global warming. But that is what the research was funded to study.

A widely publicized study by Naomi Oreskes in 2004 claimed that of 928 abstracts of published research articles dealing with "climate change," none were found that disputed the scientific consensus that recent global warming can be attributed to humans. Aside from the fact that I have a stack of such papers in my office, I would wager that neither did any of those 928 articles demonstrate that our current global warmth is not due to natural causes. Manmade global warming is simply assumed to be true because we have no reliable way of observationally separating natural sources of global warming from human sources.

Maybe the "fact" that the Earth has warmed can be considered to be "truth." *Why* the Earth has warmed, though, is another matter entirely. If you want possible physical explanations for what we observe in nature, go to science. If you want truth, go to church.

Next, I would like to give you a crash course, Weather & Climate 101. Don't worry, there are no tests, and I will keep it as simple as possible. Just bear with me, and by the end you will have a better appreciation for just how complex the climate system is. Then, you can judge for yourself whether science knows enough to claim that "the science is settled" on manmade global warming.

*. . . now I'll pointlessly show the isobar map as usual*

# Chapter 3: How Weather Works

While most books on global warming try to convince you that this or that scientific study shows evidence for or against manmade global warming, that feels too much like a contest to me. It's as if whoever can list the most published research findings supporting their side wins. But science isn't about winning debates, or taking a vote, or forming a consensus. The climate system is, or is not, sensitive to mankind's greenhouse gas emissions.

So, rather than covering an endless list of specific scientific papers and what they claim to have discovered about climate change, I instead want to equip you with a basic understanding of how weather, and thus climate, works. I want you to appreciate how complex the climate system is, how little we really know about it, and what its most fundamental purpose is: to get rid of excess heat. Finally, I will describe what I believe to be the thermostatic control mechanism that will limit the amount of climate change we will experience from human activities.

By teaching you the basics of how weather operates, I hope to make you informed enough so that you can think about the atmosphere and how it behaves and then make your own judgments. This is better than to ask you blindly to accept some scientist's claim that humanity has only ten years left to do something before we are all doomed.

So to get you going on this little lesson, let's start with weather. Weather is the source of endless fascination for me, and probably for many of you as well. It seems that everyone is interested in the weather, especially those who live in areas that are subject to severe weather threats. And that would include just about everyone. Severe thunderstorms, hurricanes, tornadoes, windstorms, floods, droughts, hail, lightning, snowstorms—all of these make us want to understand how weather operates.

I also have found that nearly everyone has some fundamental beliefs in common about the weather. There are several weather truisms that observe no geographic boundaries. The first is: where you live just happens to be the most difficult place to forecast for in the whole country. Secondly, if you don't like the weather right now, just wait ten minutes. Finally, weather forecasters are incompetent fools. While that last one might well be true, at least weather forecasters can usually explain to you, in learned terms, why they screwed up the latest forecast. We also took classes in college with names like "Effective Weather Lying."

And now, the threat of global warming makes weather even more relevant to our lives, or at least to the lives of our children, grandchildren, and the current crop of politicians and climate scientists. More people than ever are now interested in the weather. This is especially true after they learned that global warming was going to cause even more severe thunderstorms, hurricanes, tornadoes, windstorms, floods, droughts, hail, lightning, snowstorms —all possibly as soon as the day after tomorrow.

I became interested in the weather while in high school because of a buried sewer pipe and some dead sheep. Really. Late in my senior year, we had a "career day" for which we could choose any local governmental office to visit. We would learn first-hand how that office operated and what working there was like. The student assignments to these offices were on a first-come, first-served basis. The National Weather Service Office slot was always the first to go.

I would like to report here that I got that slot, but I didn't. Unfortunately, I've always been a procrastinator. Since I was the very last one in the senior class to sign up, I got what had historically been recognized as the *least* desirable choice: the public health department. While the other students had a day of fun, I traveled around the county that day with a health department employee inspecting a broken sewer line, and then a bunch of dead sheep that a farmer had left in a ditch by the side of a road.

I was soooo jealous of the kid who got to go to the weather office on that day. I think that was the first glimmer of interest in a weather career for me.

What is the difference between weather and climate? Believe it or not, there really isn't any strict definition. It is probably sufficient to say that climate is the average weather for a certain time of year at a certain location. Or, it can be the average temperature for the whole Earth over many years. Either way, climate is just average weather.

