The Thermostat Hypothesis

14
06
2009

Guest Essay by Willis Eschenbach

Abstract

The Thermostat Hypothesis is that tropical clouds and thunderstorms actively regulate the temperature of the earth. This keeps the earth at a equilibrium temperature.

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.

Historical Stability

The stability of the earth's temperature over 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, temperatures have not varied by ±1%. And during the ice ages, the temperature was generally similarly stable as well.

In contrast to Earth's temperature stability, solar physics has long indicated (Gough, 1981; Bahcall et al., 2001) that 4 billion years ago the total solar irradiance was about three quarters of the current value. 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 a 30% warming of the earth over this time. Why didn't the earth warm as the sun warmed?

This is called the "Faint Early Sun Paradox" (Sagan and Mullen, 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.

A much more likely candidate is some natural mechanism which has regulated the earth's temperature over geological time.

Theoretical Considerations

Bejan (Bejan 2005) has shown that the climate can be robustly modeled as a heat engine, with the ocean and the atmosphere being the working fluids. The tropics are the hot end of the heat engine. Some of that tropical heat is radiated back into space. Work is performed by the working fluids in the course of transporting the rest of that tropical heat to the Poles. There, at the cold end of the heat engine, the heat is radiated into space. Bejan showed that the existence and areal coverage of the Hadley cells is a derivable result of the Constructal Law. He also showed how the temperatures of the flow system are determined.

"We pursue this from the constructal point of view, which is that the [global] circulation itself represents a flow geometry that is the result of the maximization of global performance subject to global constraints."

"The most power that the composite system could produce is associated with the reversible operation of the power plant. The power output in this limit is proportional to

$$w = q\left(1 - \frac{T_L}{T_H}\right)$$

(Bejan 2005)

where q is the total energy flow through the system (tropics to poles), and TH and TL are the high and low temperatures (tropical and polar temperatures in Kelvins). The system works ceaselessly to maximize that power output. Here is a view of the entire system that transports heat from the tropics to the poles.

