THE THUNDERSTORM THERMOSTAT HYPOTHESIS: HOW CLOUDS AND THUNDERSTORMS CONTROL THE EARTH'S TEMPERATURE

Willis Eschenbach
Independent Climate Researcher
16869 Lauri Lane, Occidental, CA 95465 USA
willis@taunovobay.com

ABSTRACT

The Thunderstorm Thermostat Hypothesis is the hypothesis that tropical clouds and thunderstorms actively regulate the temperature of the earth. This keeps the earth at an equilibrium temperature regardless of changes in the forcings. Several kinds of evidence are presented to establish and elucidate the Thermostat Hypothesis – historical temperature stability of the Earth, theoretical considerations, satellite photos, and a description of the equilibrium mechanism.

1. AUTHOR'S NOTE

I am aware that this study is not written in the normal scientific format. However, it is not a normal scientific study. It is the theoretical investigation of a new paradigm for understanding the climate system. In addition, it is my own small protest against the idea that scientific papers need to be written in a dense, hard-to-read format. One of the results of the Internet is that many more people are interested in, and have access to, scientific papers. It is my belief that it is in everyone's interest to have scientific papers that are accessible to a much wider audience.

This is particularly true in climate science, which ranges over a very wide variety of disciplines (oceanography, atmospheric chemistry, geology, statistics, meteorology, solar physics, biology, and many more). As such, it is important that scientific papers in the field be accessible to scientists in one of those disciplines who may not be as well versed in the other disciplines.

2. INTRODUCTION

Why Do We Need A New Paradigm?

In 1896, Svante Arrhenius speculated that an increase in CO_2 in the atmosphere would increase the global surface temperature (Arrhenius 1896). He postulated that the relationship between the two was given by the equation:

$$\Delta T = \alpha \log2(C/C0)$$

where ΔT = temperature, C = CO_2 concentration, C0 = original CO_2 concentration, log2 is logarithm to the base 2, and alpha = climate sensitivity.

Arrhenius initially estimated that a doubling of CO_2 would result in a temperature increase of 4–5 °C. In 1906 he reduced the estimate to 2.66° per doubling. By 1988, using computer models, the result of a doubling of CO_2 was estimated at 1.5–4.5 °C.

In 1988, computer models were slow and crude. Since then, a large number of improvements have been made in both the speed and the complexity of the computer models. But despite all of these improvements, we have been unable to improve this estimate in any significant way. The most recent IPCC report estimates a temperature increase of 2–4.5 °C from a CO_2 doubling, which is only a slight increase over the accuracy of the 1988 estimate.

Thus, over a century, we have made very little improvement on the initial estimate made by Arrhenius. Despite a century of advances, despite the advent of computer models, despite huge increases in the speed and complexity of those models, despite years of increases in our understanding of climate phenomena, our estimates are not improving in any significant way.

The most reasonable explanation of this inability to improve our estimate of the climate sensitivity is that we are using the wrong paradigm to understand the climate.

The Current Paradigm

The current paradigm of climate is that the temperature of the earth is a one-dimensional problem. That is to say, the surface temperature is ruled by CO_2, and everything else averages out over time. The paradigm does not allow for the possibility that there are any preferred temperatures. The paradigm does not include any temperature regulating systems. The paradigm does not include any limits on temperature variation. The paradigm does not include any acknowledgment of the effects of the Constructal Law on flow systems (Bejan 1997, 2005). It claims that CO_2 is what governs global temperatures. Everything else is assumed to average out over a period of thirty years or more.

After all, the proponents argue, it is simple physics. Increased CO_2 → increased greenhouse effect → increased temperature. How can you argue with simple physics?”

The difficulty with this single-variable paradigm is that the climate is an almost unimaginably complex dynamic system. It has five major intricate, interrelated, and incompletely understood subsystems – atmosphere, hydrosphere, biosphere, cryosphere, and lithosphere. (And that’s not counting the extra-terrestrial system, involving solar radiation, the complex interaction of helio- and geo-magnetism, solar wind, cosmic rays, coronal mass ejections, and the like.)

Each of these subsystems has a host of known and unknown forcings, interactions, phase transitions, limitations, resonances, couplings, response times, feedbacks, natural cycles, emergent phenomena, constructal constraints, and control systems. Finally, climate is affected by things occurring on spatial scales from the molecular to the planetary, and on temporal scales from the instantaneous to millions of years.

To illustrate what this complexity means for the current “simple physics” paradigm, consider a similar “simple physics” problem in heat transfer. Suppose we take a block of aluminum six feet long and put one end of it into a bucket of hot water. We attach a thermometer to the other end, keep the water hot, and watch what happens. Fairly soon, the temperature at the other end of the block starts to rise. It’s a one-dimensional problem, ruled by simple physics.

To verify our results, we try it again, but this time with a block of iron. Once again the temperature soon rises at the other end, just a bit more slowly than the aluminum. We try it with a block of glass, and a block of wood, and a block of copper. In each case, after time, the temperature at the other end of the block rises. This is clearly simple physics in each case.

As a final test, I look around for something else that is six feet long to use in the investigation. Finding nothing, I have an inspiration. I sit down, put my feet in the hot water, put the thermometer in my mouth and wait for the temperature of my head to start rising. After all, heat transmission is simple physics, isn't it? So I just sit with my feet in the hot water and wait for the temperature of my head to rise.