For instance, for the last thirty years in Podunk, Michigan, the month of July experienced an average high temperature of 83° Fahrenheit, an average low of 62° Fahrenheit, and 5.6 inches of rainfall. Those are the climatological averages. The average surface temperature of the whole Earth is estimated to be about 57° Fahrenheit. That is the climatological average.

But there is another important distinction between weather and climate, one that helps to explain why forecasters have zero forecast skill beyond about ten days in advance, yet most climate researchers think we will be able to forecast the average climate decades in advance. Weather forecasting is an example of an "*initial value* problem." By measuring the initial state of the atmosphere with weather balloons, airplanes, and satellites, we can, in effect, extrapolate current weather trends into the future by using equations in a computerized weather prediction model. But beyond about ten days, the skill with which we can do this drops to near zero. This ten-day limit has usually been attributed to the "butterfly effect," whereby unmeasured events, even tiny ones like the flap of a butterfly wing, can influence the weather many days later. So, even if you just burp outside, within a few weeks global weather patterns will be totally different than if you had not burped. I'm glad someone named it the butterfly effect instead of the burp effect.

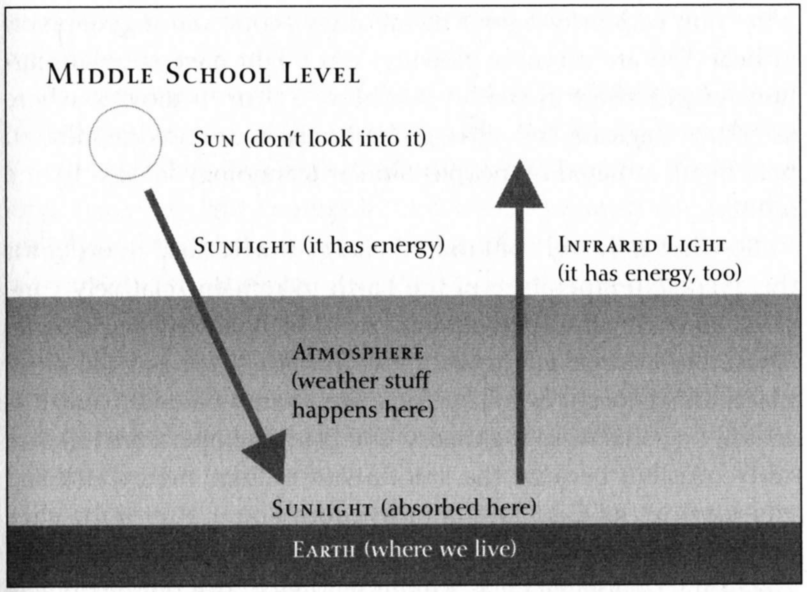
In contrast to this "initial value problem" of weather forecasting, climate forecasting is a "*boundary value* problem." In this kind of forecasting, we examine how small changes in the rules by which the climate system operates can change the average weather. In the case of global warming, mankind is adding carbon dioxide, a known greenhouse gas, to the atmosphere. This will, to some extent, change the way the atmosphere moves heat around in an average sense. Thus, even though climate modelers cannot forecast what the weather will be like on July 4, 2019, they hope to be able to estimate how much warmer the year 2019 will be than, say, 1999. They expect that a small change in the rules by which the climate system operates will translate into an ability to forecast how the average weather (climate) will change.

Now let's examine the most basic processes that determine how our weather operates. We'll use the following simplified illustration, which is appropriate for either middle school students or congressional testimony.

### THE SUN WARMS THE EARTH

The starting point is the energy source for our weather: the sun. The accompanying illustration shows that sunlight gets absorbed by the Earth, and this causes weather stuff to happen in the atmosphere (more about that later). Take a few seconds to look at the basic processes in this illustration. Go ahead ... I'll wait.

The one process that you might not recognize in this illustration is infrared radiation. As we shall see, this just happens to be the one process we are most interested in when it comes to global warming.



### INFRARED LIGHT COOLS THE EARTH

In our illustration, sunlight is warming the Earth, and by itself that sunlight would cause the Earth to get continuously hotter and hotter if there wasn't some way for the Earth to also get rid of heat. The way the Earth does this is almost entirely through infrared (or "heat") radiation, which is being continuously emitted by the Earth to outer space.

Even though the habitability of the Earth depends upon it, infrared light is not very well understood by most people. This is probably because it is invisible. But we can feel it. You are no doubt familiar with the infrared radiation you feel at a distance from a fire, or a red-hot stove element. You notice these sources of infrared light because our skin (unlike your eyes) is sensitive to it, especially if the source is very hot.

