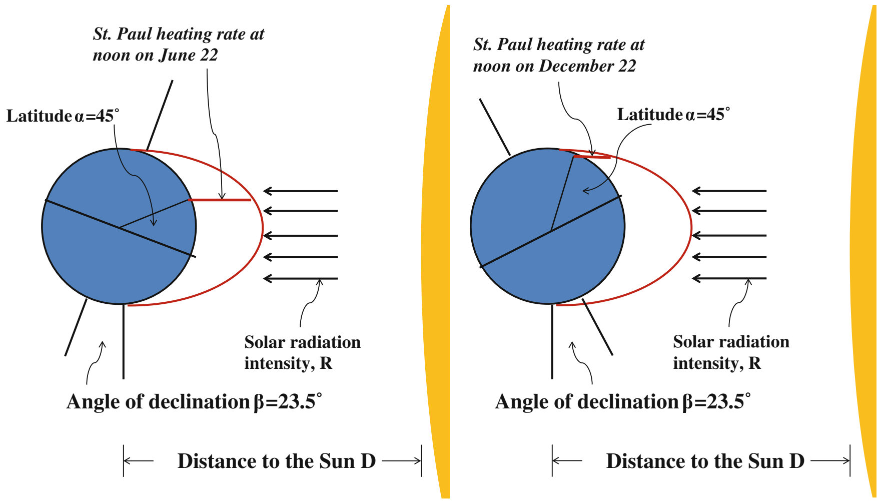

Fig. 10.5 Solar radiation in summer and winter in St. Paul, Minnesota

rate of energy radiation to Earth, R; the distance the Earth is from the Sun, D; the angle of declination of the Earth's spin, β; and, the latitude that you are located at, α. The last three of these variables are purely mechanical, and only the last two vary dramatically with when and where you are located on Earth. Furthermore, only the first—the Sun's radiation rate, is not mechanical. It is both chemical and thermodynamic, and it is usually constant when you are on the side of the Earth facing toward the Sun.

Because of the nonlinear character of trigonometric functions, this effect is even more pronounced at latitudes higher than St. Paul. Thus, if you live in Canada or

Sweden, you will have short and mild summers and harsh winters. At latitudes that are lower than St. Paul, this effect is less pronounced. Thus, if you live in Texas or Southern Italy, your winters will be milder, but your summers will be harsher. There are quite a few things that affect the climate where you live, but latitude is the most significant of these.

The axis of spin of the Earth is wobbling, called "precession", and the rate of precession of this wobble is about one cycle every 25,772 years, or 1° about every 72 years. This precession is pretty long compared to the human life span, so that it is not very apparent to us today. However, the "North Star" that is used today, as well as in the time of mariners such as Columbus and Magellan, was not all that close to North in ancient times due to the precession or wobble of the Earth's axis. According to the historical record, Hipparchus (c. 190–120 BCE) was the first person to notice this wobble (see Chap. 2) (Fig. 10.6).

You may have heard that we are now in the Age of Aquarius. This is due to the fact that the Earth's precession has caused the constellation Aquarius to be the one that is in the Sky when the Sun crosses the celestial equator at the moment of the vernal equinox. Because of the precession of the Earth, each of the constellations in the plane of the ecliptic gets its chance to be at this location at the vernal equinox, and depending on the size of that particular constellation, it gets the title "Age of…" for quite a while. Based on the 12 constellations in the plane of the ecliptic, this span of time works out to an average of 2,150 years for each constellation, but there is considerable disagreement due to the fact that some

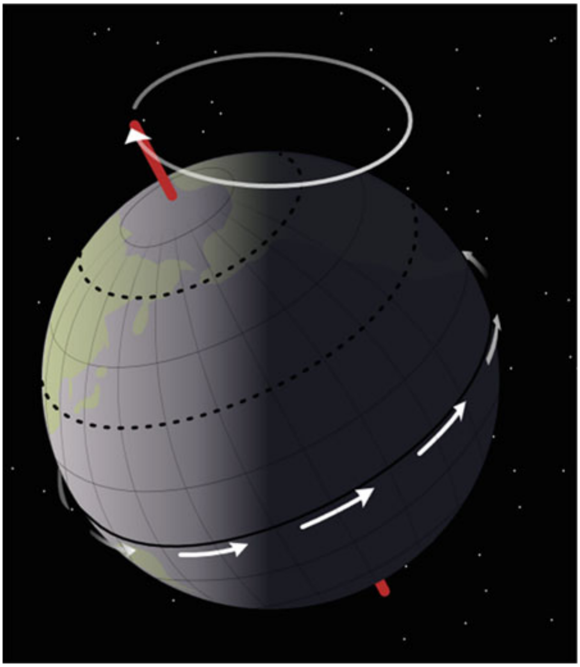

Fig. 10.6 Earth's precession

constellations are larger than others. After all, they were chosen more or less subjectively by humans. And while it is not an exact science, some astronomers agree that the Age of Aquarius has begun, so that we and our progeny will be living in the Age of Aquarius for quite a while to come.

No one knows for certain who invented the constellations. However, it is believed that they were invented primarily for the purpose of nighttime navigation at sea. Professor Archie Roy (1924–2012) of Glasgow University has proposed the (controversial) theory that the constellations were invented by the Minoans, and this theory is related to the Earth's precession [103]. According to the Author, the Minoans were at precisely the right latitude and precession at the time that the constellations were first named, making the Minoans the only seafaring nation capable of seeing all of the constellations in the night Sky from their particular location on Earth's surface at that point in time. This theory is based strictly on mechanics.