And wait.

And wait ...

The moral of the story is that in dealing with complex systems such as the climate or the human body, the simplistic application of one-dimensional analyses or the adoption of a simple paradigm based on simple physics often gives results that have no resemblance to real world outcomes. It is this inability of the current paradigm to lead us to any deeper understanding of climate that underlines the need for a new paradigm. The current paradigm is incapable of solving many of the puzzles posed by the variations in global climate.

Historical Stability

The stability of the earth's temperature over geological time has been a long-standing climatological puzzle. The globe has maintained a temperature of ± ~ 3% (including ice ages) for at least the last half a billion years during which we can estimate the temperature. During the Holocene (since the last Ice Age), temperatures have not varied by ±1% (±3 °C). And during the ice ages, the temperature was generally similarly stable. Figure 1 shows the variations of temperature over the last half billion years.

First, maximum temperature for a blackbody at our distance from the sun is less than the earth's temperature. This warming above the theoretical maximum possible temperature is a result of the so-called "greenhouse effect".

Second, although it has gotten cold at times, at no time has the temperature gone below freezing. Currently, we are at the cold end of the variation over geological time.

Third, the earth's temperature has only varied about ±3% during the last half billion years. And for much of that time, the variations have been much smaller, in the range of ±1%.

Fourth, the earth appears to have limits beyond which the temperature does not venture, although it spends long periods of time at those limits.

In contrast to Earth's temperature stability, solar physics has long indicated (Gough, 1981; Newman et al., 1977) that the sun is warming at a rate of about 10% per billion years. The warming from this is shown by the gray line in Figure 1. In early geological times, however, the earth was not correspondingly cooler. Temperature proxies such as deuterium/hydrogen ratios and 16O/18O ratios show no sign of solar driven warming of the earth over this time. Why didn't the earth warm as the sun warmed? Why didn't the earth freeze when the sun was much cooler than it is now?

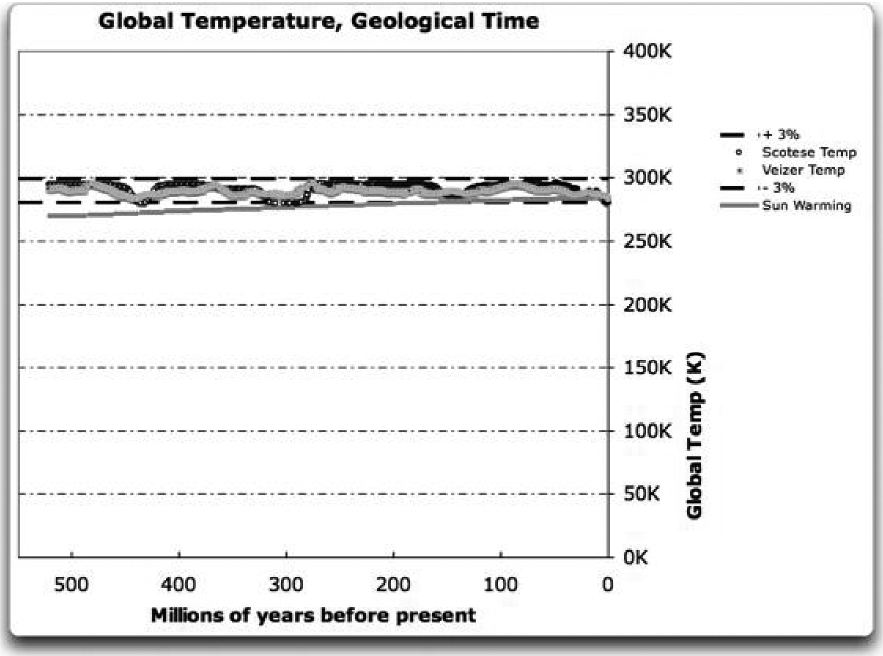

Figure 1. Variation of temperature over the last half a billion years. Two different temperature estimates are given, with data sources listed in References. Temperatures are given as anomalies around 290°. The gray line shows the warming expected from the increased strength of the sun. Warming due to the change in solar strength is calculated at the IPCC value of 3 °C per 3.7 W/m^2.

This is called the "Faint Early Sun Paradox" (Sagan et al., 1972), and is usually explained by positing an early atmosphere much richer in greenhouse gases than the current atmosphere. However, this would imply a gradual decrease in GHG forcing which exactly matched the incremental billion-year increase in solar forcing to the present value. This seems highly unlikely.

Why has Earth's temperature stayed so stable? Global temperature has stayed within a narrow band for at least the last half billion years. During that time the planet has seen meteor strikes, and millennia long widespread volcanic eruptions, and huge forest fires, and oceans disappearing as continents were lifted out of the sea, and huge changes in the land cover, and all manner of good, bad, and ugly events. Each of these events had a large effect on the forcings. Despite all of that, despite all of the variation in the forcings and the changes in the losses during all of that geological time, the earth's temperature hasn't moved around much at all. A few percent. And the variation over the last 10,000 years has been less than ±1%. For a system as complex as the climate, this is amazing stability.

