Earth's Climate Engine

Exploring the Dynamics of Earth's Climate

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Introduction

There certainly has been a great deal of discussion about the climate in the past several decades. During the 1970s there was concern over the possibility of global cooling, while more recently there has been widespread fear of global warming.

Everyone admits that the global climate is extremely complex. It appears that in the distant past the earth's climate has undergone significant changes. More recently, some scientists are predicting severe consequences from a much more modest global climate change.

As scientists seek to understand any physical process they need to isolate the effect and influence of individual variables. In terms of the climate, there is a complex interaction of the sun and the earth's atmosphere, and it is difficult to isolate the effect of individual components. The composition of the earth's atmosphere is usually given as consisting of about 78% nitrogen, 21% oxygen, 1% argon and 0.04% (380 parts per million) carbon dioxide, plus other trace gases. It also, however, contains a significant amount of water vapor, which varies widely with atmospheric conditions.

Recently, the component of the atmosphere that has generated a great deal of interest is carbon dioxide. Because the levels of carbon dioxide are so low, it is difficult to directly measure the effect of any change in concentration. In the absence of direct measurements on the effect of changes in the concentration of carbon dioxide on the climate, mathematical models have been designed. Of necessity, these models have contained certain assumptions and simplifications. It is by using these models that scientists have predicted the dire consequences of changes in atmospheric carbon dioxide.

There is more to calling something "scientific" than using numbers. While obtaining some numerical results from a model is necessary in order to meet the demands of the scientific method, that, in itself, is not sufficient. Those numerical results must be compared to actual measurements, i.e. data. Data is the language of science.

The purpose of this paper is to explore the effect of water vapor on climate. Water vapor is much more abundant in the atmosphere than carbon dioxide, and its physical properties make it more important as well. Thus, it should be possible to measure its effect on temperature.

Background

Luminous bodies, such as stars, are considered to obey a physical principle called the Stefan-Boltzmann law. This law states that the total energy radiated per unit surface area of a blackbody[1] per unit time is directly proportional to the fourth power of the absolute temperature[2] of that black body, or

$$j = \sigma * T^4 \qquad (1)$$

[1] A blackbody is one that perfectly absorbs electromagnetic energy. A blackbody in equilibrium emits as much electromagnetic radiation as it absorbs.

[2] Absolute temperature = Celsius + 273.15. The unit is Kelvins (K) and is written without the degree (°) symbol.

Here j is the irradiance measured in watts/m^2, T is the absolute temperature measured in Kelvins, and σ is the Stefan-Boltzmann constant. The Stefan-Boltzmann constant can be derived from first principles, and is

$$\sigma = 5.67 \times 10^{-8} \frac{J}{s * m^2 * K^4} \qquad (2)$$

For example, for a body at a temperature of 27°C its absolute temperature would be 300K. That body then has a blackbody irradiance of

$$j = 5.67 \times 10^{-8} * (300)^4 \frac{w}{m^2}$$

$$j = 5.67 \times 10^{-8} * 81 \times 10^{8} \frac{w}{m^2} = 459.27 \frac{w}{m^2} \qquad (3)$$

The irradiance of the sun, whose surface temperature is about 5780K, is approximately 63 x 10^6 w/m^2. [3] However, only a fraction of that energy reaches the earth. Because the earth's orbit around the sun is an ellipse, the distance between the earth and sun varies during the course of a year. Measured at the outer edge of earth's atmosphere the solar irradiance ranges from 1,413 w/m^2 at the perihelion (closest distance) to 1,321 w/m^2 at the aphelion (furthest distance). Satellite measurements give an average irradiance of 1,366 w/m^2. (Wikipedia)

The Constant Irradiance Model

One of the simplifications commonly used when designing climate models is the concept of constant irradiance. It is safely assumed that the sun is the sole provider of energy for the earth. The earth, however, is a sphere that rotates, so it is difficult to model the incident irradiance from the equator to the poles and from dawn to dusk to dawn.

The first approximation is to eliminate the effect of the rotation of the earth. Since any point on the earth receives energy 50% of the time, the daily average for a hemisphere is ½ of the total irradiance. This still leaves a hemisphere from pole to equator to pole.

A hemisphere is still a spherical surface, so the next approximation is to consider the cross-sectional area of the hemisphere as a disk that is uniformly irradiated. The surface area of a hemisphere is exactly twice the area of the cross-sectional circle, so the solar irradiance is halved again. This is illustrated in Figure 1:

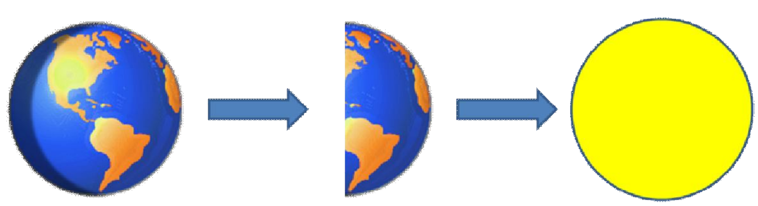


Figure 1: Sphere to hemisphere to disk

[3] A watt is a measure of power and equals one joule per second (*J/s*).

So instead of a solar irradiance equal to 1,366 w/m^2, the effective solar irradiance is considered to be ¼ of that, or 342 w/m^2. This is how the IPCC can use this diagram:

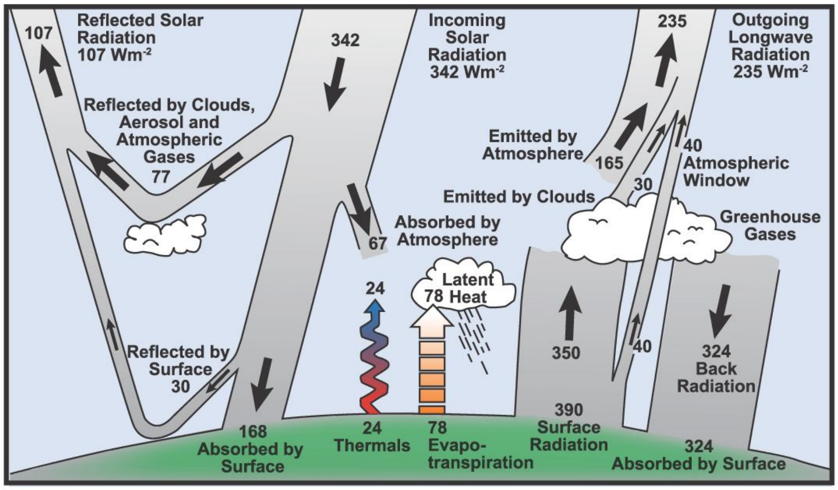


Figure 2: Energy balance from IPCC AR4 FAQ, Figure 1

Here we see the incoming energy as 342 w/m^2. However, this approach leads to a problem, and that is that there is not enough energy to account for the average temperature of the earth. Using the Stefan-Boltzmann law to calculate the blackbody temperature for a body absorbing 342 w/m^2, the resulting blackbody temperature is 278.7K, or 5.5 °C (42 °F). This is far below the accepted average temperature of about 14 °C.

To make matters worse, about 30% of the solar irradiance is estimated to reflect back from the earth without affecting the surface. The fraction of the radiation that is reflected is called the albedo, and the fraction that is absorbed is called the emissivity. The effect of emissivity needs to be added to Equation 1. (See Equation 8, below.) In general, the emissivity of the earth is considered to be 0.7, which leaves 235 w/m^2 to warm the earth. This, in turn, results in an effective blackbody temperature for the earth of only 255K or -18 °C.

The Greenhouse Effect

In order to make up the difference between the calculated and measured average temperatures of the earth the IPCC has factored in the "greenhouse effect."This effect gets its name from what is observed in a greenhouse, which is that during the day the temperature inside the greenhouse is significantly higher than the temperature outside.

Figure 3: The Greenhouse Effect

The glass in the greenhouse is transparent to visible light, which makes up the bulk of the sun's radiation. However, when the sunlight is absorbed by the plants, floor, etc. inside the greenhouse the energy is emitted as infrared radiation, i.e. heat. It is theorized (incorrectly so) that the infrared radiation is not transmitted by the glass, but is absorbed and re-emitted back into the greenhouse, thus adding to the sun's incoming energy and raising the temperature. This increase in temperature by the reflected, or re-emitted, radiation is called the "greenhouse effect."

A diagram of the greenhouse effect as it is proposed for our atmosphere is shown in the Figure 4 to the right. In terms of the climate models, it is assumed that light penetrates to the surface of the earth where it warms the ground. The ground then emits infrared radiation which is absorbed by some atmospheric gases, such as water vapor and carbon dioxide. These gases then re-emit the heat back to the earth where it adds to the energy of the sun and warms the earth some more. This additional warming causes more water to be evaporated, which in turn increases the amount of heat absorbed and re-emitted back to the earth.

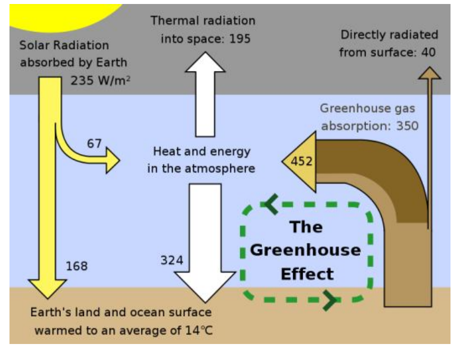


Figure 4: The Atmospheric Greenhouse Effect

This cycling of the energy is called "positive feedback". Positive feedback is well known in electronics. For example, if one holds a microphone in front of a speaker in a sound system positive feedback causes small sounds being picked up by the microphone to be amplified, which produces a louder sound at the microphone, etc. The result is an ear-splitting squeal.

In atmospheric models, positive feedback means a small change in the composition of the atmosphere from increased carbon dioxide results in a large change in the effective energy at the earth's surface. Thus, the earth experiences warming.

However, it is not difficult to show the fallacy of that explanation. Consider the greenhouse in Figure 3. Recall that, according to equation 1, temperature is a measure of the amount of energy. As the sun begins to shine on the greenhouse the solar irradiance begins to warm the inside of the greenhouse. The rate at which energy is transferred into the greenhouse is proportional to the difference in temperature between the effective temperature of the solar irradiance, as given in Equation 1, and the internal temperature of the greenhouse. When the temperature in the greenhouse reaches the effective temperature of the solar irradiance there is no longer any energy transfer from the sun into the greenhouse.