But I digress. Let's get back to the weather. What all of this spatially and time-wise uneven solar heating does to the Earth means that the Earth is never in thermodynamic equilibrium, which would only occur if the temperature at sea level on Earth was the same at every location. Since this is not the case, the Earth is in a constant state of thermal flux as it attempts to reach this thermodynamic nirvana.

A study of the First and Second Laws of Thermodynamics will show that wherever there is a temperature difference, heat will flow from hot to cold, and this is the main cause of our weather on Earth. Heat may be carried by a variety of means from hot to cold. One possibility is through the flux of heat in solids, wherein the molecules are molecularly bound. This occurs through the jostling of molecules against one another, thereby transferring kinetic energy from one molecule to the next without the molecules actually trading places (See the discussion on Joseph Fourier in Chap. 9).

What we find is that the time constant for this kind of heat flow is quite large compared to another means of transporting heat, and that is called convection. Convection can only occur in fluids (both liquids and gases), and it is accomplished through the physical transport of atoms and/or molecules, because in fluids they are not molecularly bound to a fixed physical location with respect to their neighboring molecules. The time constant for this type of heat transport is much smaller than that for heat transport in solids. What that means is that a whole lot of the transport of heat on our planet occurs in our atmosphere (a gas) and our oceans (a liquid), and not so much occurs through the Earth's crust (a solid).

There are global sized convective flow patterns set up within the oceans on Earth, and these flow patterns, such as the Gulf Stream and El Nino, are essentially constantly transporting heat from the equatorial regions to the polar regions in an attempt to make up for the spatial difference in heating from the Sun caused by Earth's spherical shape. The viscosity of water causes these currents to move rather slowly, but the latent heat capacity in the oceans causes enormous amounts of energy to be transported by this process (Fig. 10.7).

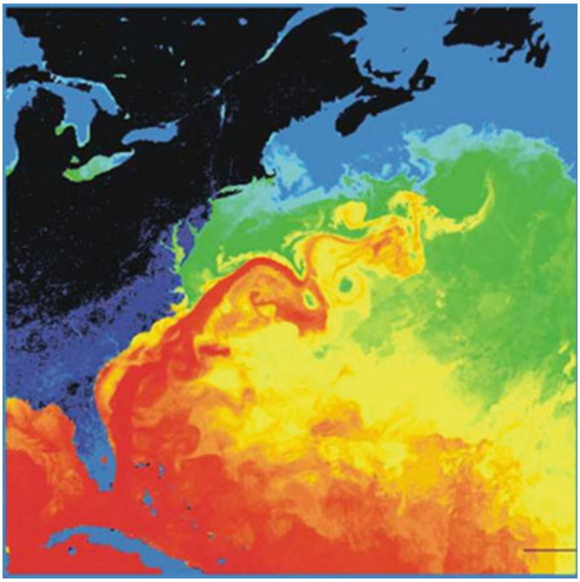

Fig. 10.7 Color enhanced satellite photo of water temperatures in the Gulf stream. *Note* the coast of North America on the *left*

The same phenomenon occurs in the Earth's atmosphere, but due to the much lower density and viscosity of air compared to water, a lot more interesting things happen in the Earth's atmosphere. We call this activity "weather".

When the wind blows where you live, this is essentially nothing more than molecules and atoms of gases in the air racing by you transporting heat by the process we call convection (meteorologists call the horizontal component "advection") from hotter regions to colder regions on Earth. What we refer to as heat is really nothing more than kinetic energy (of motions) stored within molecules and atoms, and these molecules and atoms are being transported to other locations on Earth in an attempt to restore thermodynamic equilibrium. So the next time the wind blows, remember—if the Earth were flat, we wouldn't need wind to reach thermodynamic equilibrium because the Sun would heat every point on Earth more or less equally.

In addition to the fact that the Earth is spherical, there is another interesting and unique feature of weather on Earth, and that is associated with water. So far, ours is the only planet in our immediate neighborhood (of a few light years) that we are aware of that has an abundance of water, and on which water occurs naturally in all three states: liquid, solid, and gas, and this is perhaps the single most important chemical attribute of weather on our planet (It should be pointed out that there appears to be a polar ice cap on Mercury. In addition, both Enseladus, the sixth largest moon of Saturn and Europa, one of the largest moons of Jupiter, are both covered with ice that appears to rest on top of giant oceans).

We're not exactly sure how all this water arrived on Earth. Some scientists think that our planet got hit by lots and lots of ice-laden asteroids early in its life. As a result, more than 70 % of the Earth's surface is covered by water, making it the most abundant material to humankind. Water is essential to all life on Earth. And yet, there is often a problem with water. There is either too much of it, or not enough.

There are about 10^{46} water molecules on this planet. That's a *lot* of water. Where did it all come from? In 2011 scientists photographed a quasar that is 11 billion light years from Earth. Since the Universe is about 13 billion years old, the light coming from that quasar left it only about 2 billion years after the Big Bang, making the light arriving to us from it a window into the distant past, a time that was not so long after the Universe was formed. Scientists were amazed to find a cloud of gas emanating from the quasar that contained about 1 trillion times as much water as there is on Earth. It is theorized that the water in that cloud was formed by the pressure wave that was caused by the creation of that star. That pressure wave created conditions sufficient to bond hydrogen and oxygen atoms into H_2O, which we call water. Thus, we know that water is formed when stars are created, and that it has been around in the Universe for a very long time.

It is theorized that most of the water on Earth was formed by just such a pressure wave shortly after our solar system was created around 4.5 billion years ago. Water is a very stable molecule—most water molecules on this planet mated for life, and their life (and marriage) has endured for an extremely long time!