In fact, *everything* absorbs and emits infrared radiation. The hotter something is the more infrared energy it emits. Even you, sitting there reading this book, are losing infrared radiation to your surroundings. The infrared energy you radiate helps to cool you off in response to your metabolism's continuous generation of heat. You are invisibly glowing. You might have seen simulations of this effect in the hit TV show "24," or in movies, where satellites (magically) see through buildings and sense the infrared heat being radiated by people. Similar technology is used by the military.

So what is the role of infrared energy in weather? In order for the average temperature of the Earth to remain relatively constant, all of the absorbed sunlight must be balanced by an equal amount of infrared energy escaping from the Earth back to outer space. This concept is called "radiative energy balance," and it is central to global warming theory. The Earth's temperature remains fairly constant because the amounts of radiant energy entering and leaving the Earth system are about equal. Any imbalance between the solar input and the infrared output will cause either a warming tendency or a cooling tendency. The bottom line is this: a constant temperature requires that energy in = energy out.

Let's return to the example of your body losing infrared energy to your surroundings. Since your surroundings are also losing energy (in proportion to their temperature), your body is also *absorbing* infrared light at the same time it is *emitting* it. But since your body is usually warmer than your surroundings, you send out greater amounts of infrared heat than your surroundings send back to you. In this case, the infrared energy leaving your body is greater than that being absorbed by your body, and so you are "radiatively cooling."

Now replace your body with the whole Earth (figuratively speaking, of course). The Earth is continuously emitting infrared radiation to outer space, day and night. The infrared energy emitted by outer space toward Earth is almost zero, and can be ignored. The amount of infrared radiation emitted, averaged over the whole Earth over many years, is believed to be very close to the amount of sunlight that was absorbed over the same period of time. Again, radiative energy balance, and so a relatively constant temperature. The magnitude of the solar heating and infrared cooling, averaged over the whole Earth, is estimated to run about 235 watts per square meter (which is about 22 watts per square foot).

As an everyday example of the role of infrared radiation, we all have the experience of the air cooling off after the sun goes down. Strictly speaking, it doesn't cool off at night because there is no longer any sunlight coming in. It cools off because the infrared cooling (energy out) exceeds the solar heating (energy in), which of course is zero at night.

Then during the daytime, even though the Earth is continuously losing infrared heat to outer space, the amount of energy being absorbed from sunlight is greater than that being lost. In this case, the energy in exceeds the energy out, and so everything warms up.

Since our eyes are not sensitive to infrared light, it takes some mental practice to get used to the idea that the Earth is continuously emitting infrared energy to outer space. For some reason, we humans have a difficult time believing something exists when we can't see it. There is a simple experiment you can do to actually feel the Earth cool. On a clear cool evening after the sun has set, stand on a driveway, parking lot, or even a grassy area, that had been heated by the sun during the day. Hold your hand out horizontally, palm facing down. Then turn your hand over, so that your palm is facing up. Keep flipping your hand over, palm up, then palm down. As you do this, you will be able to sense the different amount of infrared energy coming up from the warm ground versus coming down from the cold sky. *Voilà*, you are now an infrared radiometer.

Nighttime infrared cooling of surfaces exposed to the cold sky explains why dew forms on cars, grass, and other surfaces. Objects placed under a tree will stay warmer at night because those objects are being heated by infrared radiation from the tree, rather than losing so much infrared energy to the relatively cold sky.

Another aspect of infrared radiation that makes it more difficult to conceptualize than sunlight is the fact that *everything* is continuously emitting and absorbing infrared heat. Whereas only the sun can emit sunlight, infrared radiation is being continuously emitted (and absorbed) by everything—buildings, trees, grass, air, clouds, etc.

Because the upward and downward flows of infrared radiation in the atmosphere are so complex, our intuition fails us when we try to figure out how they affect the temperature structure of the atmosphere. Instead, we have to run what is called a radiative transfer model in a computer that contains the relevant physics. Don't try this at home . . . leave it to trained professionals.

This is why global warming theory is a little difficult to understand for layman and expert alike. Global warming theory involves how infrared energy is redistributed within, and lost by, the surface and atmosphere, and those processes are totally invisible.