If the heating inside the greenhouse was caused by the "greenhouse effect" then the amount of energy as measured by the temperature inside the greenhouse is greater than the amount of energy entering the greenhouse. Since there are no other sources of energy in the greenhouse, where did the heating come from? The answer is simple and has nothing to do with the glass re-emitting infrared radiation.

First of all, the assumption is made that the sun's irradiance at the greenhouse is the ¼ of the solar irradiance based on the constant irradiance model. In that model, the maximum temperature in the greenhouse would be 5.5 °C with zero reflectance. However, that is an average based on a simplified model of the earth.

At any specific point on the earth that is not true. At midday at the equator, when the sun is directly overhead, the solar irradiance in the upper atmosphere is 1366 w/m^2. On the average, 30% of that energy is reflected, which is accounted for using the emissivity, and another 20% is absorbed in the atmosphere. This means the net solar irradiance that heats the earth's surface at the equator is about 683 w/m^2. At latitudes other than the equator the net radiant flux at the surface will be given by

$$j = \cos(\Theta) * 683 \frac{w}{m^2} \,, \qquad (5)$$

where ***Θ*** is the latitude (north or south) of the location on the earth's surface that is facing the sun. For example, in Harrisonburg, VA the latitude, i.e. ***Θ***, is 38° 4'. Thus, cos(***Θ***) = 0.787, and on a clear day at the Spring Equinox[4] the solar irradiance equals

$$683 * \cos(\Theta) = 683 * 0.787 = 537 \text{ w/m}^2 \qquad (6)$$

This equates to a blackbody temperature of 312K (39 °C or 102 °F). Thus, the maximum temperature that can be reached inside the greenhouse is 39 °C.

Why, then, is not the temperature outside the greenhouse 39 °C?

There are three ways in which heat energy can be transferred: conduction, convection and radiation. Conduction is the process by which heat is transferred through solid material. The glass in the greenhouse is a relatively poor conductor of heat, and so the heat energy cannot be efficiently conducted to the outside air. In the atmosphere there is no conduction, since there is no barrier. Radiation is a relatively inefficient mode of heat transfer. The dominant mode of heat transfer from the earth's surface is convection. Convection comes about since warm air is less dense than cooler air and thus rises in much the same way as a helium balloon rises. In the example above, the surface temperature rarely reaches 100 °F since convection moves the warmer air away from the earth's surface.

The glass walls and roof of the greenhouse let in the heat from the sun, but prevent the warmed air from leaving. When the temperature of the greenhouse exceeds the outside air temperature the walls and roof of the greenhouse will transfer heat via conduction and radiation, both of which are relatively inefficient. Eventually, the temperature inside the greenhouse will rise to equal the radiant temperature of the sun, and thus bring the greenhouse into equilibrium.

This is the problem with the atmospheric "greenhouse effect." In the atmosphere there is nothing to prevent the convection of the warmer air, and it is that convection that is the primary energy transfer method over dry land.

[4] The Spring and Autumnal Equinox is when the sun is directly over the equator. This example would be for March or September.

The Failures of the Constant Irradiance Models

As was mentioned above, half of the earth is illuminated by the sun at any given time, and at least one latitude between the Tropic of Cancer and the Tropic of Capricorn points directly at the sun on any given day. This diurnal and seasonal variation has a dynamic effect on the climate that cannot be accounted for in the constant irradiance models.

The earth's surface receives more energy when directly facing the sun than when the angle is oblique. Thus the equatorial region receives the maximum sunlight while the polar regions receive little or none. In general, this results in high average daily temperatures in the tropics and low temperatures at the poles. Since the amount of energy stored as heat is proportional to the temperature, there is considerably more heat energy in the tropics than at the poles. Heat energy must move from a region of higher temperature to one of lower temperature. Thus, the overall dynamic of the climate is to transfer heat away from the equatorial region toward the polar regions. This energy transfer takes place via both the atmosphere and the oceans. Warmer air rises, and as it does so it creates air currents that move away from the equator. The same is true of the oceans. The warm surface waters produce currents, such as the Brazil and Gulf Stream currents, that move away from the equator and toward the poles. (See Figure 5)

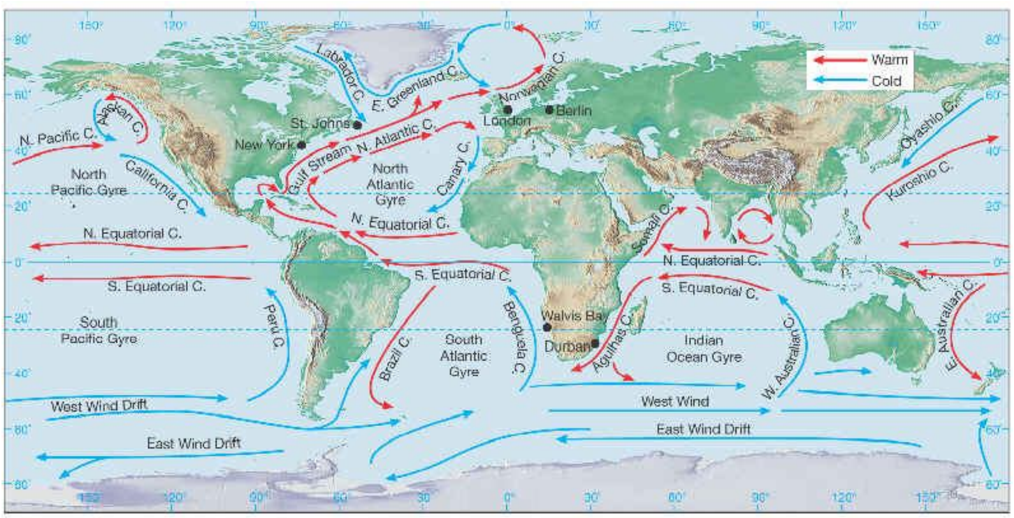


Figure 5: Major Ocean Currents (Hunter College)

None of this dynamic behavior seems to be taken into account in these models. Yet the energy transfer by convection is much greater than that by radiation.

Another Approach

The earth receives virtually all of its energy from the sun, and it is that energy that is the engine that drives all of the processes vital to the existence of life on the earth. Plants take the energy from the sun and carbon dioxide from the atmosphere, and use the chlorophyll in their leaves as a chemical catalyst to produce sugar and oxygen. That sugar is the chemical energy that the cells of all living things use to perform all the myriad functions needed for life.

The sun’s energy is primarily electro-magnetic radiation, i.e. light, that ranges from near infrared to the ultraviolet and centered in the visible range of the spectrum. The solar irradiance is the amount of energy received from the sun per second (measured in watts), per unit area (measured in square meters). Figure 6 shows the solar irradiance as a function of wavelength. The upper curve is measured at the edge of the earth’s atmosphere, and the lower curve is measured at sea level. Notice the presence of absorption bands in the lower curve. These are primarily due to the absorption of the light by water vapor, which is a powerful absorber of infrared radiation, as can be seen in Figure 6.

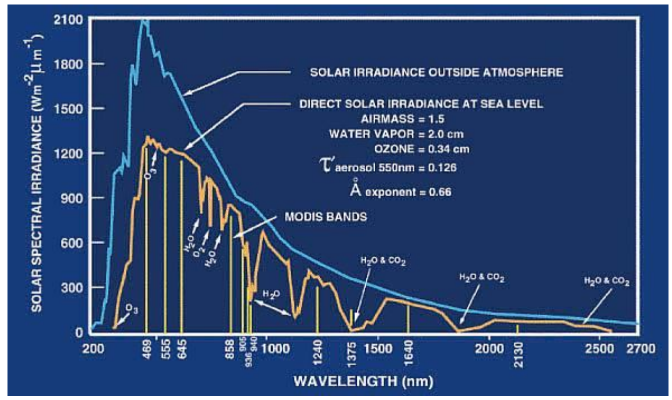


Figure 6: The Spectral Irradiance of the Sun (Wikipedia)

The solar irradiance, i.e. the amount of the sun’s energy per square meter, as it reaches the earth is a function of the latitude, which relates to the height of the sun above the horizon at zenith. The lower the sun’s angle the more the energy is spread out. Figure 7 shows the irradiance in the upper atmosphere, corrected for the angle of incidence, at midday on the Spring/Fall equinox when the sun is directly overhead at the equator.

The surface temperature at any given point on the earth is a function of how much of the solar irradiance reaches the surface. The equatorial region is the warmest since the angle of the sun is the most direct. Likewise, the poles are the coldest, since they receive little of the sun’s energy year round. At night there is no solar irradiance anywhere, and so the temperature drops, sometimes sharply.

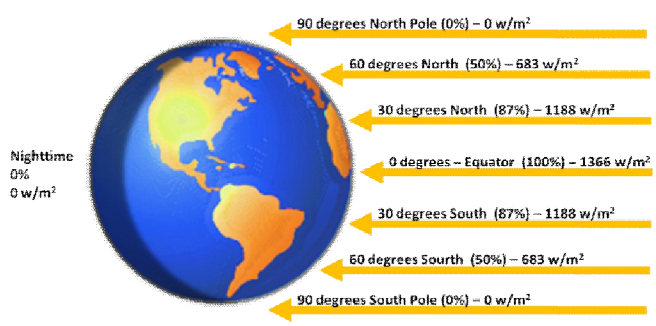


Figure 7: Solar Irradiance on the Earth

While the sun can be treated as an almost perfect blackbody, the earth is not a perfect blackbody. That is, it does not absorb all the solar energy it receives. However, before proceeding to discuss how the earth interacts with the sun’s energy, it might be useful to consider an example to illustrate how the Stefan-Boltzmann law operates.

Suppose there is a planetary body (call it Planet X) which is the same distance from the sun as is the earth, so it receives the same solar irradiance; but it has no atmosphere. Using the Stefan-Boltzmann law of Equation 1, Planet X will emit radiant energy based on its temperature. Suppose that we start with a very cold surface, say 3 K, or -270°C. The irradiance of Planet X would be close to zero.

Now turn on the sun. We still have the outgoing irradiance of Planet X, but now there is also the incoming irradiance from the sun. The incoming irradiance of the sun is much greater than the outgoing radiance of the planet, so the surface of Planet X will absorb the excess energy, and the temperature will begin to rise. As the temperature increases the outgoing irradiance increases, and this will continue until the outgoing irradiance equals the incoming irradiance.