So I began looking for some natural governing mechanism that was strong enough to hold the Earth's temperature within such narrow bounds.

3. THE CLIMATE GOVERNING MECHANISM

Bejan (Bejan 2005) has shown that the climate system can be robustly modeled as a heat engine, with the ocean and the atmosphere as the working fluids. The tropics are the hot end of the heat engine. Some of that tropical heat is radiated back into space. The system transports the rest of that tropical heat to the Poles. There, at the cold end of the heat engine, the net flow of heat is from earth to space. Fig. 2 shows the entire system.

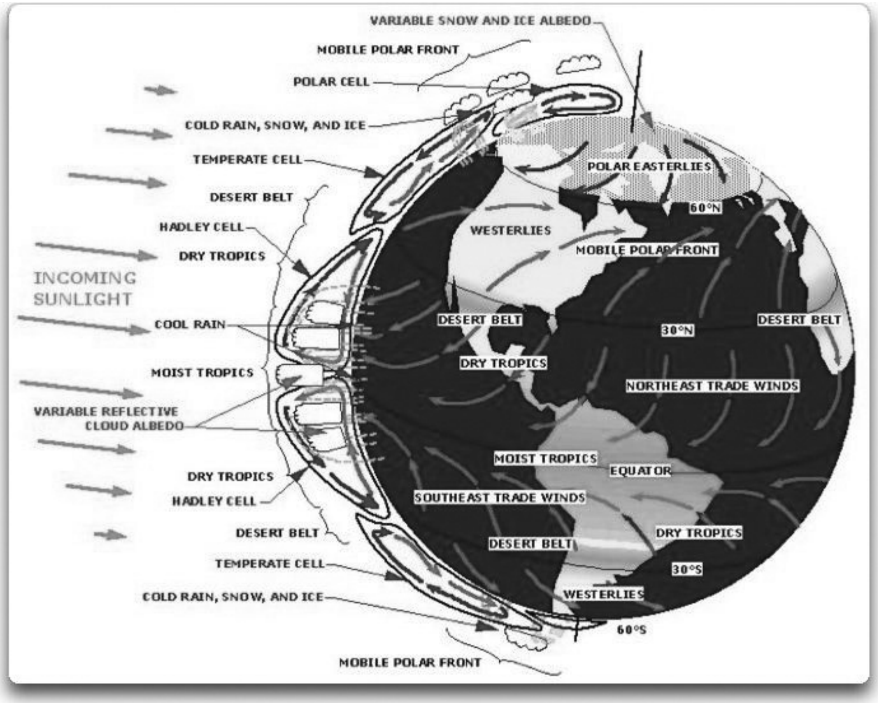

Figure 2. The Earth as a Heat Engine. The equatorial Hadley Cells provide the power for the system. Over the tropics, the sun is strongest because it hits the earth most squarely. The length of the arrows labeled "Incoming Sunlight" shows relative sun strength. Warm dry air descends at about 30N and 30S, forming the great desert belts that circle the globe. Heat is transported by a combination of the ocean and the atmosphere to the poles. At the poles, the heat is radiated to space.

Since the climate can be modeled as a heat engine as shown in Fig. 2, what might be regulating the temperature to keep it within such a narrow band? Heat engines usually have a throttle. The throttle is the part of the engine that controls how much energy enters the heat engine. A motorcycle has a hand throttle. In an automobile, the throttle is called the gas pedal. It controls how much energy (fuel) enters the car's engine.

While all heat engines have a throttle that controls incoming energy, not all of them have a governor. In a car, a governor is called "Cruise Control". Cruise control is a governor that controls the throttle (gas pedal). A governor adjusts the energy going to the car engine to maintain a constant speed regardless of changes in internal and external forcing (e.g. hills, winds, engine efficiency and losses).

A governor uses both negative and positive feedback to control a system so that it maintains a steady state. An example of negative feedback is the effect of air friction on a car. As you increase your speed, the friction goes up, reducing your speed. It is a negative feedback affecting your speed. However, it is only a negative feedback. Air friction can never speed the car up.

In the climate heat engine, the throttle is the clouds that reflect solar energy back to space. Clouds control how much energy enters the system. However, a throttle is not enough. The stability of the earth's temperature over time (including alternating bi-stable glacial/interglacial periods), as well as theoretical considerations, indicates that this heat engine we call climate must have some kind of governor controlling the throttle.

We can narrow the candidates for this climate governor by noting first that a governor controls the throttle (which in turn controls the energy supplied to a heat engine). Second, we note that a successful governor must be able to drive the system beyond the desired result (overshoot). For a governor to control a lagged system, it must be capable of overshoot.

A governor is different from a simple linear negative feedback. A linear negative feedback can only reduce an increase. It cannot maintain a steady state in the face of differing forcings, variable loads, and changing losses. Only a governor can do that. A governor must perforce be able to increase as well as decrease the overall speed. Regarding the climate, when the earth gets too cold, the governor must be able to actively warm it up. When the earth gets too hot, the governor must cool it down. A simple negative feedback cannot do that.

In order to maintain a steady climate state, a governor must be able to cool the system down below the starting point (overshoot). In terms of temperature, it must be able to more than just reduce the size of an increase. It must actively cool the earth down to a temperature cooler than the starting point.

