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Martin Hertzberg

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EARTH'S RADIATIVE EQUILIBRIUM IN THE SOLAR IRRADIANCE

Martin Hertzberg
PhD, Consultant in Science and Technology
P. O. Box 3012, Copper Mountain, CO 80443, USA
ruthhertzberg@msn.com

ABSTRACT

The average equilibrium temperature for all the Earth's entities involved in its radiative balance with the Sun and Space, is given by:

$$T (e) [K] = 278.9 [(1 - \alpha) / \varepsilon]^{1/4}$$

The controlling factor is the ratio of the absorptivity, $a = (1 - \alpha)$, to the emissivity, ε . The quantity α is the Earth's albedo. It is shown that relatively modest changes of only a few percent in α, brought about by variations in cloudiness, are sufficient to account for the observed 20th Century variations in Earth's measured temperature, provided that such variations in cloudiness can cause an imbalance in the ratio $(1 - \alpha) / \varepsilon$. The analysis suggests that in the long run, the absorptivity to emissivity ratio is near unity, as required by Kirchhoff's radiation law, which ensures a moderate average temperature of about 5.7 C for the Earth's surface entities. That calculated temperature is in fair agreement with the observed average temperature of those entities, whose mass average is dominated by the mass of the oceans. Except for the influence of clouds on the albedo, no assumptions are needed regarding the detailed composition of the atmosphere in order to explain the observed small fluctuations in the 20th Century temperatures or the larger, longer-term variations of Glacial Coolings and Interglacial Warmings.

1. INTRODUCTION

In 1994, this author, in cooperation with Prof. J. B. Stott of the University of Canterbury in New Zealand, presented a poster-session paper at the 25th International Symposium on Combustion [1]. That paper was entitled "Greenhouse Warming of the Atmosphere: Constraints on Its Magnitude". Calculations in that paper showed that CO_2 absorption was relatively insignificant in comparison to absorption by the homogeneous water vapor content of the earth's atmosphere. Several conclusions were drawn in that paper. One was that:

……water vapor plays such a dominant role that any greenhouse 'runaway' predicted for the Earth's temperature should already have occurred. But since the ocean's water vapor flux increases exponentially with temperature, the increase in cloud cover albedo, inevitably limits or 'buffers' the system.

The final conclusion of that analysis was as follows:

It is implausible to expect that small changes in the concentration of any minor atmospheric constituent such as carbon dioxide, can significantly influence that radiative equilibrium (i. e. between the Earth and the Sun) despite the fact that CO2 plays a major role in the biosphere. The most significant component in the radiative equilibrium process is water: as a homogeneous absorbing and emitting vapor; in its heat transport by evaporation and condensation; as clouds, snow, and ice cover, which have a major effect on the albedo; and as the enormous circulating mass of liquid ocean, whose heat capacity, and mass/energy transport with the atmosphere, dominate the Earth's weather.

In the detailed analysis, it was noted that

The problem of obtaining a good value for the absorptivity to emissivity ratio for all the entities at the Earth's surface and atmosphere that participate in the radiative balance, is a formidable task. It is highly unlikely that any proposed model contains a realistic ratio for the entire globe over a long enough time scale. One is not dealing with a 'surface', but with a group of distributed entities: the albedo is caused by reflection and scattering from the tops of clouds, from ocean surfaces, from land surfaces covered with vegetation, soil, snow, or ice, and from dust particles distributed in depth. They are heterogeneous entities. But the albedo also has a component from the homogeneous scatterers in the atmosphere. The absorbed fraction of the solar irradiance is absorbed at the above surfaces, and also in depth by the homogeneous components of the atmosphere.

These entities, homogeneous and heterogeneous, are also emitters of the flux of radiation that is lost to free space. They are distributed vertically from sea level to the upper reaches of the atmosphere, and horizontally at all latitudes and longitudes.

And finally, that paper contained the following caveat:

Many interacting regions, both homogeneous and heterogeneous, are involved in the complex radiative balance. Unverified models do not realistically represent that balance, <u>and it would be absurd to base public policy decisions on them</u>

It is quite clear that since that 1994 paper was presented, the above advice has not been heeded. Accordingly, this author feels obligated to expand and refine that previous analysis in this paper, in the hope that the advice he gave in 1994 will now be considered.