At this point equilibrium is reached, and the temperature stops rising. That temperature, where the radiance of the planet equals the incoming radiance of the sun, is called the "blackbody temperature." For our imaginary Planet X this temperature would be 393K or 120°C (248°F). There actually is a Planet X, and it is called the moon. In fact, the highest temperature measured on the moon's surface is quite close to 120°C. (Artemis Society International)

If, as the sun sets, the temperature of Planet X would increase above the blackbody temperature, then there would be a net outgoing energy flow, and Planet X would no longer receive any more energy from the sun. Thus, it would cool.

What matters is what happens at an imaginary boundary, which we will call the "blackbody boundary", which is just above the surface of Planet X. The outgoing energy flux, which is a function of the surface temperature, cannot exceed the incoming energy flux.

Now consider the case of the earth. Unlike Planet X, the earth has an atmosphere, which alters the dynamic somewhat. Suppose that the earth stopped rotating with the sun at the zenith. What would happen to the temperature? The answer is that the temperature would continue to rise until it reached the blackbody temperature, the same as with Planet X.

However, the blackbody boundary, instead of being at the surface, as it was with Planet X, is now located at the edge of the atmosphere. Below that point, the effect of the atmosphere is to reflect some of the incoming solar irradiance. There are several contributing factors to this. First is the presence of clouds, which, being white, reflect the sunlight. Secondly, the temperature in the upper troposphere is very cold (-60°C), and water vapor freezes into small ice crystals. (Happ) These crystals also reflect some of the energy. Next there is the reflection from aerosols, which are tiny droplets of other chemicals. Then, the surface features of the earth, such as snow or other light-colored surfaces, may directly reflect some of the irradiance. Finally, there is some atmospheric absorption of the sun's energy, primarily by water vapor in the near infrared. Some of this energy is re-emitted back towards the sun.

Altogether the fraction of the solar irradiance that is reflected as outgoing energy is called the albedo. Most estimates of an average for the earth's albedo are approximately 0.30. This fraction then gets subtracted from the incoming solar irradiance. The remaining fraction of the sun's irradiance that reaches the earth's surface is called the emissivity. The Stefan-Boltzmann law is corrected to include the effect of the emissivity, denoted by the symbol $\boldsymbol{\varepsilon}$:

$$j^* = \varepsilon * \sigma * T^4 \qquad (7)$$

The inclusion of the emissivity gives an adjusted value for the emitted irradiance, j^*. The blackbody temperature is also adjusted by the same factor and makes up the remaining portion of the earth's irradiance. It is important to keep in mind that the emissivity may vary with location and atmospheric conditions.

Equation 7 can solved for the temperature and then be used to calculate the maximum blackbody temperature for any given emissivity.

$$T = \sqrt[4]{\frac{\varepsilon * j}{\sigma}} = \sqrt[4]{\frac{j^*}{\sigma}} \qquad (8)$$

The results of calculated surface temperatures for various emissivities with a total solar irradiance of 1,366 w/m^2 are shown in the table to the right. Since there is no other source of energy at the equator, these calculated temperatures represent a theoretical maximum.

Emissivity	Temperature °C (°F)	
	Maximum	Average
0.8	100 (212)	40 (104)
0.7	87 (189)	30 (86)
0.6	74 (165)	24 (75)
0.5	58 (136)	5.5 (42)
0.4	40 (104)	-10 (14)
0.3	24 (75)	
0.2	-10 (14)	

Table 1: Emissivity vs. Surface Temperature

For example, the overall value for the emissivity of the earth is generally accepted to be about 0.7; that is, 30% of the solar energy is reflected as the albedo. That emissivity lowers the effective value of the solar irradiance from 1,366 w/m^2, as mentioned above, to 956 w/m^2. Using this value, the maximum possible temperature is given by:

$$T = \sqrt[4]{168x10^8}\,K = 360K = 87°C \qquad (9)$$

Here is the important point to remember: **No matter what the composition of the atmosphere is, the irradiance from the surface temperature of earth at the equator plus the reflected irradiance cannot exceed the total blackbody irradiance, which is equal to the solar irradiance.**

The details of what happens within the lower atmosphere and between the earth's surface and the atmosphere have no bearing on the resultant blackbody radiation. If the blackbody radiation from the earth's surface, which includes atmospheric absorption, is less than the net solar irradiance the temperature will increase. If it is the same, then the temperature will remain constant.

The so-called "greenhouse effect" cannot raise the temperature above what is caused by the incoming solar irradiance. If it did, the emitted thermal radiance of the earth would exceed the solar irradiance and the sun's heating effect would cease.

In fact, the earth's surface temperature seldom gets close to its blackbody temperature, even at the equator. As the sun's light passes through the atmosphere some if it is absorbed, almost exclusively by water vapor. These are the absorption bands shown in Figure 6 (above). Some of this energy is re-emitted back toward the sun and never reaches the earth's surface. Thus, the amount of energy that reaches the earth's surface is a function of how much water vapor is in the atmosphere.

As was mentioned above, the dry atmosphere of the earth consists of about 78% nitrogen, 21 % oxygen and 1% argon. The carbon dioxide level is less than 0.04%. These percentages are always given with no water vapor present, since water vapor is constantly present, but in varying amounts. In Figure 6 above the amount of water vapor is given as 2 cm Hg[5], which is about 2.6%. Water vapor is not visible to the eye since it is transparent in the visible region of light, but it is an excellent absorber in the near-infrared.

At any given temperature the amount of water vapor that can be held in the atmosphere varies with temperature. Relative humidity is the fraction of how much water vapor is in the atmosphere vs. how much the atmosphere can hold at that temperature. The chart in Figure 8 shows how much water is contained in the atmosphere when the humidity level is at 50% capacity and 100% capacity. While relative humidity determines how comfortable we are, what is important regarding the absorption of the sun's energy is the absolute quantity of water vapor.

As the warm air rises, the temperature drops. Since the total quantity of water vapor remains the same, the relative humidity increases. Clouds are formed when the air cools below the dew point, and the water vapor condenses into small droplets that collect together.

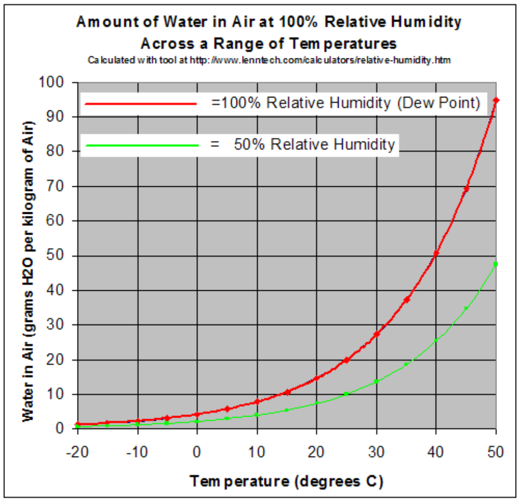


Figure 8: Relative Humidity

Data and Results

In order to test the conclusions embodied in equations 7, 8, and 9, as well as the effect of water vapor on temperature it is necessary to find appropriate temperature data. It is necessary at any given location to have good temperature records and be able to estimate the albedo closely.

At any given time and place there are too many factors that influence temperature, and thus climate, to make calculating a theoretical temperature possible. That is like trying to model the entire earth's climate; it is obviously too complex a job. For example, air and water masses move into and out of most regions resulting in wide ranging temperature, humidity and cloud conditions that are unrelated to solar irradiance. These varying conditions change the local albedo over a wide range of values, making meaningful calculations virtually impossible.

However, when one looks at the extremes, either high or low temperatures, the process is much simpler. Many variables are taken out of the picture. Consider the following examples.

Antarctica

The polar regions, the Arctic and Antarctic, are the regions that receive the lowest solar irradiance on the planet. However, the Antarctic climate is much colder than that in the Arctic. The area around the North Pole is an ocean, while the South Pole is located near the center of a continent, Antarctica. This

[5] Atmospheric pressure is the force per unit area of the atmosphere as measured at sea level. It is measured using a variety of units, among which are 76 cm Hg and 1013 mb (millibars).

difference is significant, since the waters of the Arctic Ocean moderate the temperatures in the Arctic region, making it more habitable than the Antarctic.

Although covered with ice and snow year round, Antarctica is actually the driest place on earth. With an average humidity of 0.03% it receives less than an inch of precipitation each year. Antarctica therefore is actually a desert. (Antarctic Connection)

Near the South Pole the sun never rises above the horizon for four or five months. That means there is zero solar irradiance for long periods of time. Based solely on irradiance considerations, the temperature at the South Pole should be similar to lunar temperatures, where the lunar night lasts for 28 days. At the Apollo 15 site temperatures get as low as -181°C (-294°F) during the lunar night. (Artemis Society International)

The lowest naturally recorded temperature at Antarctica is -89.2°C (-128.6°F) at the Vostok Station, Antarctica. (Wikipedia) While that is cold, it is not nearly as cold as it could be compared to the temperatures on the moon during the lunar night. The thermal energy flux for a temperature of -89°C is about 65 w/m^2, which is all from the atmosphere without any input from the sun.

The Russian operated station at Vostok has a long record of temperatures. It is located at 78.45°S, so that the “winter” night and “summer” day are quite long. The average temperature during the “summer” months of December and January is -32.1°C (241K) (Cool Antarctica), corresponding to an average energy flux of 191 w/m^2.

At the latitude of 78.45°S the solar irradiance is 20% of the maximum 1366 w/m^2, or 273 w/m^2. The difference is a result of the reflected radiation, or the albedo, which is about 0.5 when the atmospheric input of 65 w/m^2 is accounted for. This albedo is well within the range for snow covered ground.

Equatorial Regions

The other extreme is at or near the equator and is more useful. The equatorial region receives the highest level of solar radiance year round of any region on the earth. This is important since that high level of solar irradiance produces high average temperatures. This, in turn, means that energy is flowing away from the equator and not towards it from other regions. That fact alone simplifies the problem.

However, not all areas close to the equator are suitable. Areas near or within large bodies of water are severely impacted by the moderating influence of the water. For example, humidity levels in tropical rain forests are extremely high, resulting in heavy cloud cover, and the terrain is so varied it is difficult to estimate the albedo.