Each human on this planet has in him or her about 10^{22} water molecules. That may seem like a lot, but as mentioned above, there are about 10^{46} water molecules on our planet. That may also seem like a lot, and to be honest—it is! To put it in perspective, there are about 10^{33} grains of sand on Earth. Scientists estimate there are also about 10^{33} stars in the Universe. So there are about 10 trillion more water molecules on Earth than there are stars in the Universe.

Sounds like a whole lot, doesn't it! But wait a minute, not all of it is the "good" kind of water. Only about 3 % of the water on Earth is potable. Most of it is salt water found in the oceans. Salt water is toxic to humans. Of the 3 % that is potable, about 68 % is bound up in ice, making it inconvenient for human consumption. The cheapest method by far of removing salt from water is to evaporate it naturally by allowing it to escape into the atmosphere (salt does not evaporate) and return to Earth as rain or snow. This could also be accomplished artificially using the process called distillation, but it's actually quite expensive because it requires the use of lots of heat, which is not cheap.

So there may not be enough water on Earth, especially if our population keeps growing at the current rate. There are now about 7 billion humans on Earth, more than have lived in our entire past history. To put it another way, the number of funerals (including my own) in the next century will eclipse all of those in the entire past history of humankind. And within about 50 years from now the world population is expected to double. Unfortunately, nature will not see fit to supply us with a doubling in the supply of water. We will have to solve that problem ourselves. *So there may not be enough water!*

Speaking of ice, water is a really interesting substance. It is the *only* one on our planet that occurs naturally as a liquid, a gas, and a solid, sometimes even at the same physical location. Water melts at 0 °C (under little or no pressure). That is not a coincidence. We humans chose our arbitrary system of measuring temperature to coincide with the melting and boiling points of water because water is so essential to our existence. Thus, just as water melts at 0 °C, it also boils (becoming a gas) at 100 °C.

For those of you who are interested, there is another temperature scale that is commonly used in the U.S. called the Fahrenheit scale. Unfortunately, the two points on this linear scale were chosen badly (apparently based on the climate in Germany), so that the scale results in water freezing at 32°, and becoming a gas at 212°, neither of which is very convenient or descriptive, so that this scale is not used for scientific purposes, or indeed for any purpose at all anywhere but in the United States these days.

And while we're at it, I may as well inform you that temperature is really a perception we humans have of molecular motions. Thus, what we perceive as temperature is really a sensing of mechanics (see Chap. 9). Furthermore, we also measure temperature using mechanics!

This is another transgression, but it's a good one. In the nineteenth century folks were dreaming up the First and Second Laws of Thermodynamics, and they did a darned good job of it, but for one thing—when they finished the Second Law, they realized that they had forgotten to define temperature (Newton forgot to define mass before he introduced the laws of motion, too!). So they came up with the Zeroth Law of Thermodynamics. I know—this sounds silly, but it is nonetheless true.

So the Zeroth Law, attributed to none other than James Clerk Maxwell, says the following: two bodies that are in thermal equilibrium with a third body are also in thermal equilibrium with one another. This sounds terribly simple, and actually, it is! But strange as it may seem, we can use this concept to define temperature, and without it, we have failed to define the most important variable in the Laws of Thermodynamics.

Here is how you can use the Zeroth Law to define temperature. Take a long thin vile holding a highly expandable liquid such as mercury, and put that vile in contact with a cube of ice that is melting. Make a mark on the vile where the meniscus of the mercury is. Next put the vile in contact with boiling water, and make a mark on the vile where the meniscus of the mercury is. Call the first marks 0 °C , and the second mark 100 °C , and then make 100 equidistant marks in between these two marks (because mercury behaves according to the ideal gas law, see Chap. 7). Call this your temperature scale. You may then put this vile in contact with any other object you wish (such as your tongue, which you would never dream of putting in contact with boiling water, but you wouldn't hesitate to put in contact with a thermometer), and when the meniscus stops moving, the object is deemed to be in thermodynamic equilibrium with the thermometer, thus the temperature shown on the thermometer is therefore also the temperature of the object. The thermometer is the so-called "third body" in the Zeroth Law of Thermodynamics.

Interestingly, as I mentioned above, in a similar oversight Isaac Newton forgot to define mass in his book "Principia", but mass had already been more-or-less agreed upon by scientists, via the use of a mechanical balance (described concisely by Archimedes in his principles of the lever, see Chap. 2), which is exactly the same principle as the Zeroth Law of Thermodynamics. Ergo, two objects placed on a balance that cause it to be level, will have the same mass as any other object placed on either end of the balance that causes it to remain level. This is entirely analogous to the measurement of temperature described above! From this we can see quite vividly that there is no way to measure either absolute mass or temperature. They can only be determined relative to something else.

The same principle applies to length, which is why we have chosen the meter arbitrarily to be one ten-millionth of the distance from the equator to the North Pole on Earth (see Chap. 8). Similarly, there is no absolute measure of time. We have simply chosen it at various times in history to be the span of a day on Earth, the span of a year on Earth, and the resonant period of some element such as cesium. It should be apparent by now that literally *everything* is relative!

Let's get back to water. Interestingly, water is denser in the liquid state than it is in the solid state. This is of course why ice floats in your glass of water. That physical property is diametrically opposite to the behavior of most substances known to man. It is so counterintuitive that a great dispute broke out in the early seventeenth century. This unusual behavior of water was actually confirmed by none other than Galileo Galilei.