I propose that two inter-related but separate mechanisms act directly to regulate the earth's temperature – cumulus and other reflective clouds provide the throttle, and cumulonimbus clouds (thunderstorms) are the governor.

Cumulus clouds are the fluffy "cotton ball" clouds that abound near the surface on warm afternoons. Thunderstorms start life as simple cumulus clouds. Both types of clouds are part of the throttle control. Globally, clouds reflect about 20% of the incoming solar energy. Locally, of course, the effect is far greater. Both cumulus and cumulonimbus clouds are part of the throttle system. In addition, the cumulonimbus clouds are active heat engines that provide the necessary overshoot to act as a governor on the system.

The majority of the earth's absorption of heat from the sun takes place in the tropics. This is due to a combination of factors that reduce insolation as we move towards the poles. These include increasing tilt of the surface, increasing depth of atmosphere to traverse, increasing reflection from clouds, increasing albedo due to the angle of incidence, and increasing albedo from snow and ice. Combined, these mean that very little solar energy heats the poles, and most of it is absorbed at the tropics.

The tropics, like the rest of the world, are mostly ocean; and what land is there is wet land. The steamy tropics, in a word. The entire global heat engine we call climate is spun into motion by the ascending air and thunderstorms at the tropics, as shown in Fig. 2. The tropics are the hot end of the heat engine, where the majority of the solar energy enters the system. It absorbs much more heat than it can radiate to space. This heat is exported from the tropics and transported pole wards. There the heat is eventually radiated to space. Because they regulate incoming energy, the tropics play a huge part in the thermal balance of the earth. There is little ice there, so the clouds are the throttle that controls how much energy enters the climate heat engine. And the thunderstorms are the governor.

A pleasant thought experiment shows how this thunderstorm governor works. I call it "A Day In the Tropics".

I live in the deep, moist tropics, at 9°S, with a view of the South Pacific Ocean from my windows. Here's what a typical day looks like. In fact, it's a typical summer day everywhere in the Tropics. The weather report goes like this:

> *Clear and calm at dawn. Light morning winds, clouding up before noon. In the afternoon, increasing clouds and wind with a chance of showers and thundershowers as the storms develop. Clearing around or after sunset, with an occasional thunderstorm after dark. Progressive clearing until dawn.*

That's the most common daily cycle of tropical weather, common enough to be a cliché around the world.

It is driven by the day/night variations in the strength of the sun's energy. Before dawn, the atmosphere is typically calm and clear. As the ocean (or moist land) heats up, air temperature and evaporation increase. Warm moist air starts to rise. Soon the rising moist air cools and condenses into clouds. The clouds reflect the sunlight. That's the first step of climate regulation. Increased temperature leads to clouds. The clouds close the throttle slightly, reducing the energy entering the system. They start cooling things down. This is the negative feedback part of the cloud climate control.

The tropical sun is strong, however. Despite the negative feedback from the cumulus clouds, the day continues to heat up. The more the sun hits the ocean, the more warm, moist air is formed, and the more cumulus clouds form. This, of course, reflects more sun, which is to say the throttle closes a bit more. But despite that the day continues to warm.

The full development of the cumulus clouds sets the stage for the second part of temperature regulation. This is not simple negative feedback. It is the climate governing system. As the temperature continues to rise, as the evaporation climbs, some of the fluffy cumulus clouds suddenly transform themselves. They rapidly extend skywards, thrusting up to form pillars of cloud thousands of meters high in a short time. These cumulus clouds are transformed into cumulonimbus (thunderstorm) clouds. The columnar body of the thunderstorm acts as a huge vertical heat pipe. The thunderstorm sucks up warm, moist air at the surface and shoots it skyward. At altitude the water condenses, transforming the latent heat into sensible heat. The air is re-warmed by this release of sensible heat, and continues to rise.

At the top, the air is released from the cloud up high, way above most of the CO_2. In that rarified atmosphere, the air is much freer to radiate to space. By moving inside the thunderstorm heat pipe, the air bypasses most of the greenhouse gases and comes out near the top of the troposphere. During the transport aloft, there is no radiative or turbulent interaction between the rising air and the lower and middle troposphere. Inside the thunderstorm, the rising air is tunneled through most of the troposphere to emerge at the top.

In addition to reflecting sunlight from their top surface as cumulus clouds do, and transporting heat past the greenhouse gases to the upper troposphere where it radiates easily to space, thunderstorms cool the surface in a variety of other ways, particularly (but not exclusively) over the ocean.