A more ideal situation would be within equatorial deserts. In addition to receiving only energy from the sun, the humidity is relatively low, resulting in less cloud cover and a more constant albedo. With the cloud cover either absent or thin the main factor affecting the albedo is the reflection of sunlight off the sand. The albedo for desert areas is in the range of 0.30 – 0.50. (The Encyclopedia of Earth)

The Sahara Desert, where the air is extremely dry, meets both of these conditions and is the hottest region on earth. The annual mean temperature exceeds 30°C (86°F). The highest recorded temperature anywhere on the earth is 57.8 °C said to have occurred at Al 'Aziziyah, Libya on September 13, 1922. However, the specifics surrounding that claim make it highly doubtful.

A more reasonable highest temperature reading of 49.6 °C (121.3 °F) occurred at the city of Dongola, Sudan on June 25, 2010. (Wikipedia) Dongola sits at latitude 19.2 °N and longitude 30.5 °E. That date is very close to the Summer Solstice, which would place the sun at 23.5 °N, just 4.3° off the zenith. The cosine of that angle is 0.997, so that is not a factor in the calculations.

Here we have the smallest number of variables, so it should be possible to calculate that temperature. Consider the following.

At sunrise the desert's surface is relatively cool, and the sun's rays are low on the horizon. As the sun rises, the energy flux increases until the sun is directly overhead at noon. As the sun's angle changes, the energy density on the earth's surface also changes. At dawn the angle is 0°, and the energy density is near zero. Six hours later, at noon, the angle is 90°, and the energy density is at the maximum. However, the ground temperature is lagging behind as it slowly heats. The surface will continue to heat until thermal equilibrium between ground temperature and solar irradiance is reached. That is when the highest temperature of the day will be measured.

Actual temperature measurements in Dongola confirm that the desert does not reach its maximum temperature until approximately 3 pm. By then the sun is halfway down towards the western horizon, and the energy flux is decreasing.

In order to account for the change in angle as the earth rotates, equation 7 needs to be modified to include the effect of the sun's angle at the time of day:

$$j^* = \varepsilon * \sigma * T^4 * \sin(\Theta') \qquad (10)$$

Where $\boldsymbol{\Theta'}$ is the angle the sun's light makes with the earth's surface. At 3 pm the angle of the sun is 45°, so that $\sin(\Theta') = 0.707$.

Calculating the emissivity is necessary for any specific location. Since Dongola is located in the southern Sahara Desert, the ground albedo is in the range 0.35 – 0.40

The temperature record for that day is available at the weather website Weather Underground and is a bit sketchy. (Weather Underground) Based on a dew point of about 8.3°C (47°F) the relative humidity was 9%, the absolute humidity was 7.4 g/m^3, and the sky was clear, except for some dust. It is difficult to estimate the effect of the dust on the albedo. However, the visibility that day ranged from 2 – 7 mi., which would indicate the dust level was light and probably had relatively little effect on the albedo.

If we let T = (49.6 + 273.15) K = 322.75 K, and $\sin(\Theta') = 0.707$, then the thermal irradiance is 615 w/m^2. The solar irradiance, corrected for the same angle, is 966 w/m^2. This value can then be used to find the effective albedo:

$$albedo = \frac{966-615}{966} = 0.36$$

This is in reasonable agreement with an estimate for the southern Sahara Desert.

While this is interesting, it could be serendipitous. Is there a way to actually demonstrate the effect of water vapor on temperature? Since the albedo should be relatively constant, there being few clouds, it should be possible to demonstrate whether water vapor is the critical factor that determines how much solar irradiance reaches the surface.

Tombouctou, Mali

Tombouctou, Mali is a small town on the southern edge of the Sahara Desert. It is known as the jumping off point for caravans entering the desert. Located at coordinates 16.7°N and 3°W, Tombouctou would seem to be an ideal location since the longitude would place it close to the Prime Meridian and the sun would reach its zenith directly overhead twice during the year. Being close to the Prime Meridian assures that the clock time and sun time are very close. A longitude of 3° means there is only 12 minutes difference between sun time and clock time. It is also estimated from the latitude that the sun would pass its zenith on or about 22 May on its way north and on July 24 on its way south.

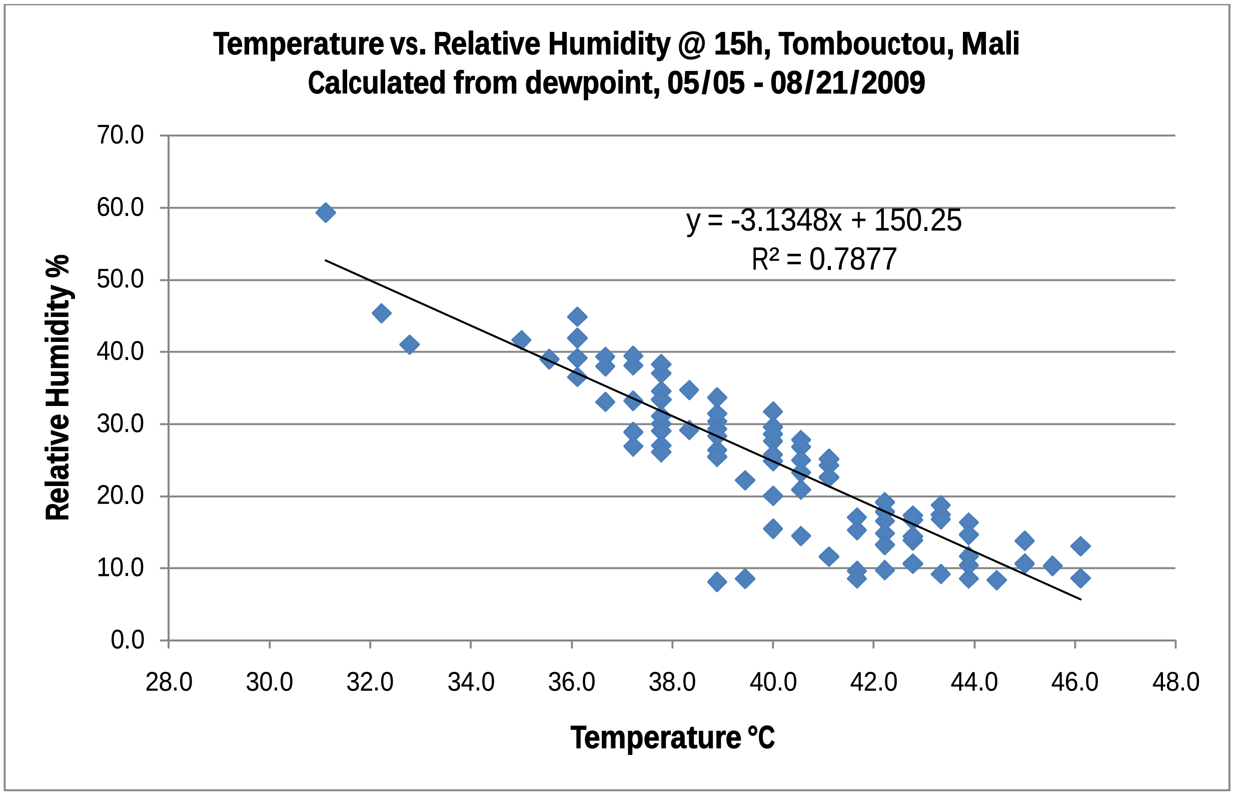
The weather website Weather Underground has data from weather reporting stations all over the world, and Tombouctou is no exception. What is exceptional is the quality of the data. It includes High Temperature, Low Temperature, a graph of the temperature and dew point as a function of time of day, and a table that generally records temperature, dew point and general conditions at 3 hr intervals daily. From the graph it is possible to estimate the time of maximum temperature within 15 minutes. In 62% of the days recorded in 2010 the high temperature was reached within 15 minutes of 3 pm. Relative humidity and absolute humidity were calculated at 3 pm from the temperature and dew point at that time. Data was collected daily from 04/26 to 08/21/2010 and 05/19-08/21/2009. (The data for the dates 04/26-05/18/2009 was considered to be of poor quality.) The range of dates was chosen so that the sun was never more 6 or 7 ° from zenith and gave a significant number of values.

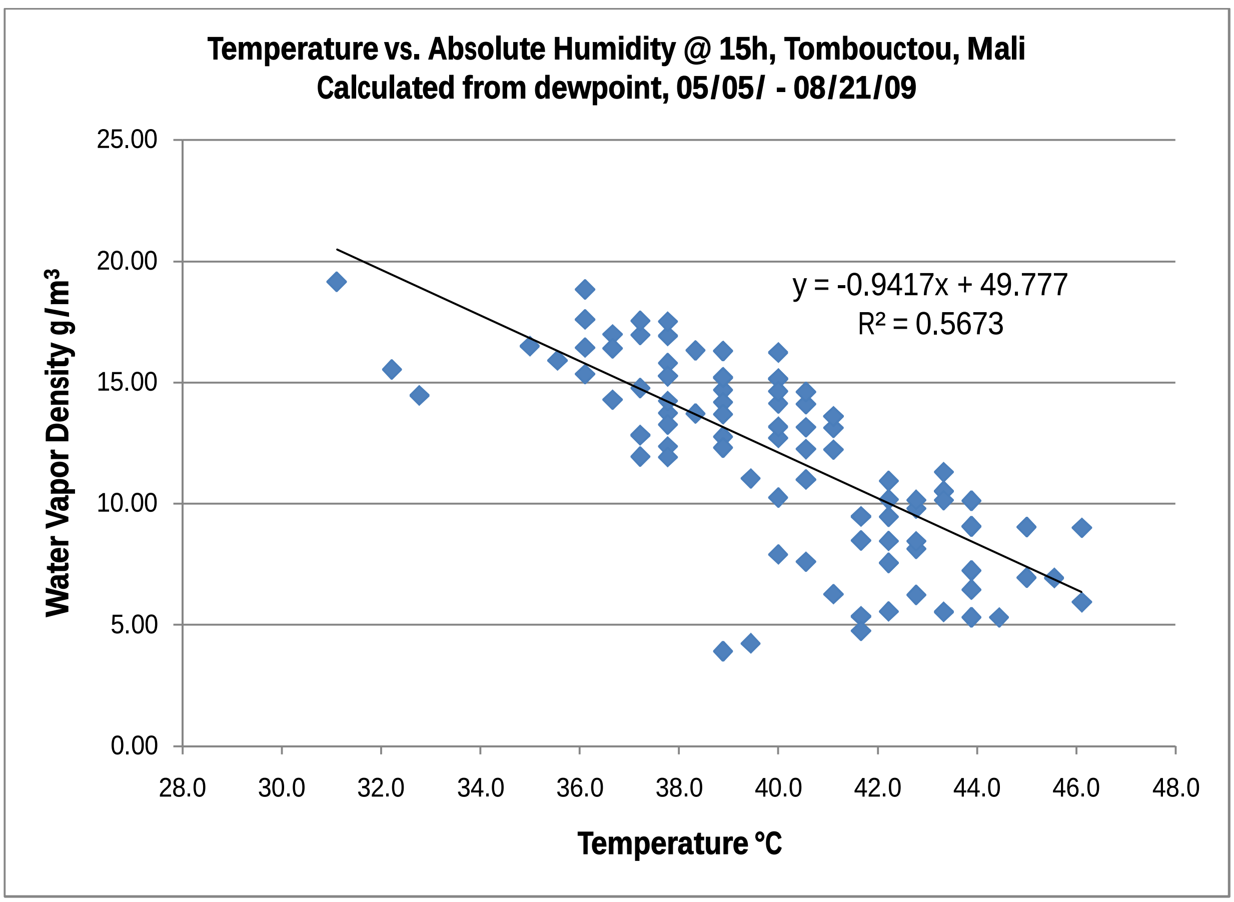
The data were very interesting and are summarized in Table 2.