Scientists today know that the reason for this rather bizarre circumstance is that oxygen forms covalent bonds with hydrogen in such a way that the molecules can pack together very tightly in the liquid state, even more tightly than they can in their crystallized solid state. Thus, ice floats in liquid water.

The complex packing of water in the liquid state also leads to very high surface tension in water, which allows water to exhibit capillary action. What this means is that water likes to climb upwards against Earth's gravitational force in thin tubes. This is the means whereby water goes upwards in plants. Without it there would be little or no plant life on Earth, at least not as we know it today. Need I say, this is yet another problem in mechanics.

Surface tension is also a contributor to evaporation. Although there is a lot of water on Earth, there is only about 0.001 % of it in the Earth's atmosphere. Nevertheless, this is where a lot of the interesting stuff goes on involving water. Most of the water in the atmosphere is popped off the surface of large bodies of water such as oceans, lakes, and rivers on our planet by this surface tension. These molecules get captured by the air at the interface to the water in a process we call evaporation. The surface of the liquefied water is typically heated by solar radiation during the daytime, and the water near the gas–liquid interface reradiates some of this energy at a different frequency back to the air above it, where it is captured by some of the molecules, thus heating the air that contains the evaporated water molecules.

All of this suspension gets excited (resulting in enhanced kinetic motions and therefore energy) and tries to rise above its neighbors. Anyone who has ever seen a hot air balloon in flight will understand that hot air rises. Those parcels of air that succeed in doing so rise further from the Earth's center, but they do so adiabatically,

Fig. 10.8 Firefly 7 hot air balloon in flight

meaning that their total energy remains constant. Since their potential energy is increasing as they rise, some other form of energy must be decreased due to the First Law of Thermodynamics. Typically, the first thing to decrease is the kinetic energy, meaning heat, as reflected in a decrease in temperature of the rising parcels. Eventually, the parcels rise far enough that their temperature is decreased sufficiently for the air to reach saturation, which is a fancy term meaning that the water molecules condense back into the liquid state (or sometimes even the solid state if the air temperature is below freezing), thus forming the bases of clouds (Fig. 10.8).

This is the reason that cloud bases formed by this process tend to be at more or less the same elevation from the Earth's surface. When this rising air is caused by vertical convection, the clouds that form are called cumulus clouds, those puffy clouds that we see so often in summer that appear to be similar to balls of cotton. Alternatively, when the rising air is captured by the wind driving the air nearly horizontally but with a slight uphill component, such as near mountain slopes, the clouds are typically called stratus clouds, those grey and plate-like clouds that we see so often in winter (Fig. 10.9).

As it turns out, this condensation of water into liquid in the atmosphere is another absolutely essential feature for virtually all life on our planet. That is because when water condenses, it undergoes a chemical phase change that releases energy into the atmosphere *(about 600 calories per gm of water vapor!)*, most of

Fig. 10.9 Cumulus clouds

which turns into heat [104]. As described previously, heat is nothing more than increased vibration of the molecules. So the molecules get excited, and they bump up against their neighbors, and that excites their neighboring molecules. A party breaks out, and sometimes the party gets out of hand. The partiers get more and more excited, and they become unstable. Armed with this new-found increase in kinetic energy, the parcels of air rise even more, and as they do so, more and more condensation occurs, creating more clouds, and releasing more energy into the atmosphere, causing the party to grow without any outside intervention. Now we are headed for a thunderstorm!

A thunderstorm occurs when the difference in the potential energy aloft and at the ground becomes so large that the most efficient way for the difference in energy (as required by the First Law) to be mitigated is through the transfer of energy electromagnetically. It takes a staggeringly large difference in potential energy between clouds and the Earth's surface for this to happen. When you see a lightning bolt, it is physically the same phenomenon that produces a shock to you when you walk across a rug at home, but since the distance between the cloud and the ground is so much larger, it takes a much larger energy difference for this to occur.

The thunderclap that results from lightening is nothing more than the acoustic wave produced by the air rushing back into the vacuum created within the shaft produced by the electromagnetic energy rushing from altitude to the ground. All of this happens because water releases energy to the atmosphere when it condenses, and this energy, just like all energy, is trying to reach thermodynamic equilibrium (once again due to the First Law of Thermodynamics) by the path of least resistance (Fig. 10.10).

A cold front is a mass of cold air that is pushing southward in an attempt to find thermodynamic equilibrium. It in turn pushes warm air Northwards ahead of the front (due to conservation of mass). A cold front is capable of producing dangerous thunderstorms. The warm air ahead of the front has moisture in it if it has travelled