2. THE RADIATIVE BALANCE

The gained solar power absorbed by the Earth is determined by its cross-sectional area, and is given by:

$$(1 - \alpha)\, I\, (\pi\, r^2)$$

where I is the solar 'constant' irradiance, α is the albedo (the fraction reflected and scattered back to space), and r is the radius of the earth. The quantity ($1 - \alpha$) = a , is the Earth's absorptivity.

The entities near Earth's surface that are involved in the radiative equilibrium with the Sun and Space are the physical surface, atmosphere, and oceans. They are not at a uniform temperature, but they are nevertheless characterizable by some average equilibrium temperature, T(e). Those entities radiate to Space from the entire surface area of Earth, and their emitted, lost power is given by:

$$\varepsilon\ \sigma\ T(e)^4\ (4\,\pi\, r^{2})$$

where ε is the average emissivity of those entities, and σ is the Stefan-Boltzmann constant, and T(e) is the temperature in Kelvin.

Equating the absorbed or gained solar power to balance the emitted or lost power at equilibrium, gives an average Earth temperature of :

$$T(e) = [\,(1 - \alpha)\, I / 4\, \varepsilon\, \sigma\,]^{1/4} \tag{1}$$

Now the solar irradiance I is fairly constant, and σ is a fundamental constant so that the controlling factor in determining Earth's average temperature is the ratio of the absorptivity to emissivity , $(1 - \alpha) / \varepsilon$. Substituting 1373 Watts / m^2 for I [2], and 5.671 x 10^{-8} Watts / m^2 deg^4 for the Stefan-Boltzmann constant [3], gives:

$$T(e) = 278.9\, [\,(1 - \alpha) / \varepsilon\,]^{1/4} \tag{2}$$

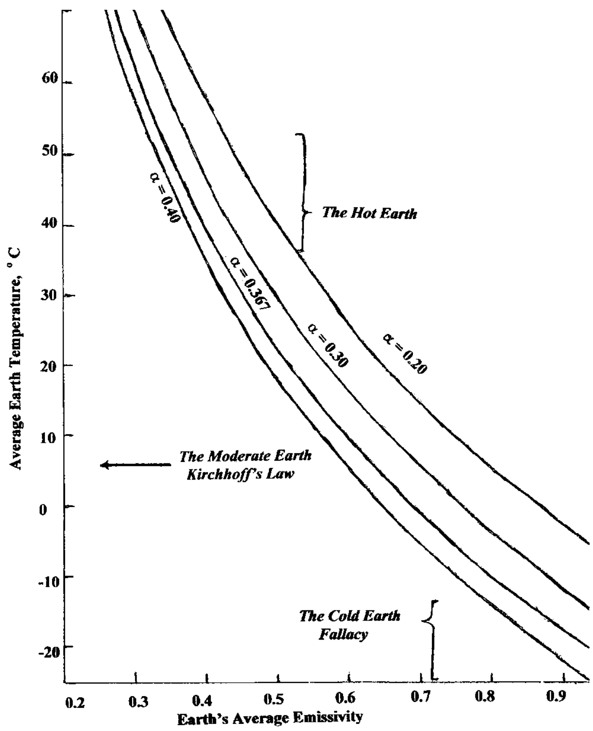

Figure 1. The calculated average Earth temperature, T (e) in degrees Celcius, as a function of average Earth emissivity, ε, for various values of Earth's albedo, α. Figure 1 is a plot of T(e) in degrees Celsius as a function of the emissivity for four values of the albedo. One tabulated value for Earth's average albedo is 0.367 [4], and the graph also plots albedo values of 0.20, 0.30, and 0.40.