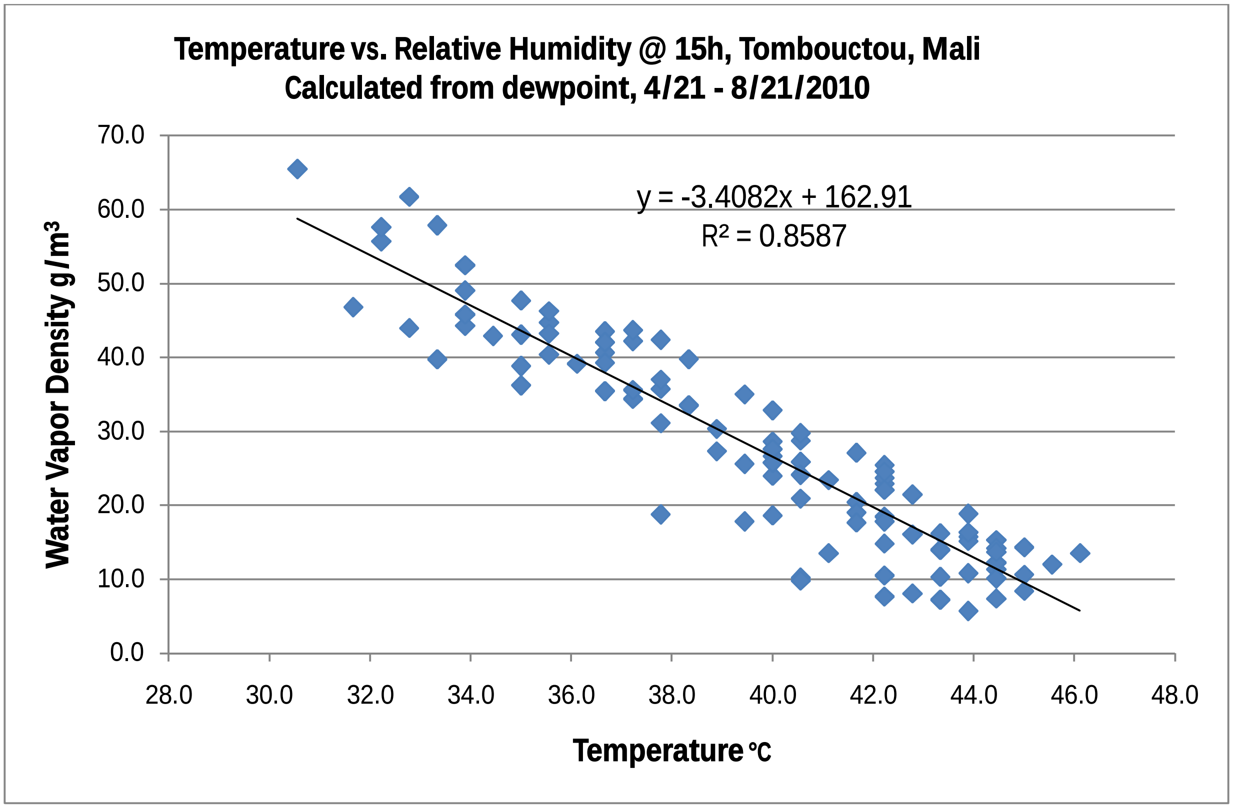
Year	3 pm Temp Range	3 pm Rel. Humidity	3 pm Abs. Humidity	Equation	R^2	Std. Dev.
2010	30.6-46.1°C	5.8-65.5%	3.6-21.8	-0.9457x+50.482	0.6449	2.6
2009	31.1-46.4°C	8.1-59.3%	3.9-19.1	-0.9417x+49.777	0.5673	2.5

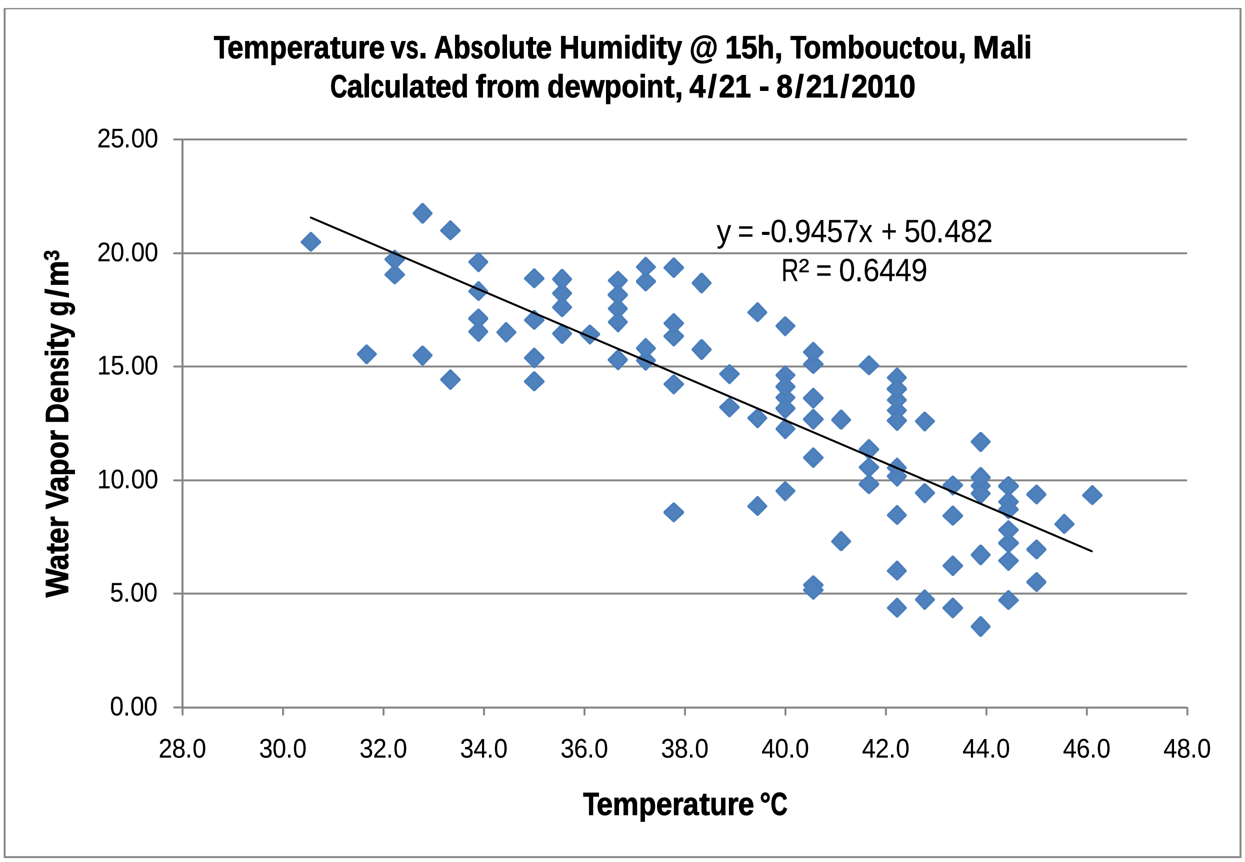
Table 2:Summary Data for Tombouctou, Mali

Below are the charts of 3 pm Temperature vs. 3 pm Relative Humidity and 3 pm Absolute Humidity.


Temperature vs. Relative Humidity @ 15h, Tombouctou, Mali
Calculated from dewpoint, 05/05 - 08/21/2009
y = -3.1348x + 150.25
R² = 0.7877
Relative Humidity %
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
28.0
30.0
32.0
34.0
36.0
38.0
40.0
42.0
44.0
46.0
48.0
Temperature °C


Temperature vs. Absolute Humidity @ 15h, Tombouctou, Mali
Calculated from dewpoint, 05/05/ - 08/21/09
y = -0.9417x + 49.777
R² = 0.5673
Water Vapor Density g/m³
25.00
20.00
15.00
10.00
5.00
0.00
28.0
30.0
32.0
34.0
36.0
38.0
40.0
42.0
44.0
46.0
48.0
Temperature °C


Temperature vs. Relative Humidity @ 15h, Tombouctou, Mali
Calculated from dewpoint, 4/21 - 8/21/2010
y = -3.4082x + 162.91
R² = 0.8587
Water Vapor Density g/m³
Temperature °C
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
28.0
30.0
32.0
34.0
36.0
38.0
40.0
42.0
44.0
46.0
48.0


Temperature vs. Absolute Humidity @ 15h, Tombouctou, Mali
Calculated from dewpoint, 4/21 - 8/21/2010
y = -0.9457x + 50.482
R² = 0.6449
Water Vapor Density g/m³
Temperature °C
25.00
20.00
15.00
10.00
5.00
0.00
28.0
30.0
32.0
34.0
36.0
38.0
40.0
42.0
44.0
46.0
48.0

While both relative humidity and absolute humidity were calculated from the dew point and are presented above, it is considered that the absolute humidity, which is also the density of water vapor, is more important in measuring solar absorption. There is more scatter with the absolute humidity data than with relative humidity, but there is sufficient correlation between temperature and absolute humidity to consider these data as significant.