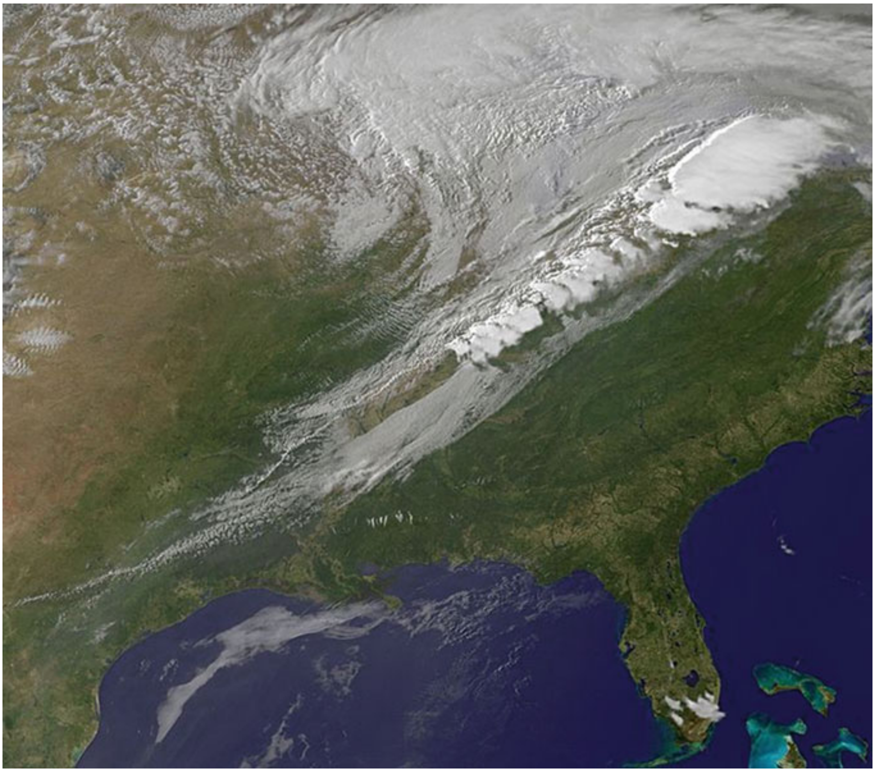

Fig. 10.10 Satellite photo of a line of thunderstorms over the Eastern U.S. on May 3, 2012, photo taken by the Goes-13 satellite

over a large body of water. In the United States, the large body of water that injects most of the moisture into the atmosphere ahead of cold fronts is the Gulf of Mexico. This is due to the fact that the air is flowing in a generally Northerly or Northeasterly direction ahead of the front. Because the Gulf of Mexico is south of only the eastern half of the country, cold fronts produce far fewer thunderstorms over the western half of the country (Fig. 10.11).

The mass of cold air pushing southwards forms a bubble that slides under the warm air. This is due to the fact that the warm air has more kinetic energy, so it rides over the cold air. The warm air has lots of moisture in it from the Gulf, and as it is pushed upwards by the cold bubble of air beneath it, the warm air is cooled adiabatically, thereby causing clouds to form (thus releasing energy to the atmosphere), and eventually enough condensation causes rain, and usually thunderstorms as well. This type of phenomenon would not be nearly so pronounced if we didn't have the Gulf of Mexico feeding moisture into the atmosphere. So the United States has some rather unique geography that encourages the formation of severe weather when cold fronts push south. All of this is driven at least in part by mechanics (Fig. 10.12).

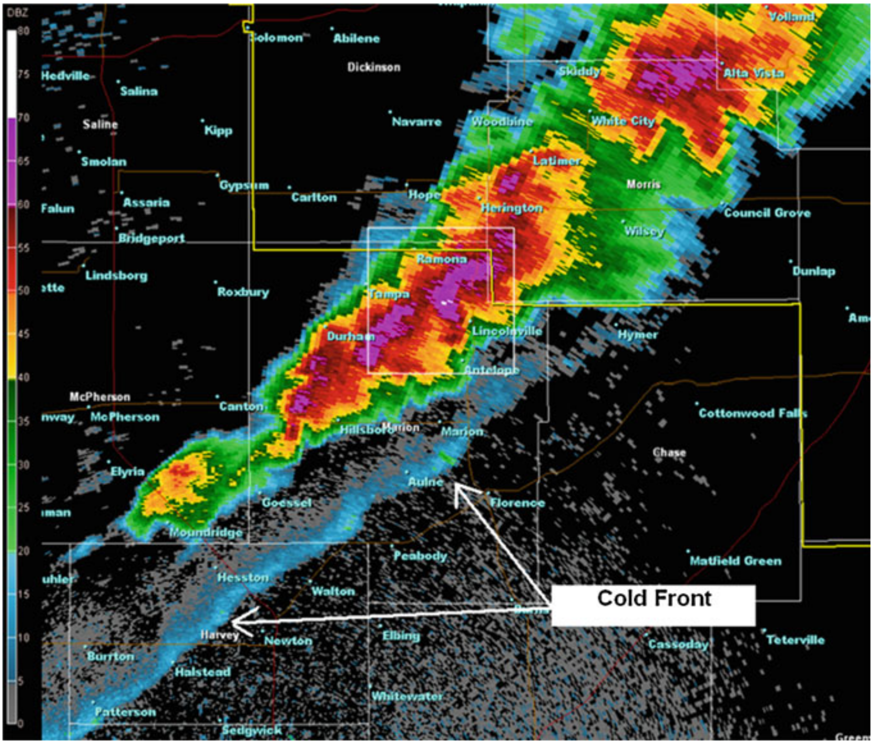

Fig. 10.11 Radar image taken by national weather service Wichita, Kansas WSR-88D on April 3, 2011

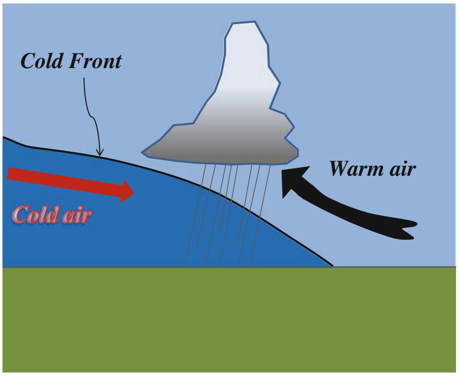

Fig. 10.12 Cross-section of a typical cold front

If water didn't undergo an exothermic reaction when it condenses in the atmosphere, the amount of rainfall on Earth would be negligibly small compared to what we experience. If that were the case, nearly all plant life would not exist on this planet. In that case we would not have an atmosphere, in which case there would be little animal life. So once again we come back to the realization that the peculiar chemical properties of water underlie the nature of our planet.