1. Wind driven evaporative cooling. Once the thunderstorm starts, it creates its own strong wind around the base. This self-generated wind increases evaporation in several ways, particularly over the ocean.
   a) Evaporation rises linearly with wind speed. At a typical squall wind speed of 10 metres per second (mps) (20 knots), evaporation is about ten times higher than at "calm" conditions (conventionally taken as 1 mps).
   b) The wind increases evaporation by creating spray and foam, and by blowing water off of trees and leaves. These greatly increase the evaporative surface area, because the total surface area of the millions of droplets is evaporating as well as the actual surface itself.
   c) To a lesser extent, ocean surface area is also increased by wind-created waves (a wavy surface has larger evaporative area than a flat surface).
   d) Wind created waves in turn greatly increase turbulence in the boundary layer. This increases evaporation by mixing dry air down to the surface and moist air upwards.
   e) As the spray rapidly warms to air temperature, which in the tropics is often warmer than ocean temperature, evaporation also rises above the sea surface evaporation rate.
2. Wind driven albedo increase. The white spray, foam, spindrift, changing angles of incidence, and white breaking wave tops greatly increase the albedo of the sea surface. This reduces the energy absorbed by the ocean.
3. Cold rain and cold wind. As the moist air rises inside the thunderstorm's heat pipe, water condenses and falls. Since the water is originating from condensing or freezing temperatures aloft, it cools the lower atmosphere it falls through. It also cools the surface when it hits. In addition, the falling rain entrains a cold wind. This cold wind blows radially outwards from the center of the falling rain, cooling the surrounding area.
4. Increased reflective area. White fluffy cumulus clouds are not tall, so basically they only reflect from their tops. On the other hand, the vertical pipe of the thunderstorm reflects sunlight along the sides of its entire height. This means that thunderstorms shade an area of the ocean out of proportion to their footprint, particularly in the late afternoon.
5. Modification of upper tropospheric ice crystal cloud amounts (Lindzen 2001, Spencer 2007). These clouds form from the tiny ice particles that come out of

the smokestack of the thunderstorm heat engines. It appears that the regulation of these clouds has a large effect, as they are thought to warm (through IR absorption) more than they cool (through reflection).

6. Enhanced nighttime radiation. Unlike long-lived stratus clouds, cumulus and cumulonimbus generally die out and vanish as the night cools, leading to the typically clear skies at dawn. This allows greatly increased nighttime surface radiative cooling to space, particularly in the early morning.
7. Delivery of dry air to the surface. The air being sucked from the surface and lifted to altitude is counterbalanced by a descending flow of replacement air emitted from the top of the thunderstorm. This descending air has had the majority of the water vapor stripped out of it inside the thunderstorm, so it is relatively dry. The dryer the air, the more moisture it can pick up for the next trip to the sky. This increases the evaporative cooling of the surface.

In part because they utilize such a wide range of cooling methods, cumulus clouds and thunderstorms are extremely good at reducing the surface temperature of the earth. Together, they form the governing mechanism for the tropical temperature.

But where is that mechanism?

The problem with my thought experiment of describing a typical tropical day is that it is always changing. The temperature goes up and down, the clouds rise and fall, day changes to night, the seasons come and go. Where in all of that unending change is the governing mechanism? If everything is always changing, what keeps the temperature within a narrow range month-to-month and year-to-year? If conditions are always different, what keeps the temperature from going off the rails?

In order to see the governor at work, we need a different point of view. We need a point of view without time. We need a timeless view without seasons, a point of view with no days and nights. And curiously, in this thought experiment called "A Day In the Tropics", there is such a timeless point of view, where not only is there no day and night, but where it is always summer.

The point of view without day or night, the point of view from which we can see the climate governor at work, is the point of view of the sun. Imagine that you are looking at the earth from the sun. From the sun's point of view, there is no day and night. All parts of the visible face of the earth are always in sunlight; the sun never sees the nighttime. And it is always summer under the sun.

If we accept the convenience that north is up, then as we face the earth from the sun, the visible surface of the earth is moving from left to right as the planet rotates. So the left hand edge of the visible face is always at sunrise, and the right hand edge is always at sunset. Noon is a vertical line down the middle. From this timeless point of view, morning is always and forever on the left, and afternoon is always on the right. In short, by shifting our point of view, we have traded time coordinates for space coordinates. This shift makes it easy to see how the governor works.

The tropics stretch from left to right across the circular visible face. We see that near the left end of the tropics, after sunrise, there are very few clouds. Clouds increase as you look further to the right. Around the noon line, there are already cumulus clouds. And as we look from left to right across the right side of the visible face of the earth, towards the afternoon, more and more cumulus clouds and increasing numbers of thunderstorms cover a large amount of the tropics.

It is as though there is a graduated mirror shade over the tropics, with the fewest cloud mirrors on the left, slowly increasing to extensive cloud mirrors and thunderstorm coverage on the right.

After coming up with this hypothesis that as seen from the sun, the right hand side of the deep tropics would have more cloud than the left hand side, I realized this was a testable proposition to support or demolish my hypothesis. So in order to investigate whether this postulated increase in cloud on the right hand side of the earth actually existed, I took an average of 24 pictures of the Pacific Ocean taken at local noon on the 1st and 15th of each month over an entire year. I then calculated the average change in albedo and thus the average change in forcing at each time. Fig. 3 shows the changes in the clouds and the albedo.