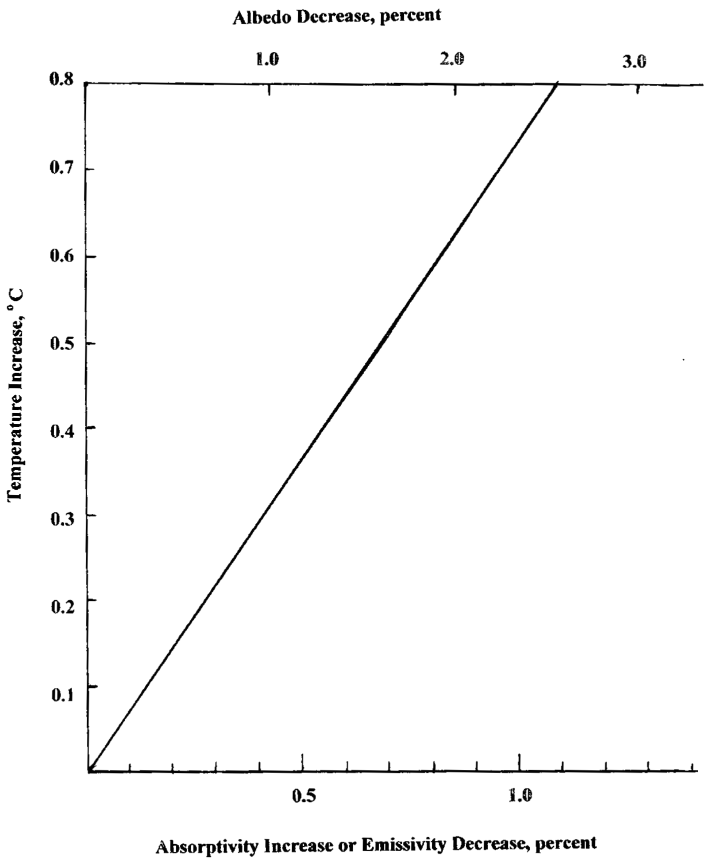

Figure 2. The calculated average Earth temperature increase in degrees Celcius, as a function of the decrease in Earth's albedo in per cent, from an initial value of α = 0.30. The corresponding increase in the absorptivity for those albedo changes is shown, as well as the independent decreases in emissivity that would give the same resultant temperature increases.

Taking the logarithm of Eq. (2), and taking differentials of the result, allows one to calculate the change in average Earth temperature associated with various changes in emissivity, absorptivity, or albedo. That sensitivity curve is plotted in Figure 2 for the current average atmospheric temperature of 291 K, and for an average albedo of 0.30.

Various agencies, including IPCC [5] have estimated the measured changes in the average atmospheric temperature near the Earth's surface over the last century to be as follows:

1910 - 1940, increase of 0.5 C;
1940 - 1970, decrease of 0.2 C;
1970 - 2000, increase of 0.5 C.

As can be seen from Fig. 2, those increases of 0.5 C for the two thirty year spans from 1910 to 1940 and from 1970 to 2000, correspond to a relatively small decrease of only 1.5 percent in Earth's albedo. The observed decrease in temperature of 0.2 C from 1940 to 1970 corresponds to an albedo increase of only 0.5 percent.

Those modest changes in temperature are thus readily explained in terms of minor changes in albedo, brought about by small changes in cloudiness and/or snow and ice cover over the Earth's surface.

There are many possible physical mechanisms at the surface of the Earth, and in its atmosphere, which could generate such modest changes in albedo - and thus account for the observed temperature changes during the 20th Century. For example, the gained solar power absorbed by the Earth is limited to the daylight hours, whereas the power lost from Earth by its radiation emitted to Space occurs continuously from the entire surface, both night and day. Thus, for example, if Earth's cloud cover varied diurnally in a systematic way so that the night hours became cloudier than the daylight hours throughout the year and the seasons, then there would be a net upward trend in the Earth's temperature. Alternatively, if the night hours were less cloudy than the daylight hours throughout the year and the seasons, then there would be a downward trend in temperature.

Such an effect is directly observable in the frost or dew which appear during calm, *cloudless* nights as the Earth's surface cools by radiative losses to Space. For similar calm nights, but with *cloudy* skies, frost or dew do not appear because that radiation is not lost, but is reflected back, keeping the surface warm enough to prevent condensation.

Another example of a heating mechanism, would be a reduction in the fraction of the Earth's surface covered with ice and snow. Replacing those highly reflective surfaces by darkened soil would decrease Earth's albedo, and increase its absorptivity. If there is no compensating increase in the emissivity of that darkened soil, there would be a resultant increase in Earth's temperature.

Another mechanism that could lead to an imbalance in the absorptivity to emissivity ratio, involves the fact that the incoming solar radiation that Earth receives during the daylight hours peaks in the visible region of the spectrum - whereas the outgoing radiation is mainly in the infrared region of the spectrum, in the range of 8 to 24 micrometers in wave length. Cloud droplets are generally much larger in size than the wavelength of the solar radiation, so even thin clouds will scatter and reflect solar radiation and increase the albedo. On the other hand, if cloud droplets are comparable in size to the outgoing infrared radiation and those clouds are thin, they could be relatively transmissive of that outgoing radiation. As a result, the Earth's emissivity for outgoing radiation could be higher than its absorptivity for incoming radiation.