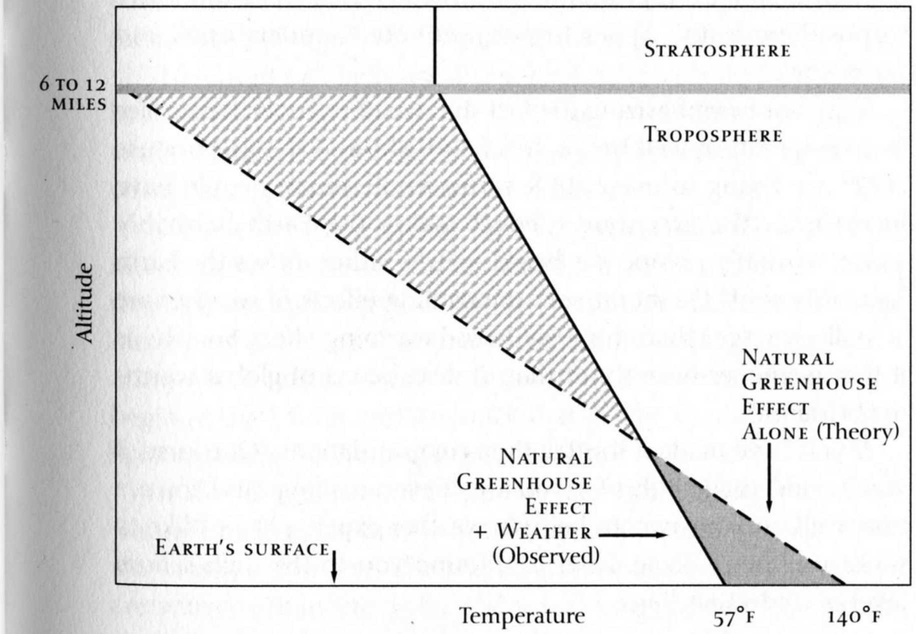
While we will address global warming theory in more detail in the next chapter, at this point I am just trying to get you used to the idea that solar heating and infrared cooling are what "drive" our weather. And those infrared processes in the atmosphere are what lead to the Earth's natural "greenhouse effect."

## The Natural Greenhouse Effect and Weather

Greenhouse gases are those atmospheric gases that strongly absorb and emit infrared energy. If your eyes were sensitive to the infrared wavelengths of light that greenhouse gases absorb and emit, you would not be able to see very far. Looking around, you would see an infrared "fog" everywhere, as if you were in a cloud. The major greenhouse gases in the Earth's atmosphere are water vapor (which accounts for about 70 percent to 90 percent of the Earth's natural greenhouse effect), carbon dioxide, and methane. Additionally, clouds also have a large greenhouse effect, but clouds are not a gas. They are made up of tiny liquid water droplets or ice crystals.

The most important thing to remember about greenhouse gases in the atmosphere is that they act like a blanket, making the lower atmosphere warmer, and the upper atmosphere cooler, than those layers would otherwise be without the greenhouse gases. This is somewhat analogous to a blanket covering your body. The blanket keeps you warmer and the air on the outside of the blanket cooler, than if the blanket was not there. But whereas a blanket primarily works by preventing the movement of the air that is heated by your body, a greenhouse gas is a "radiative blanket" that keeps the lower atmosphere from cooling too rapidly.

Even most meteorologists don't realize this, but the existence of our weather depends upon the greenhouse effect. The dotted line in the following diagram shows how the temperature of the troposphere (the lowest layer of the atmosphere, where our weather occurs) would change with height if there was no weather. The average surface temperature of the Earth would be around 140° Fahrenheit, and the altitudes at which jets fly would be so cold that their fuel would gel. Since we can't actually prevent the atmosphere from producing weather, this is a theoretical calculation made from a radiative transfer model.



*The Earth's natural greenhouse effect "wants" to make the Earth's surface unbearably hot, but the cooling effects of weather prevent most of that warming from occurring.*

This 140° Fahrenheit greenhouse temperature is, I believe, the best starting place to explain what drives our weather. The combination of solar and infrared radiation together "tries" to make the Earth's surface extremely hot. But long before that temperature state is reached, the atmosphere becomes "convectively unstable," which just means that warm air starts to rise and cooler air starts to sink. The real atmosphere overturns continuously, transporting excess heat from the surface to high in the atmosphere. All of the processes associated with this overturning are part of what we call weather.