The graph below the image of the earth in Fig. 3 shows the albedo and solar forcing in the rectangle that contains the Pacific Inter-Tropical Convergence Zone. Note the sharp increase in the albedo between 10:30 and 11:30. You are looking at the

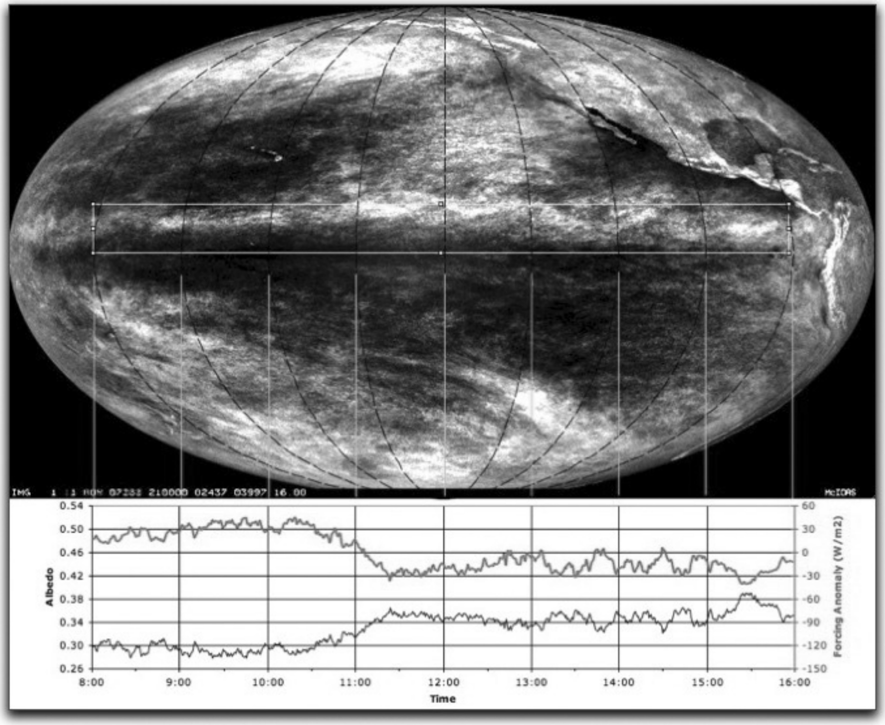

Figure 3. Average of one year of GOES-West weather satellite images taken at satellite local noon. The Intertropical Convergence Zone is the bright band in the gray rectangle. Dashed black lines on the image show local time on earth. Time values are shown at the bottom of the attached graph. Upper line on graph is solar forcing anomaly (in watts per square meter) in the area outlined by the rectangle (right scale). Lower line is albedo value in the area outlined by the rectangle (0°–15°N).

mechanism that keeps the earth from overheating. It causes a change in insolation of -60 W/m^2 between ten and noon.

Now, consider what happens if for some reason the surface of the tropics is a bit cool. The sun takes longer to heat up the surface. Evaporation doesn't rise until later in the day. Clouds are slow to appear. The first thunderstorms form later, fewer thunderstorms form, and if it's not warm enough those giant surface-cooling heat engines don't form at all.

And from the point of view of the sun, the entire mirrored shade shifts to the right, letting more sunshine through for a longer time. The 60 W/m^2 reduction in solar forcing doesn't take place until later in the day, increasing the local insolation.

When the tropical surface gets a bit warmer than usual, the mirrored shade gets pulled to the left, and clouds form earlier. Hot afternoons drive thunderstorm formation, which cools and air-conditions the surface. In this fashion, a self-adjusting cooling shade of thunderstorms and clouds keeps the temperature within a narrow range. A change in albedo of a mere 2%, from say 30% albedo to 32% albedo, is equivalent to two doublings of CO_2 (from the current 380 ppmv to 1,520 ppmv!) . . . so a tiny, undetectable change in cloud cover is more than enough to offset any conceivable variation in CO_2.

One of the unexpected findings in Fig. 3 above is the nature of the change in albedo from early morning to late afternoon. Albedo runs level at ~ 0.30 from eight am to ten-thirty AM. In the next hour, it takes a very quick jump to ~ 0.34. From there it stays roughly level until 16:00.

My interpretation of this is that once the cumulus starts to form, it forms in an hour or so. At the end of that time, it has covered the maximum area possible. Remember that a cumulus cloud is not a "thing". It is a flag marking an area of rising air. What goes up must come down. So these areas of rising air have to be surrounded by areas where the air is descending. Fairly quickly, the limit of cumulus growth is reached. At that point the uprising and descending areas have reached their full growth balance. Fig. 3 shows that cumulus growth ends around 11:30. The growth limit is where cloud cover starts to seriously cut into the area available for descending air. That ratio of cumulus area to area of descending air appears to be maintained for the rest of the day. To me, this is a sign of a system that is fully developed. The clouds are not able to stop the temperature rise, much less drive the temperature down below the starting point. As evaporation increases and more water vapor condenses, the clouds are forced to grow vertically rather than horizontally. The lapse rate decreases over a larger vertical area and the effective heat capacity of the formation increases dramatically relative to its surroundings. More energy is available but temperature changes more slowly. And as the temperatures continue to rise, at some point, the thunderstorms begin to form. They begin cooling the surface immediately, stopping the temperature increase.

It is this daily regulation of tropical temperature that governs the temperature over millennia. I used to think that the governor system would have to operate over geological timescales. I wasted a lot of time trying to imagine what that hugely slow, long timescale system might be. But one day, after years of looking, I realized that since on average the cloud/thunderstorm combo keeps the daily tropical temperature on average within say a 6° range, then the million year average would also be within the same 6° range. I smote my forehead in frustration over wasted time ...