Now consider the "butterfly effect". This term seems to have been coined by MIT Professor Edward Lorenz in the 1960s. Dr. Lorenz noticed during simulations he was performing to model atmospheric physics that due to inherent nonlinearities in the model small changes in initial and boundary conditions could lead to amazingly large changes in the predicted response. This problem seems to have been first recognized by French Physicist Henri Poincaré in the 1890s, and is nowadays termed "chaos theory".

From a layman's perspective, an example serves to illustrate the issue. Suppose that a butterfly flaps its wings near a tree in West Africa. The tiny disturbance caused by the flap of its wings propagates into the nearby tree (or perhaps even a blade of grass), and this causes a small vortex of air to begin spinning counterclockwise. It has to be spinning counterclockwise, otherwise the Coriolis Force (to be described below) will cause the vortex to dissipate.

The conservation of the angular momentum (Newton's Second Law) in this vortex causes the vortex to tend to continue to spin. Additional energy is added to the vortex by the surrounding environment, and the vortex persists, expanding as it does so. The vortex is transported along by the prevailing breeze, whereupon it is transported over a body of water, whence it picks up water molecules by the evaporation process described above. Upward flow of water molecules within the vortex causes condensation, thereby injecting further energy into the vortex. This process becomes unstable, feeding on surrounding supplies of energy, primarily in the form of energy acquired from solar radiation and stored as heat in bodies of water. If the prevailing wind direction is just right, the vortex floats out over the ocean, and under just the right set of climatic conditions a hurricane is born.

As we have previously seen, the Earth is spherical (due to gravitational forces), and the radiation from the Sun comes to us in an essentially planar wave structure. Due to the incompatibility of these two shapes, more energy is supplied to equatorial regions of the Earth than at the poles, thus the Earth is constantly trying to reach thermodynamic equilibrium (due to the First and Second Laws of Thermodynamics).

Our newborn hurricane now goes on a quest to mitigate the spatial difference in energy state caused by the spherical shape of the Earth. So where does the hurricane go? The answer is—wherever it can equilibrate the spatial variation in the state of energy the most expediently. Typically, in the case of West Africa, the best place for this to occur is the Southeastern United States during the late summer months, where a great deal of heat has been stored up over the preceding summer months. So off goes this hurricane in search of plunder.

A typical category four hurricane has about 1 PW of power during the daytime. In layman's terms, this means that the hurricane is expending energy at the rate of about one ten megaton nuclear explosion every 20 min. Needless to say, it's a good idea to stay away from this monster if at all possible, but that is not always expedient. Thus far no one has figured out on this planet how to tame one of these wild freaks of nature. Until they do, the weather will be one of the most powerful

Fig. 10.13 Satellite photo of hurricane Katrina on August 28, 2005

destructive forces on our planet. Thus, as water giveth, it also taketh away (Fig. 10.13).

So we have these two major causes of global weather: the shape of the Earth; and, the peculiar properties of water. Without both of these, weather on this planet would be at the very least quite different.

Another interesting feature of our weather that is directly caused by mechanics is due to the Earth's spin on its axis. As we all know, the Earth makes one complete revolution on its axis every day, and that is in fact how we define the duration of a day. This rotation is caused by left over angular momentum from the impact of the Earth with an object about 2.5 billion years ago, as discussed above.

When the Earth was struck by this object the impact occurred at an angle that was oblique to the surface of the Earth, causing the Earth to start spinning. In the absence of any external forces, this momentum will persist forever. However, this left over angular momentum is slowly depreciating with time, so that a day is growing ever so slightly longer with time (about 1 s every 18 months). This slowing of the Earth's rotation is caused by tidal friction, thus causing the Earth to slowly transfer momentum to the Moon, which is causing the Moon to slowly move away from the Earth. In fact, if the Earth and the Moon continue on this pace, a day and a month will eventually converge, meaning that the Moon will be orbiting about the Earth at the same rate that the Earth is spinning, but you needn't worry about that happening any time soon.

Anyway, the Earth's spin about its own axis causes every point both within and on the Earth's surface to possess a small amount of angular momentum with respect to any coordinate system constructed relative to a given location on the Earth's surface. The force generated by this angular momentum is called the Coriolis Force, after Gaspard-Gustav Coriolis, who was the first to describe it in a scientific paper in 1835. The force is caused by the moment resulting from the angular momentum multiplied with the moment arm about the center of rotation of the object.

This force is the physical principle behind Foucault's pendulum, first demonstrated in 1851 by Léon Foucault (1819–1868) in the Paris Observatory. A few weeks later it was put on public display at the Panthéon in Paris (No, it's not the Roman Pantheon. That one is in Rome.). If you travel to Paris, make sure that you visit the Panthéon, because there is a reproduction of Foucault's pendulum therein, and it is 67 m tall!

Interestingly, if you are standing on the Earth's equator, the vector representing this angular momentum is parallel to the Earth's surface, as shown in Fig. 10.14. That means that the Earth's angular momentum tends to make you fall down. Of course, you do not fall down, and that is because this component is very small and your body is compensating for this.