The shaded region in the lower part of the diagram represents how much temperature decrease is caused in the lower troposphere by weather processes. The hatched region in the upper troposphere represents the temperature increase that results from weather processes transporting that heat up from below. The most dramatic examples of this transfer of heat from the lower troposphere to the upper troposphere are thunderstorms and hurricanes.

Why am I emphasizing the fact that weather cools the surface to a temperature well below what sunlight and the greenhouse effect are trying to make it? Because, while many people have heard that "the greenhouse effect makes the Earth habitably warm," virtually no one has heard that "weather makes the Earth habitably cool." Quantitatively, the cooling effects of weather are actually stronger than the greenhouse warming effect. So, why is it that we never hear about that in discussions of global warming? Hmmm?

If you have made it this far, then congratulations. (Of course, if you haven't made it this far, you aren't even reading this.) You are now well on your way to being a weather expert—or as I like to say, a weather weenie. I am promoting you to the high school level of understanding.

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## HEAT REMOVAL FROM THE EARTH'S SURFACE

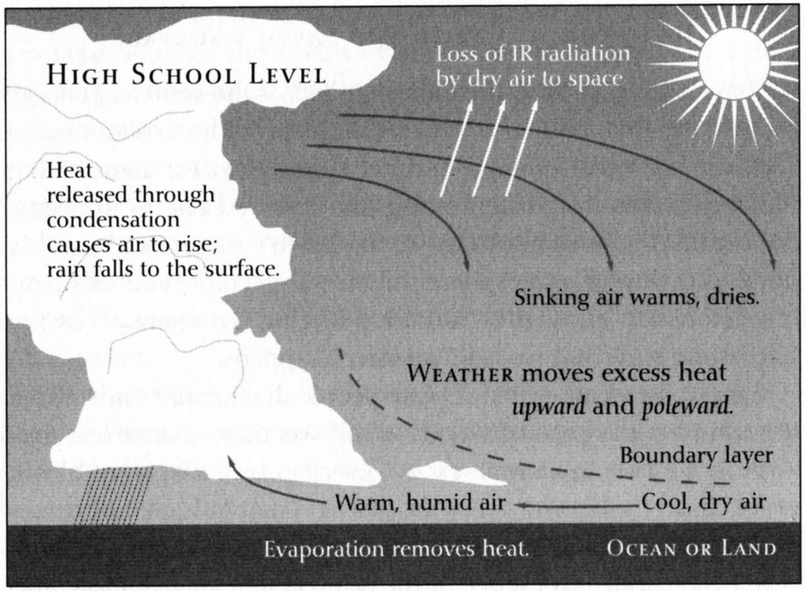
We have addressed how incoming sunlight is the source of energy for our weather, and how infrared light provides a way for the Earth to lose excess energy to outer space. Next we learned that the combination of solar heating and infrared energy transfers are continuously trying to make the Earth's surface unbearably hot and the upper atmosphere unbelievably cold. What happens in response to all of this "radiative forcing" is where all of the interesting stuff that we call "weather" happens.

Even most weather and climate people don't really think about the ultimate purpose of what we call weather: *to move heat from where there is more, to where there is less.* Every gust of wind that blows, every cloud that forms, every drop of rain that falls, all happen as part of processes which continuously move excess heat from either the surface to higher in the atmosphere, or from low latitudes (tropical regions) to high latitudes (polar regions).

These flows of heat are a demonstration of one of the most basic laws in science—the Second Law of Thermodynamics—which in simple terms just states that energy tends to flow from where there is more to where there is less.

Now we are ready for the high school version of our weather illustration. It shows an idealized thunderstorm extending through the full depth of the troposphere. While there are a number of pathways that energy can follow in the process of creating our weather, here I will describe the dominant one. We begin at the Earth's surface, since that is where most of the sunlight entering the atmosphere is absorbed.

In our illustration, the land surface and upper ocean are warmed by the sun. But the resulting temperature increase is not the same everywhere. The tropics receive more sunlight, and so are warmer, than the polar regions. Clear regions receive more sunlight, and so get warmer, than cloudy regions. The land warms up faster than the oceans. The point is that the temperature of the Earth's surface is pretty uneven.



Ultimately, it is the difference in temperature between one region and another that cause air currents (wind) to blow across the surface of the Earth, which then pick up heat from the surface and move it someplace else. The heat transferred from the surface to the overlying air is either *sensible* (an increase in air temperature) or *latent* (water evaporated from the surface, adding water vapor that contains the latent heat of vaporization to the air). Now stick with me here, because this is really important.