The maximum recorded temperature is 46.7°C. Performing the same calculation for computing the albedo as was done above for Dongola yielded an albedo of 0.39.

It is also of interest to note the value of the intercepts. Projecting the linear fit to zero water density would give a temperature that is the maximum possible for that location. For 2009 the intercept is 52.8°C, and for 2010 it is 53.4°C. These temperatures are in close agreement with the high temperature recorded at Dongola, Sudan.

The average intercept is 53°C, which corresponds to a maximum solar irradiance of 640 w/m^2, which yields a computed albedo of 0.34 at 0% humidity. This is also consistent with being in a desert area.

Nairobi, Kenya

Another potential region of interest is Nairobi, Kenya. Located on a high plateau, Nairobi sits at an altitude of 1628 m in an area that is semi-arid. Its coordinates are 1.3°S and 36.9°E, so it sits almost directly on the equator. Because of its altitude, however, it is significantly cooler than Tombouctou. Cooling with an increase in altitude is called “adiabatic lapse”, and the rate of adiabatic lapse is generally taken to be about 6.5°C per Km for moist air to 10°C per Km for dry air. (Integrated Publishing) A comparison of Tables 2 and 3 shows that the range of temperatures between the two locations is in good agreement with those estimates.

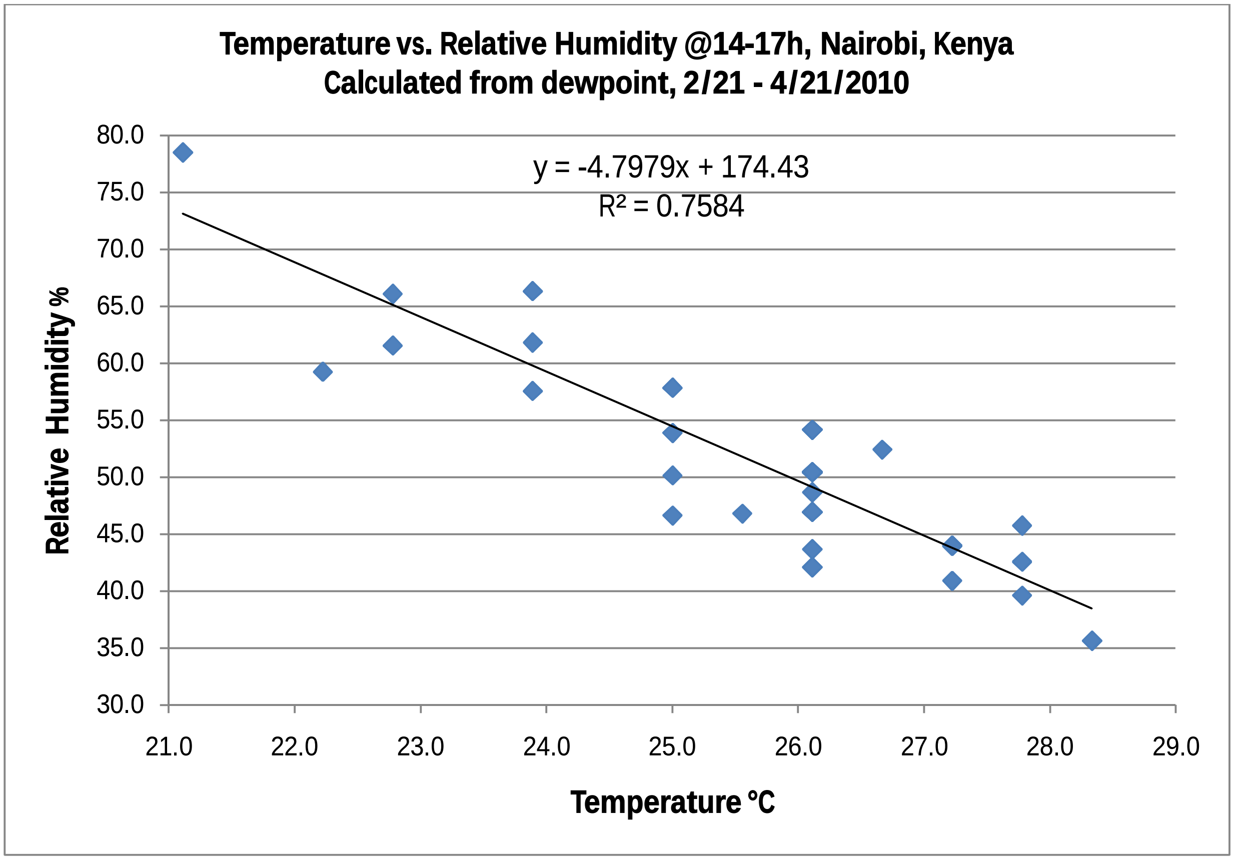
Being on the equator means the sun is at its zenith on March 21 and September 20. Data was therefore recorded from 2/21-4/21/2010 and 8/21-10/21/2010 when the sun was directly overhead.

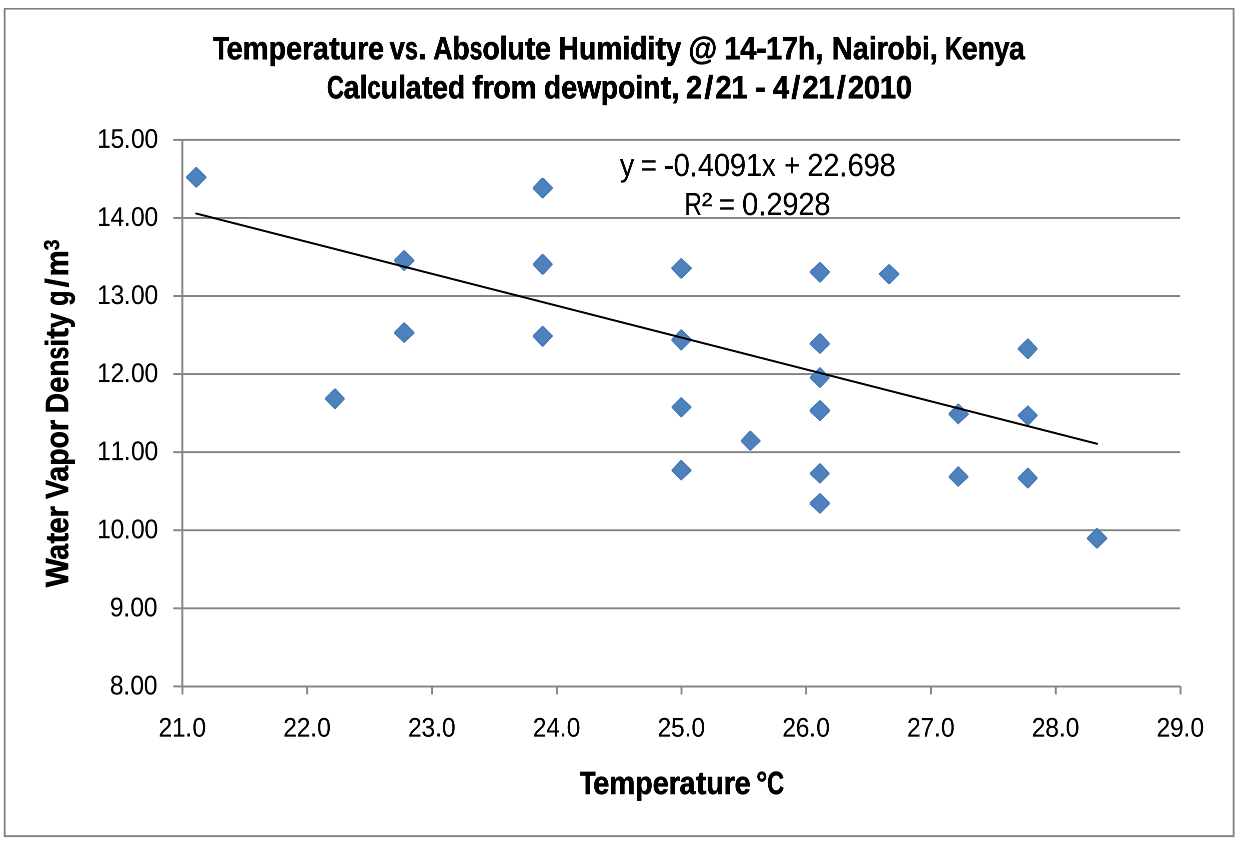
Year	3 pm Temp Range	3 pm Rel. Humidity	3 pm Abs. Humidity	Equation	R^2	Std. Dev.
Spring	21.1-28.3°C	35.7-78.5%	9.90-14.52	-0.4091x+22.698	0.2928	0.9
Fall	20.0-30.0°C	21.7-63.2%	5.84-10.95	-0.2845x+16.481	0.3467	0.9