4. HOW THE GOVERNOR WORKS

Tropical cumulus production and thunderstorm production are driven by air density. Air density is a function of temperature (affecting density directly through air parcel expansion/contraction) and the water content of the air (water vapor is lighter than air).

A thunderstorm is both a self-generating and self-sustaining heat engine. The working fluids are moisture-laden warm air and liquid water. Self-generating means that whenever it gets hot enough over the tropical ocean, which is almost every day, at a certain level of temperature and humidity, some of the fluffy cumulus clouds suddenly catch fire. The tops of the clouds streak upwards, showing the rising progress of the moisture laden surface air. At altitude, the rising air exits the cloud, replace by more moist air from below. Suddenly, in place of a placid cloud, there is an active thunderstorm.

Self-generating means that the thunderstorms arise spontaneously as a function of temperature and evaporation. Above the threshold necessary to create the first thunderstorm, the number of thunderstorms rises rapidly. This rapid increase in thunderstorms limits the amount of temperature rise possible.

Self-sustaining means that once a thunderstorm gets going, it no longer requires the full initiation temperature necessary to get it started. This is because the self-generated wind at the base, plus dry air falling from above, drive the evaporation rate way up. The thunderstorm is driven by air density. It requires a source of light, moist air. The density of the air is determined by both temperature and moisture content (because curiously, water vapor at molecular weight 18 is a third lighter than air, which has a weight of about 29). This means that a thunderstorm is a "dual-fuel" engine. It runs off of combination of temperature or water vapor. A lack of one fuel can be made up by more of the other fuel. (Chang 2009)

Evaporation is not a function of temperature alone. It is governed by a complex mix of wind speed, water temperature, air temperature, and vapor pressure. Evaporation is calculated by what is called a "bulk formula", which means a formula based on experience rather than theory. One commonly used formula is:

$$E = VK(es - ea)$$

where

E = evaporation
V = wind speed (function of temperature difference [ΔT])
K = coefficient constant
es = vapor pressure at evaporating surface (function of water temperature in degrees K to the fourth power)
ea = vapor pressure of overlying air (function of relative humidity and air temperature in degrees K to the fourth power)

Regarding thunderstorms, the critical thing to notice in the formula is that evaporation varies linearly with wind speed. This means that evaporation near a thunderstorm can be an order of magnitude greater than evaporation a short distance away.

In addition to the changes in evaporation, there at least one other mechanism increasing cloud formation as wind increases. This is the wind-driven production of airborne salt crystals. The breaking of wind-driven waves produces these microscopic crystals of salt. The connection to the clouds is that these crystals are the main condensation nuclei for clouds that form over the ocean. The production of additional condensation nuclei, coupled with increased evaporation, leads to larger and faster changes in cloud production with increasing temperature.

Increased wind-driven evaporation means that for the same density of air, the surface temperature can be lower than the temperature required to initiate the thunderstorm. This means that the thunderstorm will still survive and continue cooling the surface to well below the starting temperature. (Chang 2009).

This ability to drive the temperature lower than the starting point is what distinguishes a governor from a negative feedback. A thunderstorm can do more than just reduce the amount of surface warming. It can actually mechanically cool the surface to below the temperature required to start the thunderstorm. This is the overshoot that allows it to actively maintain a fixed temperature in the region surrounding the thunderstorm.

A key feature of this method of control via clouds and thunderstorms is that *the equilibrium temperature is not governed by changes in the amount of losses or changes in the forcings in the system*. The equilibrium temperature is set by the response of wind and water and cloud to increasing temperature, not by the inherent efficiency of, or the inputs to, the system.

In addition, the equilibrium temperature is not affected much by changes in the strength of the solar irradiation. If the sun gets weaker, evaporation decreases, which decreases clouds, which increases the available sun. This is the likely answer the long-standing question of how the earth's temperature has stayed stable over geological times, during which time the strength of the sun has increased markedly. The answer is that if there is extra heat in the ocean from any source, the cloud cover increases. The thunderstorms increase. This is visible in the course of each day. As the sea heats, clouds increase. A change in albedo of 2% is equivalent to two doublings of CO_2 (from the current 380 ppmv to 1,520 ppmv!) . . . so a tiny, undetectable change in cloud cover is more than enough to offset any conceivable variation in CO_2.

Some climate modelers say that the clouds are not a response to the warmer weather. The models all predict positive cloud feedback, that is to say, as clouds increase it makes the earth warmer. This, they say, is the reason that warm temperatures are correlated with increased clouds.