*Latent heat loss by the Earth's surface through evaporation is the dominant mechanism for cooling it.* "Latent" refers to the fact that the heat energy added to the air does not increase its temperature, but is instead used to change the water from its liquid form to its vapor form. The process of evaporation requires energy, and explains why a breeze blowing on your wet skin feels so cold. The water is stealing heat from your body so it can turn into water vapor.

At least 90 percent of the heat lost by lakes and oceans is through the energy required just to evaporate water from the surface. For land surfaces, much of the evaporation occurs from

water cycled through plants as part of the growing process, which is called evapotranspiration.

The astute reader at this point might be a little confused about the role of water vapor. I previously had described how water vapor has a strong greenhouse warming effect on the lower atmosphere. Now I have just told you that the evaporation of water is the dominant cooling mechanism for the surface. So, which is it? Does water vapor cool the surface, or warm the surface?

The answer is—it does both. When the surface water is evaporated to form vapor, it removes heat from the surface. After that, the vapor then helps warm the surface through the greenhouse effect. Of course, both of these effects are happening at the same time, continuously. Water is a miraculous substance, performing a wide variety of functions in weather and climate. Even if surface water is polluted, once it evaporates it is then once again pure, ready to perform its assigned tasks all over again.

If neither surface water nor vegetation is present, then all of the sun's energy is turned into sensible heat (a temperature rise). Without water to absorb some of that heat through its conversion to vapor, all of the energy goes into raising the temperature of the air instead. This is what causes the "urban heat island effect" in cities, and it also explains why temperatures in the desert get so hot. There is very little water to absorb the heat through evaporation.

To help counter the urban heat island effect, some cities are encouraging the planting of vegetation on the roofs of buildings and elsewhere. This helps convert more of the absorbed sunlight into latent heat (stored in the vapor) rather than sensible heat (stored as temperature).

As a side note, deserts are not hot because the sand is so bright. The brightness, in fact, keeps the desert air cooler than if the desert sand was black, by reflecting more sunlight back to outer space. If we painted everything in our cities white, they would not absorb so much sunlight, and would stay much cooler. The brightness, however, would probably be unbearable.

### HEAT TRANSPORTED UPWARD IN THE ATMOSPHERE

All of the heat being lost by the surface and accumulating in the lowest layers of the atmosphere results in parcels of warm air rising, and cool air sinking. If the warmest air parcels rise far enough, their temperature becomes too cold to keep all of the water vapor in its vapor form. Now at 100 percent relative humidity, some of the vapor starts to condense (convert back to its liquid form) as tiny cloud droplets. It is at this precise moment, when a cloud is formed, that the latent heat that was lost by the Earth's surface during evaporation is released, and the air is warmed.

This warming from condensational heating then causes the cloudy air parcels to continue their ascent even higher. You might have felt this rising air while flying in and out of clouds in an airplane. The bumpy ride is due to the latent heat that is being released as some of the water vapor turns into cloud water. If you look out the window at the airplane's wing, you can get some idea of how much heat has been released by how well you can see the tip of the wing when you fly through the cloud. In some cases where a lot of water vapor has condensed into cloud water, the cloud will be so thick that you won't be able to see the wing.

If the warm, cloudy, rising air contains enough water vapor and ascends high enough, the cloud water droplets grow and combine to form raindrops. If the air is sufficiently cold, snowflakes are formed. At altitudes near the freezing point (32° Fahrenheit), rain and snow can occur together. You might be surprised to learn that, even on a hot summer day, the upper parts of thunderstorms are actually mini-snowstorms.

Some of the precipitation then usually makes its way to the ground. Any water that doesn't reach the ground as precipitation eventually re-evaporates to humidify the air once again. Since this re-evaporation absorbs as much latent heat as was released when the vapor condensed into cloud, there ends up being no net warming of the atmosphere. It is only when precipitation actually reaches the ground that a net warming of the atmosphere is realized.

Therefore, every drop of rain, and every flake of snow, that reaches the ground represents absorbed solar energy that has been transferred from the surface to the upper atmosphere.

It is one of the curiosities of weather systems that, even though all of the moist air ascending in cloud systems releases huge amounts of heat, those rising air currents end up being at about the same temperature as the air surrounding them. This is because the warm, cloudy air parcels rise and cool by expansion so that they remain near the same temperature as the surrounding air. As long as they are warmer than their environment, they will rise. When the rising air parcels cool to the point that they are the same temperature as their environment, they stop rising.