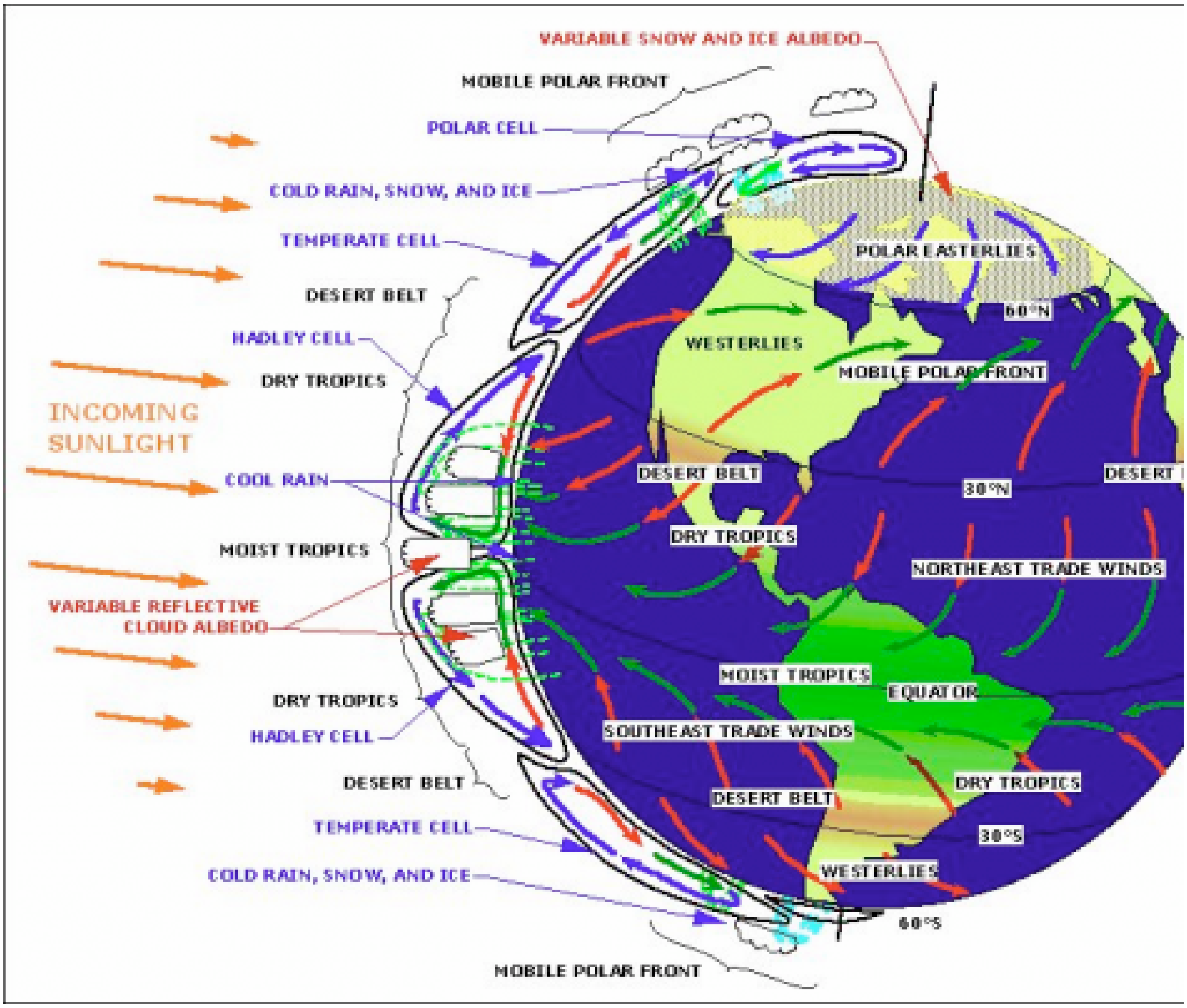

Figure 1. The Earth as a Heat Engine. The equatorial Hadley Cells provide the power for the system. Over the tropics, the sun (orange arrows) is strongest because it hits the earth most squarely. The length of the orange arrows shows relative sun strength. Warm dry air descends at about 30N and 30S, 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.

In other words, flow systems such as the Earth’s climate do not assume a stable temperature willy-nilly. They reshape their own flow in such a way as to maximize the energy produced and consumed. It is this dynamic process, and not a simple linear transformation of the details of the atmospheric gas composition, which sets the overall working temperature range of the planet.

Note that the Constructal Law says that any flow system will “quasi-stabilize” in orbit around (but never achieve) some ideal state. In the case of the climate, this is the state of maximum total power production and consumption. And this in turn implies that any watery planet will have an equilibrium temperature, which is actively maintained by the flow system. See the paper by Ou listed below for further information on the process.

Climate Governing Mechanism

Every heat engine has 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 incoming energy.

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.

While all heat engines have a throttle, 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).

We can narrow the candidates for this climate governing mechanism 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).

(Note that a governor, which contains a hysteresis loop, is different from a negative feedback. A negative feedback can only reduce an increase. It cannot maintain a steady state despite differing forcings, variable loads, and changing losses. Only a governor can do that.)

The majority of the earth's absorption of heat from the sun takes place in the tropics. The tropics, like the rest of the world, are mostly ocean; and what land is there is wet. The steamy tropics, in a word. There is little ice there, so the clouds control how much energy enters the climate heat engine.

I propose that two inter-related but separate mechanisms act directly to regulate the earth's temperature — tropical cumulus and cumulonimbus clouds. Cumulus clouds are the fluffy "cotton ball" clouds that abound near the surface on warm afternoons. Cumulonimbus clouds are thunderstorms clouds, which start life as simple cumulus clouds. Both types of clouds are part of the throttle control, reducing incoming energy. In addition, the cumulonimbus clouds are active heat engines which provide the necessary overshoot to act as a governor on the system.