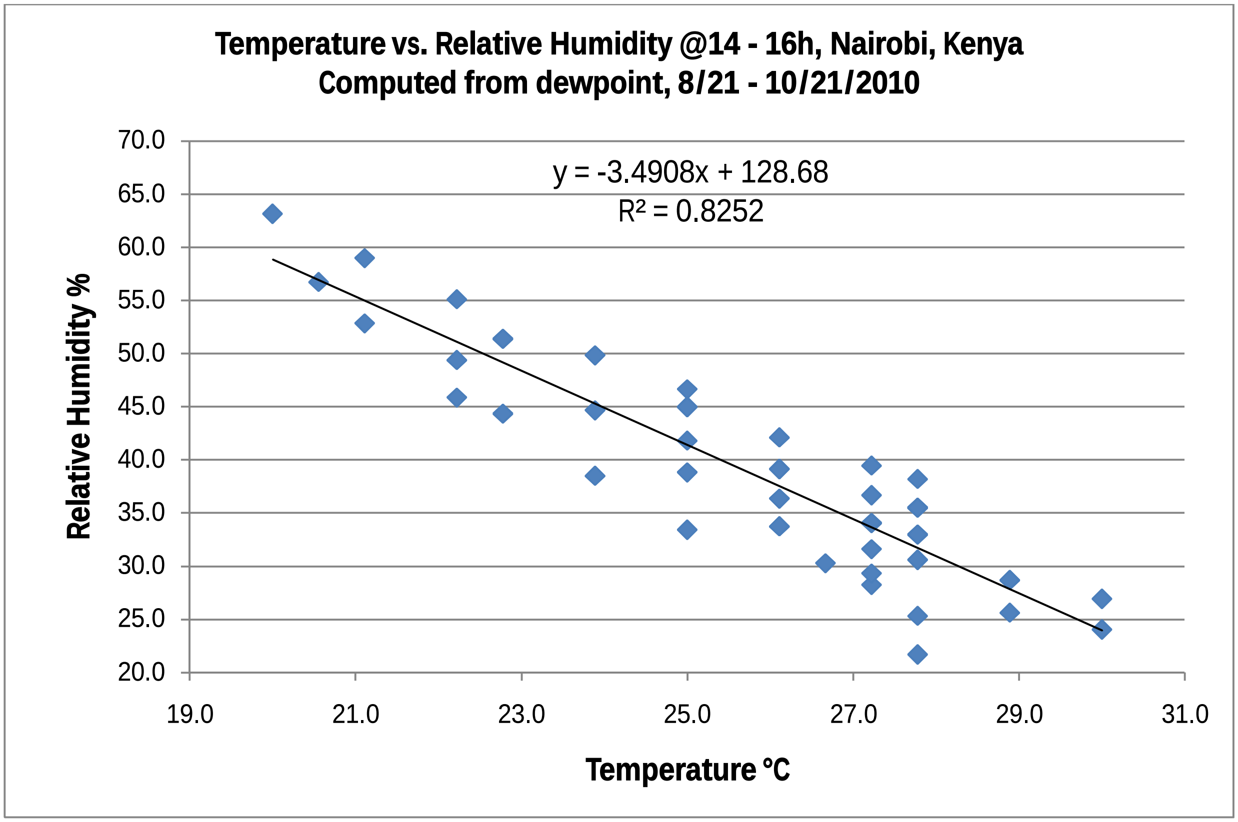
Table 3: Summary Data for Nairobi, Kenya

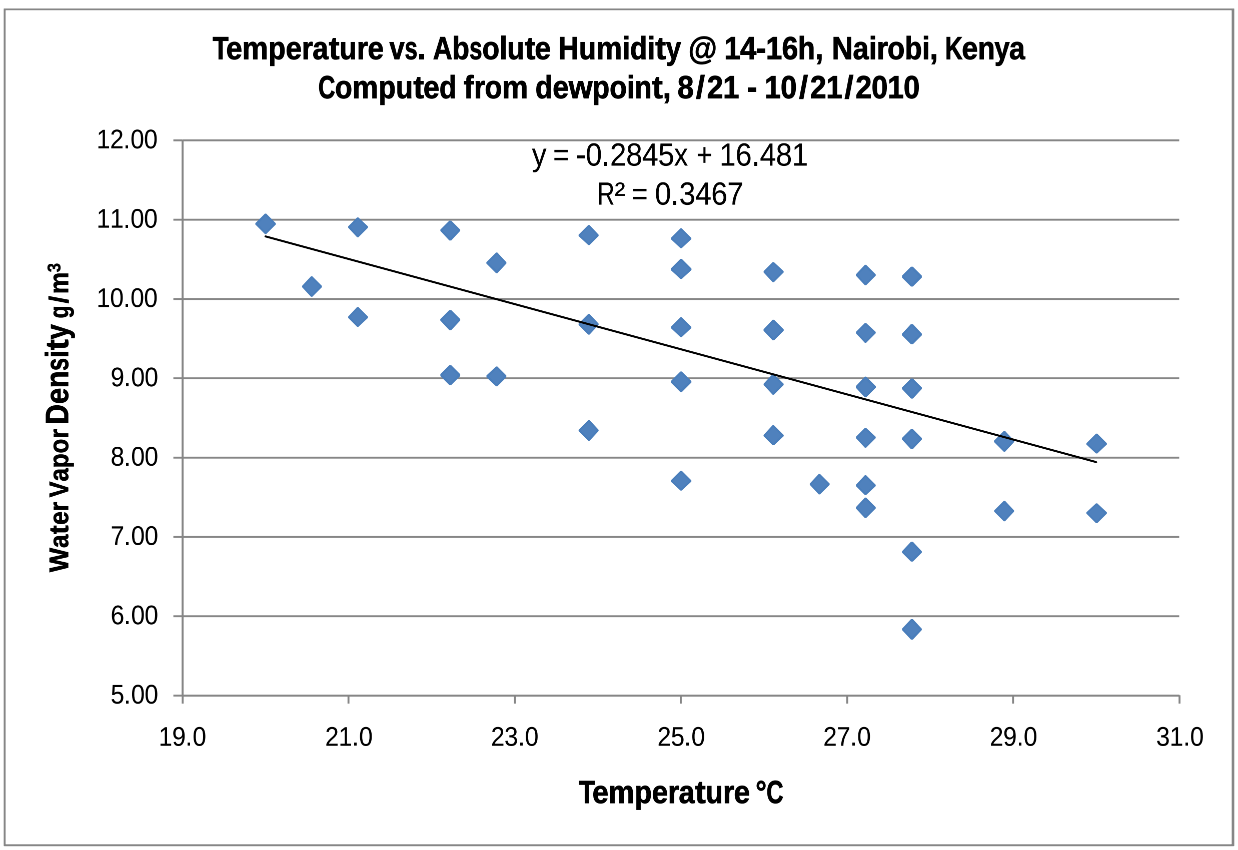
Nairobi is an interesting choice, because while it is on the equator it is semi-arid, and not desert. Nevertheless, a relatively strong correlation exists between water vapor content and temperature. The intercepts for the two sets of data are 55.5°C and 57.9°C. The average of 56.7°C gives a solar irradiance of 672 w/m^2. When this is used to calculate the albedo the result is an albedo of 0.30, which is within the range for dry soil.

Below are the charts of the Temperature vs. Relative Humidity and Absolute Humidity.


Temperature vs. Relative Humidity @14-17h, Nairobi, Kenya
Calculated from dewpoint, 2/21 - 4/21/2010
y = -4.7979x + 174.43
R² = 0.7584
Relative Humidity %
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
21.0
22.0
23.0
24.0
25.0
26.0
27.0
28.0
29.0
Temperature °C


Temperature vs. Absolute Humidity @ 14-17h, Nairobi, Kenya
Calculated from dewpoint, 2/21 - 4/21/2010
y = -0.4091x + 22.698
R² = 0.2928
Water Vapor Density g/m³
15.00
14.00
13.00
12.00
11.00
10.00
9.00
8.00
21.0
22.0
23.0
24.0
25.0
26.0
27.0
28.0
29.0
Temperature °C


Temperature vs. Relative Humidity @14 - 16h, Nairobi, Kenya
Computed from dewpoint, 8/21 - 10/21/2010
y = -3.4908x + 128.68
R² = 0.8252
Relative Humidity %
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
19.0
21.0
23.0
25.0
27.0
29.0
31.0
Temperature °C


Temperature vs. Absolute Humidity @ 14-16h, Nairobi, Kenya
Computed from dewpoint, 8/21 - 10/21/2010
y = -0.2845x + 16.481
R² = 0.3467
Water Vapor Density g/m³
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
19.0
21.0
23.0
25.0
27.0
29.0
31.0
Temperature °C

The Role of Water Vapor

Water vapor plays a very important function in moderating the earth's climate. If there was no water vapor in the atmosphere, that is, the atmosphere consisted of only nitrogen and oxygen, it would get very hot at the equator during the day, get extremely cold at night, and stay extremely cold year round at the poles, not unlike the moon. Without the sun's energy at night, temperatures would plunge, and the temperature swings between night and day would be so great that few organisms could survive.

As was mentioned above, the lowest naturally recorded temperature at Antarctica is -89.2°C (-128.6°F) at the Vostok Station, Antarctica. (Wikipedia) That temperature represents a thermal energy flux of about 65 w/m^2 without any input from the sun. This is the equivalent of about 10% of the solar irradiation that reaches the surface at the equator as measured at Dongola, Sudan. This is a significant amount of energy flux, and it comes from the atmosphere pumping energy from the equator to Antarctica. The mechanism for this starts with the evaporation of water vapor in the oceans, where it rises to the upper atmosphere. The condensation and freezing of this water releases the energy necessary to produce the winds that buffet Antarctica during the winter and bring in energy.

The North Pole is a bit different. While it also endures the same periods without the sun's irradiance, it is not quite as cold. This is because there is no land at the North Pole, and the Arctic Ocean adds to the energy transfer from the equator that moderates the temperature somewhat.

This is all because of water vapor. It is important that the role that water plays in climate is understood. Water is an amazing substance, but in this context there are four properties of water that are exceptionally important.

The first of these is the heat capacity of water and water vapor. Heat capacity is the amount of energy (in joules) it takes to raise the temperature of 1 gram of material one degree C. It is constructive to compare the heat capacities of the three most important constituents of earth's atmosphere: Nitrogen (78%), Oxygen (21%) and water, both as vapor (variable) and liquid.

Substance	Heat Capacity (j/g*°C)
Nitrogen	1.040
Oxygen	0.918
Water (gas)	2.080
Water (liquid)	4.181

Table 4: Heat Capacities of Atmospheric Gases

Both as a gas and as a liquid, water has exceptional heat capacities. This means that water vapor is capable of absorbing and moving significant amounts of energy from one place to another.

Even more important is water's latent heats of fusion and vaporization. Like most substances, water can exist in one of three forms: liquid, gas and solid. As water goes from one to the other forms, also called phases, energy is required or released. The heat of fusion is the amount of energy required to go from ice to liquid, or liquid to ice, without a change of temperature. The heat of vaporization is the amount of energy required to convert water from a liquid to gas, i.e. water vapor, also without a change in temperature.

The heat of fusion for water is normally measured at 0 °C and is the amount of energy (in joules) required to convert one gram of ice at 0 °C to water at 0 °C. Water, of course, freezes at 0 °C, and to convert one gram of ice at 0 °C to one gram of water at 0 °C requires the addition of 333 joules of energy. By way of comparison, this is 160 times more energy that is required to raise the temperature of that same gram of water to 1 °C.

Even more important than water's heat of fusion is water's latent heat of vaporization. There is some temperature dependence of this latent heat, and Table 5 to the right gives the range over normal temperatures. Notice, however, that the heat of vaporization is greater than one thousand times the heat capacity of water.