Now note from Fig. 10.14 that if you are standing at the North Pole this vector causes you to want to spin around, but once again your body compensates for it

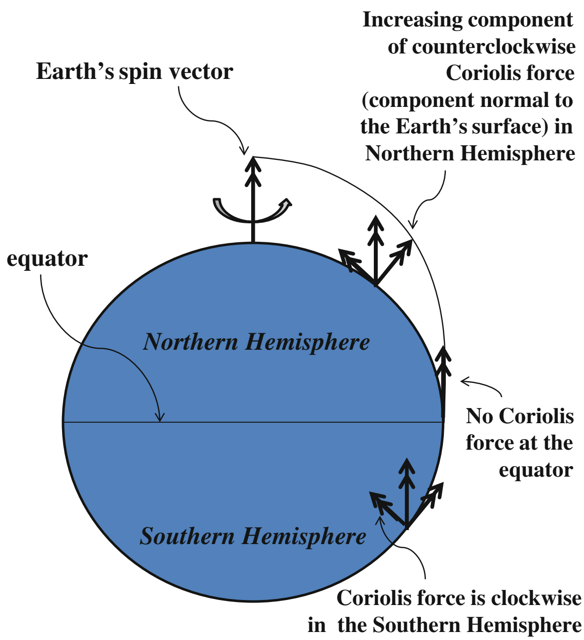

Fig. 10.14 The Coriolis force

(I'm assuming that you have actually been to the North Pole!). Still, the liquid and gaseous molecules within your body will tend to spin (at the rate of exactly one revolution per day) in a counterclockwise direction (and in a clockwise direction if you are at the South Pole, where, since you will naturally invert your coordinate system so that you are not standing on your head, thus resulting in a change in sign of the direction of spin relative to you). In between the poles, the component of spin normal to the Earth's surface decreases as you approach the equators, due to the decomposition of the angular momentum vector into components perpendicular and parallel to the Earth's surface, as shown in Fig. 10.14.

The Coriolis Force therefore tends to make liquids and gases appear to spin counterclockwise in the Northern hemisphere, and clockwise in the Southern hemisphere. I say "appear to" because it is really a matter of what coordinate system you are referring the movement with respect to, another example of relativity. If you use a coordinate system that is rotating with the surface of the Earth, it will appear that the object is rotating, but if the coordinate system itself is fixed so that the Earth spins with respect to it, the object will not appear to be spinning.

What all this means is that air in our atmosphere tends to spin counterclockwise with respect to a local coordinate system aligned with one axis pointed away from the center of the Earth in the Northern Hemisphere (and conversely, clockwise in the Southern Hemisphere), and this effect is ever more pronounced as the air approaches the North Pole because the component of the Coriolis Force perpendicular to the Earth's surface increases with latitude, as shown in Fig. 10.14.

Interestingly, right at the equator, the component of the Coriolis Force perpendicular to the Earth's surface is zero, so that air particles do not tend to spin horizontally at the Earth's equator. Unfortunately, there is sufficient force outside this equatorial band to nevertheless cause enough rotation to overcome the small amount of friction in the air, so that once a volume of air begins to rotate, the Coriolis Force is large enough to provide sufficient angular momentum to the spinning volume of air to keep it rotating. This is bad news, because air that is rotating counterclockwise in the Northern Hemisphere (and vice versa in the Southern Hemisphere) will have a small amount of what we call "convergence", which is a fancy term for molecules wanting to come to together, and this effect will inject more and more kinetic energy per unit volume into the atmosphere, thereby providing fuel for water vapor to condense. And as we now know, when water condenses, it injects more energy into the atmosphere. So this counterclockwise spinning seems to just keep going and going, almost as if it is self-fueling. But it really gets its start from the Coriolis Force. Later on, it gets its fuel from wherever it wants to, but a lot of it comes from condensation of water vapor in the atmosphere. And this is how major weather patterns are formed on our planet. So once again we see that mechanics plays a big part, but without water, weather wouldn't be very interesting.

Now we have a bit of an understanding of how big weather patterns get going. They can be hurricanes, but they can also be cold fronts. In either case, it's all about the Earth trying to reach thermodynamic equilibrium, thus pushing warm air

Fig. 10.15 Tornado in central Oklahoma, May, 1999, photo shot by en:VORTEX-99 team

towards the poles, and cold air towards the equator. These big weather systems can be on the scale of hundreds or even thousands of miles. But typically, the highly active portions of these systems are usually on a scale about one tenth of the Earth's radius, which is about 6,366 km (3820 mi). So a typical hurricane or cold front has an active portion on the order of 640 km (380 mi). Interestingly, there are nasty things that can happen on one length scale down from this, such as the width of a line or band of thunderstorms, which might be about 60 km (35 mi) in scale. And we can go down another length scale to about 6 km (3.5 mi), which is about the scale of a single cell in a line of thunderstorms. One more length scale down, and we come to the scale of a tornado, about 0.6 km (0.35 mi). And yes, we can go even further down, to about 0.06 km, (0.035 mi), which is the scale of a typical gust of wind (Fig. 10.15).

My, what a mess! We have nasty things occurring within our atmosphere on Earth at virtually every length scale up to the size of the Earth itself. Why is all of this occurring? The answer is—because it can! Whether it was a sadistic plan by a supernatural being, or whether it was just plain luck that produced the physics that govern our Universe is neither here nor there. The fact is, the physics that governs weather on our planet is nonlinear, and this nonlinearity causes really nasty things to occur on a wide range of length scales.