A pleasant thought experiment shows how this cloud governor works. It's called "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 towards 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, reduce 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, and 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, the throttle closes a bit more. But 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 are transformed into cumulonimbus or 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 rewarmed 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 CO2. 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 to the upper troposphere where it radiates easily to space, thunderstorms cool the surface in a variety of other ways, particularly over the ocean.

1. Wind driven evaporative cooling. Once the thunderstorm starts, it creates its own 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 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, 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 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, and it 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 the tops. On the other hand, the vertical pipe of the thunderstorm reflects sunlight along its entire length. 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 (Linden 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 night-time 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.

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 mechanisms mechanisms, cumulus clouds and thunderstorms are extremely good at cooling the surface 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 it the same month to month and year to year? If conditions are always different, what keeps it 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’s 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 night time. And it’s 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. 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 though “Hey, that’s 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. Here is the result:

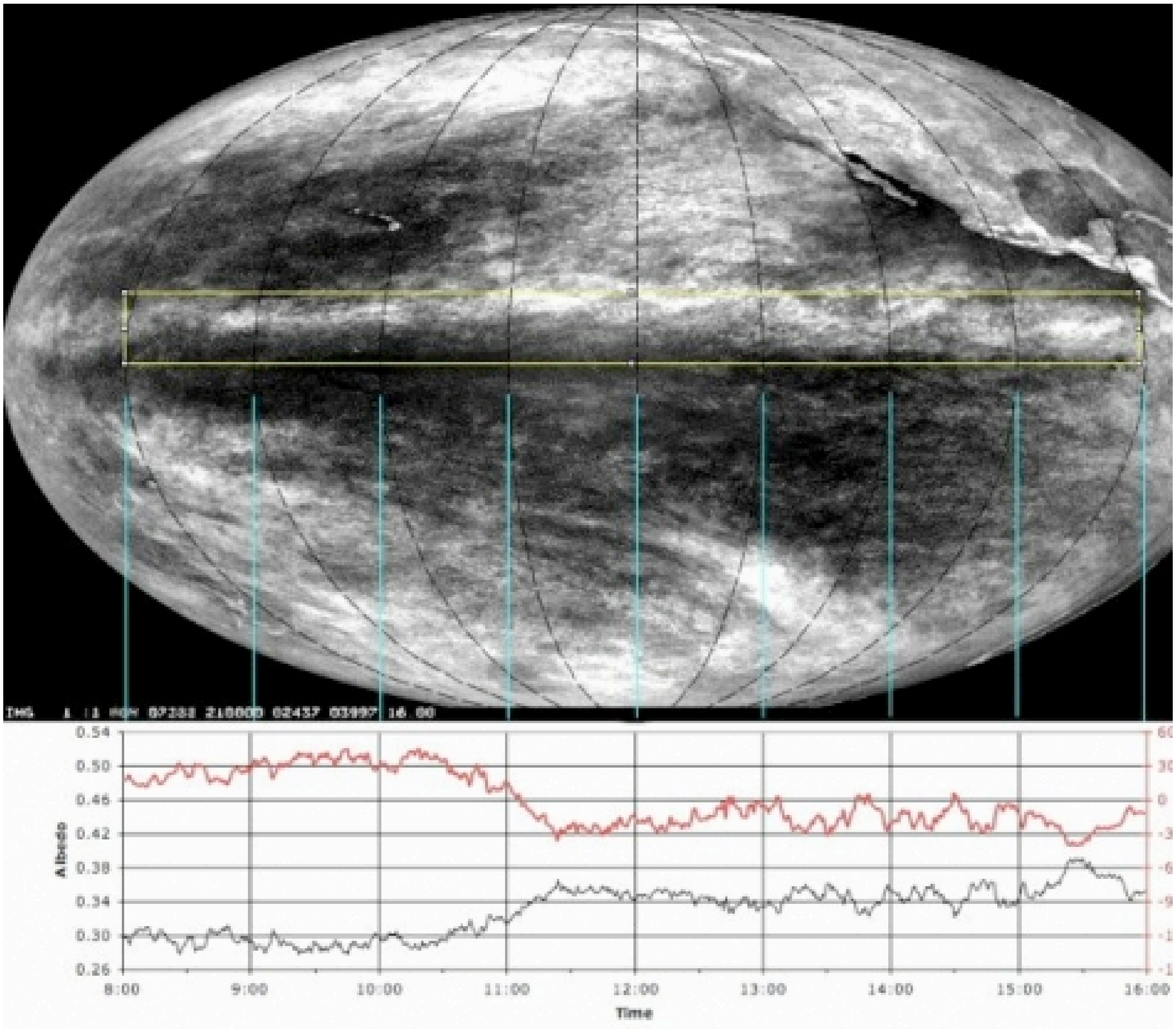