Temperature °C	Latent Heat of Vaporization (j/g)
30	2430
20	2454
10	2477
0	2501
-10	2524
-20	2548
-30	2573
-40	2598

Table 5: Latent Heat of Vaporization

The fourth property of water is its absorption/transparency of radiation. In general, water is an excellent absorber in the infrared (IR) region of the spectrum, while being transparent to visible. Figure 9 shows the absorption spectrum of water vapor in relationship to other atmospheric gases. The large shaded box outlines the region of solar irradiance, which is the region shown in Figure 6 (p. 8), and the smaller box outlines the visible region of the spectrum. Figure 6 shows the net intensity of the solar irradiance as a result of the water vapor and carbon dioxide absorption.

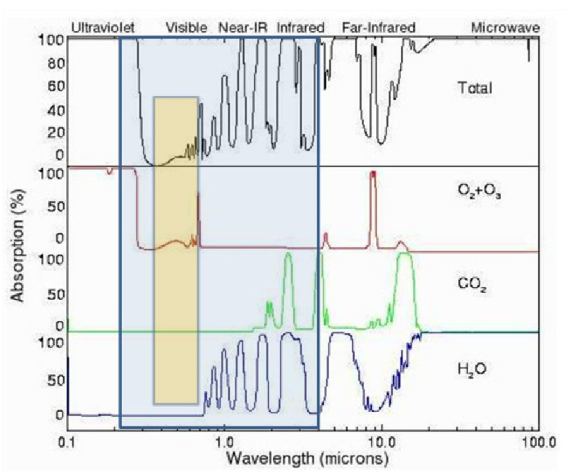


Figure 9:: Absorption Spectrum of Atmospheric Gases

The vast majority of the absorption shown in Figure 6 comes from water. Almost all of the carbon dioxide absorption bands coincide with the bands of water, as shown in Figure 6. It is of interest to note that the IR absorption of carbon dioxide on solar irradiance is of marginal effect since the absorption by water vapor is virtually 100% without any contribution from carbon dioxide.

The sun's irradiance peaks in the visible region at a wavelength of 0.5 microns. The earth's irradiance peaks in the far infrared, between 9 and 10 microns. Figure 10 shows the same absorption spectra of several of the atmospheric gases as Figure 9, but with the addition of the spectral distribution of the earth's emittance at -18°C. Notice that there is a transmittance window in the 10 micrometer region for both water vapor and carbon dioxide.

The other point to note in regard to the effect of carbon dioxide, particularly with respect to global warming debate is that the atmospheric partial pressure of water vapor as shown in Figure 6 is 2.0 cm (Hg)[6] or 2.7 kPa[7], whereas the atmospheric partial pressure of carbon dioxide (400 ppm) is 0.04 kPa. In

[6] This corresponds to saturation vapor pressure at 22.5 °C (72 °F).

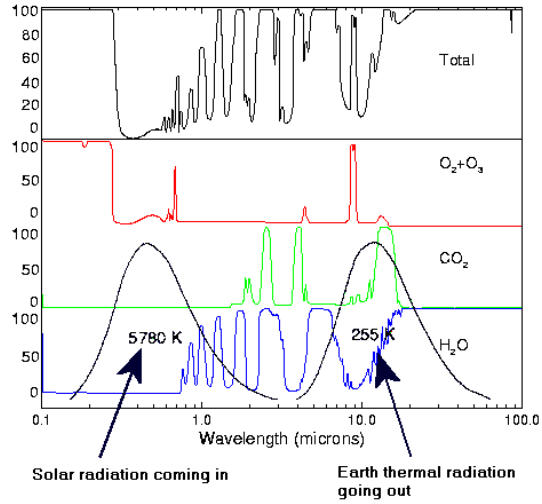


Figure 10: Absorption Bands of Atmospheric Gases

other words, there is more than sixty times more water vapor than carbon dioxide in a normal atmosphere.

A very large part of the surface area of the earth is covered in water, particularly in the tropical areas. The energy from the sun acting on the oceans causes the water to evaporate. To illustrate the effectiveness of this evaporation, compare what happens during the course of a day on land and over the ocean.

On land the sun rises and begins to heat the air and the ground. However, the surface of the ground heats slowly resulting in the air temperature rising faster than the ground. As the sun sets the air temperature begins to drop, since there is no longer a source of energy. There is some heat stored in the ground during the day, but since the heat capacity of the ground tends to be low, it does little to slow the cooling. In the absence of significant cloud cover the result is a significant change in temperature between day and night.

Over the ocean, however, the situation is quite different. Here there is little or no change in sea surface temperature between day and night. The process of evaporation requires the addition of the latent heat of vaporization, which is supplied by the sunlight. Thus a large portion of the energy from the sun is converted into water vapor without changing the temperature of the water or the water vapor, and the surface temperature is maintained relatively constant. At night, when the air temperature would tend to cool, the large heat capacity of the water warms the air and continues to maintain the daytime temperature.

Furthermore, the sun is no longer supplying energy during the night, which allows the air well above the surface to cool. Near the ocean surface, however, the ocean is the primary source of heat. This keeps the temperature of the air at the surface higher resulting in a temperature gradient to the cooler air above. This temperature gradient causes the warm air to ascend and carry the water vapor with it into the upper levels of the atmosphere. As the relatively warm and moisture-laden air rises it moves toward the cooler regions of the earth. It then is replaced with cooler air, which warms and ascends. This circulation of air is like an engine that is pumping energy, in the form of water vapor, from the ocean's surface to the upper atmosphere. From there it eventually gets distributed all the way to the poles.

There is a fascinating illustration of just how dramatic this movement can be. In a news item entitled "NOAA Researchers Study Rivers of the Sky" the NOAA writers said,

> Atmospheric rivers are a key feature of nature's atmospheric water supply pipeline. While scientists and forecasters have long recognized that the water vapor that fuels rain, snow, stream flow and storms is transported by a variety of atmospheric processes, it has only recently

[7] Average atmospheric pressure at sea level is 101.325 kPa , 1013 mbar, 29.92 inches Hg, or 760 mm Hg.

become apparent how much of this is focused in very narrow regions of the atmosphere—the so-called rivers—that move with the storms.

> Using a combination of computer simulations and atmospheric observations, NOAA ETL scientists have confirmed that more than 90 percent of the water vapor that is transported towards the poles in the heavily populated mid-latitudes are channeled into these rivers, narrow regions of very moist and fast moving air, roughly 240-480 kilometers (150-300 miles) wide, within the lowest 3,000 meters (10,000 feet) of the atmosphere. (NOAA)

Included with the article was a map showing the presence of these “atmospheric rivers,” which is shown in Figure 11.

Take note of the second paragraph in the quotation. When they speak of water vapor being transported towards the poles they are in effect speaking of the transfer of energy from the equator to the poles.

The temperature of the air itself is not much of an issue, nor is its ability to absorb/emit infrared radiation in the lower atmosphere. This is because the energy is transmitted via the water vapor, not by radiation. As the moist air rises further the temperature continues to drop, increasing the relative humidity. Air at any given temperature has the ability to hold a certain amount of water vapor. As the air cools, the amount of water vapor that the air can hold decreases. The higher in the atmosphere the air goes it continues to cool until the air is saturated with the water vapor.

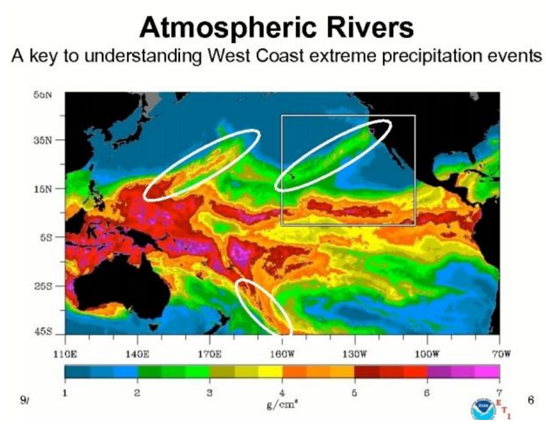


Figure 11:Atmospheric Rivers. The color scale represents the total amount of water vapor between the ocean surface and space. (NOAA)

At that point the water vapor begins to condense into small droplets which form into clouds. It is at this point that the latent heat of vaporization becomes the latent heat of condensation. The solar energy that was absorbed by the water molecules as they were vaporized is now released in the upper atmosphere as they condense into droplets.

Clouds can either move by air circulation away from the tropics or drop some of the rain in the areas we know as tropical rain forests. Much the same thing happens over the tropical rain forests that occurs over the oceans. Evaporation moderates the temperature, which is typically 30-35 °C during the day and about 10 °C cooler at night. The warm, moist air rises and condenses to form more clouds.

The energy which is released as the water vapor condenses becomes the engine that drives the air circulation from the equatorial region to the poles.

> The circulation of the atmosphere is driven by differences in surface temperature and the release of latent heat giving rise to columns of rising air particularly over the tropical rain forests. Air descends over the cold oceans in the subtropics and also over the Polar Regions especially in their winter season when the pole is dark and the surface is the coldest. (Happ)

Conclusion

The role of water vapor in determining surface temperatures is ultimately a dominant one. During daylight hours it moderates the sun's energy, at night it acts like a blanket to slow the loss of heat, and carries energy from the warm parts of the earth to the cold. Compared to that, if carbon dioxide has an effect, it must be negligible.

It is also clear from the data presented above that water vapor acts with a negative feedback. The data clearly shows that the relationship between the amount of water vapor in the air and temperature is negative; that is, the higher the amount of water vapor in the atmosphere the lower the surface temperature. In that regard, it almost acts as a thermostat.

As the air cools as a result of an increasing moisture content in the atmosphere, there is a decrease in the amount of water vapor produced by evaporation. Eventually this decrease of the level of water vapor being introduced into the atmosphere results in a decrease in moisture content. At this point more sunlight reaches the earth's surface resulting in higher temperatures and increasing evaporation.

In the positive feedback mechanism as proposed by the global warming ptoponents this behavior would be reversed. Then the data would show a positive relationship between moisture content and temperature. But it does not.

As suggested before, data is the language of science, not mathematical models.

About the Author

Dr. Daniel M. Sweger, AB (Physics, Duke University, 1965) and Ph.D. (Solid State Physics, American University, 1974) has been a research scientist at NIST, where he was active in a variety of research areas, including cryogenic thermometry, solid state and nuclear physics, and molecular spectroscopy. He also operated a computer software business and performed consulting for the US Army. He is now semi-retired and is an adjunct instructor at National College of Business and Technology (www.ncbt.edu), where, among other subjects, he teaches Environmental Science.

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