However, there is a simple way to show that for the Tropics the causation is the other way around, that the increased tropical clouds are a result of increased temperatures. This is to look at the difference in the cloud cover in the Northern and Southern Tropics summer and winter. The equatorial cloud cover is shown in Fig. 4. In the NH summer, we see greatly increased cloud cover north of the equator in Colombia and the Sahel, and decreased clouds south of the equator. In the SH summer, the reverse is true, with the Amazon and southern Africa seeing increased cloudiness, and the areas north of the Equator seeing less clouds. Since the clouds are not causing the seasonal changes in insolation leading to warming, it is clear that the warming is

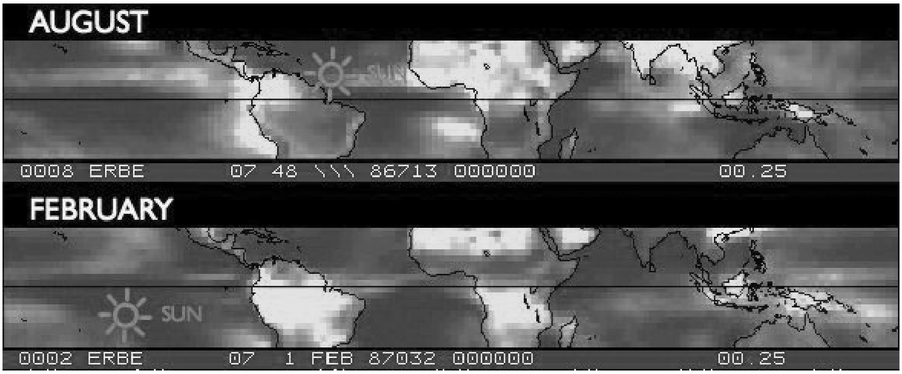

Figure 4. Tropical albedo during the Northern and Southern Hemisphere summer from the ERBE data. Upper panel shows NH summer. Lower panel shows SH summer.

causing the increase in clouds. Fig. 4 also shows that because the land warms more than the ocean, the increase in clouds is greater over the land than the ocean. Clearly, temperature is driving the clouds, and not vice-versa.

5. GRADUAL EQUILIBRIUM VARIATION AND DRIFT

If the Thunderstorm Thermostat Hypothesis is correct and the earth does have an actively maintained equilibrium temperature, what causes the slow drifts and other changes in the equilibrium temperature seen in both historical and geological times?

As shown by Bejan, one determinant of running temperature is how efficient the whole global heat engine is in moving the terawatts of energy from the tropics to the poles. On a geological time scale, the location, orientation, and elevation of the continental landmasses is obviously a huge determinant in this regard. That’s what makes Antarctica different from the Arctic today. The lack of a landmass in the Arctic means warm water circulates under the ice. In Antarctica, the cold goes to the bone.

In addition, the oceanic geography which shapes the currents carrying warm tropical water to the poles and returning cold water (eventually) to the tropics is also a very large determinant of the running temperature of the global climate heat engine. Continents drift together and apart, volcanoes build the Isthmus of Panama and close off the Central American Seaway. These large-scale gradual changes from volcanism and tectonic drift are responsible for some of the historical temperature swings that the Earth has experienced.

On a shorter term, there could be slow changes in the albedo. The albedo is a function of wind speed, evaporation, cloud dynamics, and (to a lesser degree) snow and ice. Evaporation rates are fixed by thermodynamic laws, which leave only wind speed, cloud dynamics, and snow and ice able to affect the equilibrium.

The variation in the equilibrium temperature may, for example, be the result of a change in the worldwide average wind speed. Wind speed is coupled to the ocean through the action of waves, and long-term variations in the coupled ocean-atmospheric momentum occur. These changes in wind speed may vary the equilibrium temperature in a cyclical fashion.

Or it may be related to a general change in color, type, or extent of either the clouds or the snow and ice. The albedo is dependent on the color of the reflecting substance. If reflections are changed for any reason, the equilibrium temperature could be affected. For snow and ice, this could be e.g. increased melting due to black carbon deposition on the surface. For clouds, this could be a color change due to aerosols or dust.

Finally, the equilibrium variations may relate to the sun. The variation in magnetic and charged particle numbers may be large enough to make a difference. There are strong suggestions that cloud cover is influenced by cosmic rays (Svensmark 2000). And since cloud cover is the throttle on solar energy entering the system, this could affect the climate.

6. CONCLUSIONS AND MUSINGS

1. Since we only use 70% of the sun's energy, it is clear that the sun puts out more than enough energy to totally roast the earth. It is kept from doing so by the clouds reflecting about 20% of the sun's energy back to space, and the surface reflecting back another 10%. As near as we can tell, this system of cloud formation to limit incoming solar energy has never failed.
2. A reflective shield of clouds forms in the tropics in response to increasing surface temperatures passing a critical threshold.
3. As tropical temperatures continue to rise, the reflective shield is assisted by the formation of independent heat engines called thunderstorms. These cool the surface in a host of ways. In addition, they can drive the temperature down below the temperature at which they form (overshoot). This is a requirement for controlling any lagged system.
4. Like cumulus clouds, thunderstorms also form in response to increasing temperatures passing a second threshold. The number that form is temperature driven. Once past the threshold, many storms form quickly in response to any local temperature increase.
5. Because they are temperature driven, as tropical temperatures rise, both tropical thunderstorms and cumulus production increase. These combine to regulate and limit the temperature rise. When tropical temperatures are cool, tropical skies clear and the earth warms rapidly. But when the tropics heat up, cumulus and cumulonimbus put a limit on the warming. This system keeps the earth within a fairly narrow range of temperatures.
6. The earth's temperature regulation system is based on the unchanging response of wind, water, and cloud to changes in temperature. It is not based on losses or forcings.
7. This is a reasonable explanation for how the temperature of the earth has stayed so stable for hundreds of millions of years.

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