Figure 2. Average of one year of GOES-West weather satellite images taken at satellite local noon. The Intertropical Convergence Zone is the bright band in the yellow rectangle. Local time on earth is shown by black lines on the image. Time values are shown at the bottom of the attached graph. Red line on graph is solar forcing anomaly (in watts per square meter) in the area outlined in yellow. Black line is albedo value in the area outlined in yellow.

The graph below the image of the earth shows the albedo and solar forcing in the yellow rectangle which contains the Inter-Tropical Convergence Zone. Note the sharp increase in the albedo between 10:00 and 11:30. You are looking at the mechanism that keeps the earth from overheating. It causes a change in insolation of -60 W/m2 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 longer. The 60 W/m2 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 afternoon temperature within a narrow range.

Now, some scientists have claimed that clouds have a positive feedback. Because of this, the areas where there are more clouds will end up warmer than areas with less clouds. This positive feedback is seen as the reason that clouds and warmth are correlated.

I and others take the opposite view of that correlation. I hold that the clouds are caused by the warmth, not that the warmth is caused by the clouds.

Fortunately, we have way to determine whether changes in the reflective tropical umbrella of clouds and thunderstorms are caused by (and thus limiting) overall temperature rise, or whether an increase in clouds is causing the overall temperature rise. This is to look at the change in albedo with the change in temperature. Here are two views of the tropical albedo, taken six months apart. August is the warmest month in the Northern Hemisphere. As indicated, the sun is in the North. Note the high albedo (areas of light blue) in all of North Africa, China, and the northern part of South America and Central America. By contrast, there is low albedo in Brazil, Southern Africa, and Indonesia/Australia.