So, if rising warm, cloudy air is always cooled by its ascent, how does the upper atmosphere experience a net temperature increase from all of this upward heat transport? The answer is, *in response to all of the rising air, an equal amount of air somewhere else is being forced to sink*. It is in those sinking regions where the greatest amount of air experiences a temperature increase.

This sinking almost always occurs over much larger areas than the rising air within cloud systems. As a result, a small area of rapidly warming and rising cloudy air can cause very slow sinking and weak warming of air over a large area. The most extreme example of concentrated sinking and warming over a relatively small region is in the eye of a hurricane.

Almost without exception, this sinking air is cloud-free, and has low humidity since much of its water vapor has been wrung out as precipitation. Even most meteorologists and climate experts don't realize that when we experience a sunny day with a clear blue sky, it is because precipitation systems somewhere else are forcing the air overhead to sink.

As is shown in the previous illustration, we have now followed the heat from the surface, where the sunlight was originally absorbed, to the air flowing over the surface and picking up some of that heat, to the cloudy ascending air currents where precipitation is formed, to the descending air currents where the actual temperature increase of the middle and upper troposphere takes place. This is the dominant pathway by which heat is transported from the Earth's surface to the upper troposphere, thereby cooling the surface and lower troposphere. There is now one more step in the heat transfer process.

### THE HEAT IS LOST TO OUTER SPACE

As the last part of this process, the clear, warm, dry sinking air cools by emitting infrared radiation to outer space, thus completing the cycle of energy into, though, and back out of the atmosphere.

I have neglected some of the weaker pathways by which some of the energy follows. For instance, a small portion of the heat that builds up at the Earth's surface is lost directly to outer space in the form of infrared radiation, thereby bypassing the sequence of events I just described. Proof of this kind of heat loss is in the infrared satellite imagery you see on the TV or the internet. Those satellite sensors are design to sense infrared energy at wavelengths where the atmosphere is transparent, and so they can see infrared radiation coming directly from the ground.

### ATMOSPHERIC CIRCULATION SYSTEMS

Note that the processes of heat transfer we have just described constitute an entire atmospheric circulation system. Air picks up heat from the Earth's surface, releases it as it rises in precipitation systems, then flows away from the precipitation systems and slowly sinks and radiatively cools before it once again reaches the surface to start the whole process all over again.

Even though our high school–level illustration shows what appears to be a warm season circulation system over a rather limited region, in reality some tropical circulations can extend for thousands of miles. In the wintertime, outside of the tropics, the ascending moist air flows in a slantwise fashion, rather than straight up, covering large areas and traveling hundreds or thousands of miles to get from the surface to the upper troposphere. These flows occur in association with low pressure areas called

extratropical cyclones whose main function is to carry excess heat from the tropics to the higher latitudes.

These are the lows that produce large precipitation shields, which then ruin your October weekend. If you experience sunshine on one day, and rain on the next, this is most likely due to the ascending and descending branches of a single low pressure/high pressure circulation system moving across your area.

To further complicate things, the turning of the Earth causes the air in most large circulation systems to flow *around* high and low pressure areas, rather than to travel directly from high pressure to low pressure. This is called the Coriolis effect. In the Northern Hemisphere, air flows in a counterclockwise direction around low-pressure areas. In the Southern Hemisphere, it flows clockwise. Very close to the equator, air simply flows from high to low pressure.

(And, no, the Coriolis effect does not cause the water draining down your sink to spin in one direction. The sink is too small, has too many irregularities in its shape, and the water flow happens too rapidly for it to "feel" the turning of the Earth underneath it. But experiments with a large, perfectly cylindrical water tank with a very small drain hole in the exact center have shown that, over a period of hours, the water in the tank does indeed spin in only one direction.)

All of these circulation systems, whether in the tropics or high latitudes, are continuously occurring on a global basis. The atmosphere never stops overturning and flowing from one place to another. It is constantly removing heat from the surface and depositing it high in the atmosphere, and carrying it from tropical latitudes where more sunlight is absorbed, toward the poles where less sunlight is absorbed. And remember, all of these weather elements are fulfilling one ultimate purpose: to move heat from where there is more, to where there is less.

Now that you understand the basic processes involved in the operation of weather, we are now ready to address global warming. If you don't understand these basics ... well, just pretend that you do.