So let's talk a little bit about how that works. There are about 10^{44} molecules of air on Earth. That's a lot! Because there are so many, shortly after the turn of the nineteenth century, several scientists decided to assume that's pretty close to infinite. Thus, the field that we call today "continuum mechanics" was born (see Chap. 9). Among the early practitioners of continuum mechanics was the French scientist Claude-Louis Navier (1785–1836). He proposed a model for predicting the motions of liquids and gases in 1821 that was later more fully elucidated by George Gabriel Stokes (1819–1903), so that today we call the equations resulting from this model the Navier–Stokes equations. These equations have been shown to do a pretty good job of predicting the motions of most fluids, including liquid water and gaseous air. Unfortunately, these equations are nonlinear, and that nonlinearity introduces instabilities that cause all sorts of bad things to happen, not the least of which are spinning vortices on multiple length scales such as found in our global weather. So much of our problems with weather stem from mechanical nonlinearities in the way that fluids behave. In other words, mechanics plays a big part in Earth's weather.

But this doesn't explain the entire problem. The Navier–Stokes equations don't account for the chemistry resulting from water changing phases (from gas to liquid to solid), nor do they account for electromagnetic effects in our atmosphere (such as lightning). In order to account for these effects, the Navier–Stokes equations have to be modified and made quite a bit more complicated, and this has in fact been done by atmospheric physicists. What all of this means is this—we understand the chemistry, thermodynamics and mechanics of what goes on in our Earth's atmosphere, but *we nevertheless still cannot predict the weather accurately!*

This situation is rather baffling to most people who have never encountered such a complicated situation. However, there is in fact a similar situation that occurs in an application that many more people on our planet are studying than the weather, and that is the human body. So those of you who are in the medical field should understand what I am referring to when I say that we understand the problem, but we still can't solve it, because we have encountered the same situation with many diseases. We will discuss this problem more later, but for now, let's get back to the weather.

For the sake of convenience, let's just assume that if we had a model that could predict where every molecule in the Earth's atmosphere would go in the future as a function of time and space, then we could predict our global weather on Earth (because we do in fact already have this model!). Now, let's talk about taking that model and putting it into practice. As I said before, there are about 10^{44} molecules of air on Earth. In order to model each and every one of those molecules, we will have to deploy each of the equations in our model for every one of those molecules. That will raise the number of unknowns by about an order of magnitude, to 10^{45}, and we will have to know all of this information at each instant of time as far out in the future as we need to predict. So let's suppose that we can write up our model into a computer code for this purpose (because this has in fact been done!). Let's now go find a computer that will handle all of this computing for us. It shouldn't surprise you to know that we will need a computer that can handle 10^{45} pieces of information at each instant of time. Let's go find that computer.

Okay, first we'll look in our general neighborhood. The very best laptops that we can find today can handle about 10^{15} bits of information. That's not going to cut it. Well, let's get all of our neighbors together and link up our computers into a "cloud computer" (pun intended!). For convenience, suppose our neighborhood is really big, like it includes every person on Earth, and they all have this same powerful laptop. That will get us to 7 billion $\times$ 10^{15}, or about 10^{25}. Unfortunately, that's only a very tiny bit of the way there, so this approach is not going to work.

So let's go another way. Let's go find the best supercomputer that we can. The fastest supercomputers on Earth today can only run at speeds of tens of petaflops (10^{15} calculations per second). It is estimated that the ability to run at exaflop

Fig. 10.16 Photo of Earth taken from Apollo 17 showing the global scale of weather

(10^{18}) speeds are still about 20 years away. Therefore, we're not going to get there that way any time soon either (Fig. 10.16).

But wait a minute. Suppose we don't feel the need to model every molecule on Earth. What we'll do is only model one hemisphere (Say, the Northern). That will cut our time in half. But that is still not good enough. Let's just model North America. That will cut it down by an order of magnitude. So we're now down to perhaps 10^{44} calculations per second that are needed, but we still have no computer that is even close to what we need in order to model weather phenomena on multiple length scales.

How long will it be before we can solve this problem of predicting the weather accurately? Fortunately, we have an accurate model for that. It's called Moore's Law, named after Gordon E. Moore (1929), who reported his law in a journal article in 1965 [105]. What it says is that computers will double their performance every eighteen months, and Moore's Law has been accurate for more than a century now. So if Moore's Law continues to hold, how long will it be before we have a supercomputer large enough to predict global weather? The approximate answer to this question can be obtained by solving the following equation for n:

$$10^{46} = 2^n \times 10^{18}$$

Solving the above will tell us that there will have to be $n = 93$ doublings of computer capacity, or 140 years will pass before we have a computer powerful enough to make accurate predictions of global weather patterns. This is absolutely amazing! We seem to have a model, but we do not have the computing power to solve it. Our generation is not quite the first in human history to encounter this problem (see Chap. 9), but we are now encountering it in a number of disciplines. For the first time in human history, we understand a myriad of problems well enough to construct robust models, but we can't solve them using our current state of technology.

So if you were planning to become a meteorologist, this discussion should give you some comfort. The weather is not going to become concisely predictable any time soon, meaning that your chosen profession is likely to be needed for several generations to come, at least on planet Earth. Until then, we will likely continue to make weather forecasts that rely heavily on satellite imagery, another problem related to mechanics.

We have now seen that mechanics plays a pivotal role in the Earth's weather. So once again we come back to the subject of this book, and in this case we are talking about weather. Just exactly how does weather shape our world? Here is a partial list for starters:

- Erosion from rain and wind forms hills, valleys, and rivers
- Rain provides sustenance for plant and animal life
- Humans plan their travel based on weather where they are going, thus affecting global transportation networks
- Major storms bring many (or sometimes all) means of transportation to a halt
- Weather can upset world financial markets, such as when orange groves freeze in Florida
- Weather can make your day or ruin it
- Extreme weather is known to wipe out entire species (possibly someday including our own).

Thus, it should be clear that the mechanics of weather plays a major role in shaping our modern world.