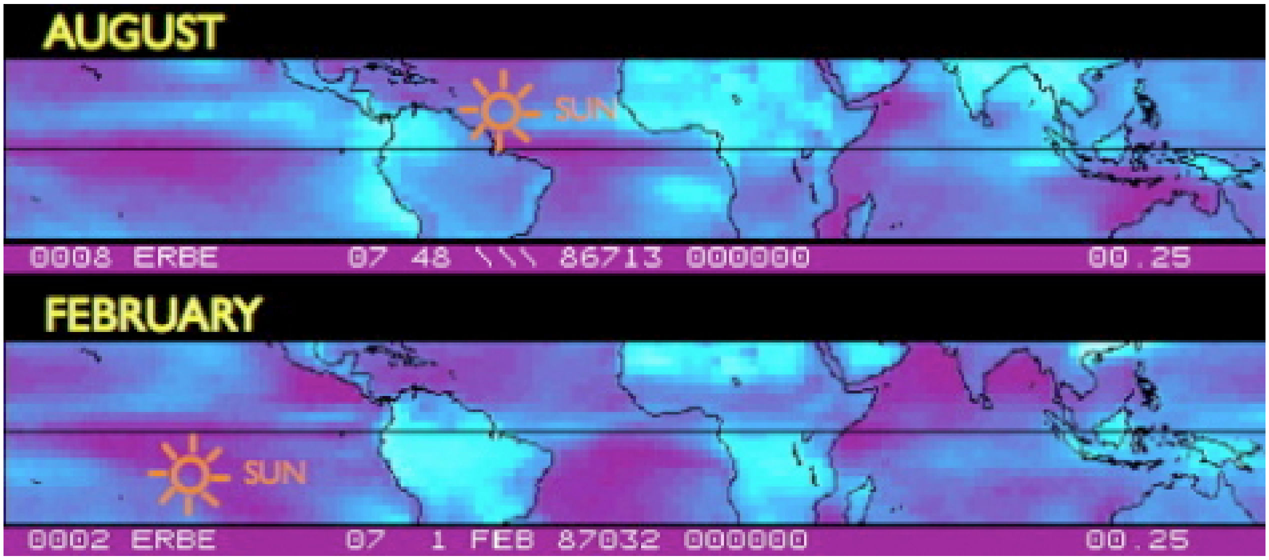

Figure 3. Monthly Average Albedo. Timing is half a year apart. August is the height of summer in the Northern Hemisphere. February is the height of summer in the Southern Hemisphere. Light blue areas are the most reflective (greatest albedo)

In February, on the other hand, the sun is in the South. The albedo situation is reversed. Brazil and Southern Africa and Australasia are warm under the sun. In response to the heat, the clouds form, and those areas now have high albedo. By contrast, the north now has low albedo, with the exception of the reflective Sahara and Rub Al Khali Deserts.

Clearly, the cloud albedo (from cumulus and cumulonimbus) follows the sun north and south, keeping the earth from overheating. This shows quite definitively that rather than the warmth being caused by the clouds, the clouds are caused by the warmth.

Quite separately, these images show in a different way that warmth drives the cloud formation. We know that during the summer, the land warms more than the ocean. If temperature is driving the cloud formation, we would expect to see a greater change in the albedo over land than over the ocean. And this is clearly the case. We see in the North Pacific and the Indian Ocean that the sun increases the albedo over the ocean, particularly where the ocean is shallow. But the changes in the land are in general much larger than the changes over the ocean. Again this shows that the clouds are forming in response to, and are therefore limiting, increasing warmth.

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) and evaporation (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 16 is only a bit more than half as heavy as air, which has a weight of about 29).

Evaporation is not a function of temperature alone. It is governed a complex mix of wind speed, water 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)
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.

So 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.

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 required initiation temperature. This allows it to actively maintain a fixed temperature in the region surrounding the thunderstorm.

A key feature of this method of control (changing incoming power levels, performing work, and increasing thermal losses to quelch rising temperatures) 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.

Gradual Equilibrium Variation and Drift

If the 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 timese?

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 land masses is obviously a huge determinant in this regard. That's what makes Antarctica different from the Arctic today. The lack of a land mass 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.

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 the 22-year solar Hale magnetic cycle, and this 14-year record only covers part of a single Hale cycle.

Conclusions and Musings

1. The sun puts out more than enough energy to totally roast the earth. It is kept from doing so by the clouds reflecting about a third of the sun's energy back to space. As near as we can tell, this system of cloud formation to limit temperature rises has never failed.

2. This reflective shield of clouds forms in the tropics in response to increasing temperature.

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, move heat aloft, and convert heat to work.

4. Like cumulus clouds, thunderstorms also form in response to increasing

temperature.

5. Because they are temperature driven, as tropical temperatures rise, 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 rapidly warms. But when the tropics heat up, cumulus and cumulonimbus put a limit on the warming. This system keeps the earth within a fairly narrow band of temperatures.

6. The earth's temperature regulation system is based on the unchanging physics of wind, water, and cloud.

7. This is a reasonable explanation for how the temperature of the earth has stayed so stable (or more recently, bi-stable as glacial and interglacial) for hundreds of millions of years.

Further Reading

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