There are many other possible mechanisms that could lead to similar changes in the absorptivity to emissivity ratio which could generate the modest net temperature changes observed during the 20th Century, and in other periods of the Earth's history. Svensmark [6, 7] has shown that Earth's cloud cover underwent a modulation in phase with the cosmic ray flux during the last solar cycle. His suggested mechanism for that correlation involves a decrease in cosmic ray flux during high solar activity, when the "solar wind" and magnetic activity shield Earth from cosmic rays. The reduced

incidence of cosmic rays results in the absence of adequate nucleating agents for cloud formation, a decrease in the Earth's albedo, a corresponding increase in absorptivity, and hence a heating of the Earth. The opposite occurs during low solar activity, when the cosmic ray flux into the Earth's atmosphere is high, nucleating agents are plentiful, and cloudiness increases albedo. This results in a decrease in absorptivity, and hence a cooling of the Earth. The analysis summarized in Figs. 1 and 2 supports the Svensmark mechanism as the cause of the 20th Century fluctuations in the average Earth temperature. As Fig. 2 shows, relatively modest changes of only a few percent in the Earth's albedo are sufficient to account for the observed temperature changes of that Century. *Those are precisely the magnitudes of the changes in cloudiness that are observed by Svensmark to vary in phase with the variations in solar activity.*
However, one must be cautious in this argument - as will be shown in the next section. While an absence of clouds during periods of low cosmic ray intensity will result in an increase in the absorptivity of solar radiation by Earth, the same absence of clouds would mean a corresponding increase in the emissivity of infrared radiation to Space. The net effect could be no change in the average temperature of the Earth *unless those changes in cloudiness also resulted in an overall imbalance in the absorptivity to emissivity ratio.*

3. COLD EARTH FALLACY, WARM EARTH, AND MODERATE EARTH

As shown in Fig 1, and as indicated from Eqs. (1) and (2), the controlling factor in determining the average temperature of the Earth is its absorptivity to emissivity ratio. Now, there appears to be a consensus among both believers in the anthropogenic global warming hypothesis and skeptics of the hypothesis that, in the absence of an atmosphere, Earth would be a frozen "ice-ball" with a sub-zero average temperature of -20 to -25 ^{o}C . That argument is now faithfully reproduced in science textbooks, as an introduction to the subject of global warming from infrared absorption by greenhouse gases in the atmosphere. The theme of the argument is that it is the Earth's atmosphere that "keeps the heat in" via the 'greenhouse effect', and it is that effect which makes Earth warm enough for human habitation. The natural corollary of the theme is that too much 'greenhouse effect' from too much carbon dioxide and other infrared absorbing gases, would make Earth too hot for human habitation.

Let us examine that argument in more detail using Fig. 1, which was obtained from Eqs. (1) and (2). As can be seen from the graph, for an average albedo of 0.367 (which equates with an absorptivity of 0.633) the only way one can obtain sub-zero temperatures as low as -20 to -25^{o}C, is to have an almost perfectly emissive Earth (emissivity near unity). *Such a unit emissivity assumption, however, directly contradicts the use of an albedo of 0.367.* Since most of the albedo is caused by cloud cover, it is impossible for Earth to radiate out into Space with unit emissivity if 37% of that radiation is reflected back to Earth, or absorbed by the bottom of those same clouds. Even for those portions of Earth that are not covered with clouds, the assumption that the ocean surface, land surfaces, or ice and snow cover would all have blackbody emissivities of unity, is unreasonable.

This unrealistic set of assumptions - leading to sub-zero average temperatures for Earth - is shown in Fig.1; and it is referred to there as the "Cold Earth Fallacy".

It is certainly true that in the absence of an atmosphere, temperatures would drop drastically at night as the darkened portions of Earth lost infrared energy by radiation to Space; however, with all the incoming solar radiation being concentrated on the daytime half of the surface, daytime temperatures would rise as drastically as the night time temperatures would fall. That is what is observed on the surface of the moon in the absence of an atmosphere, and to a much lesser extent in the desert regions of Earth. The conductivity of the ground surface is too low to moderate those extremes. By contrast, the fluid motions within the atmosphere and oceans, together with the energy exchanges between the oceans and the atmosphere, do provide the convective flows and energy exchanges that moderate those surface temperature extremes. In addition, the enormous heat capacity of the oceans and the high heat capacity of the atmosphere, in comparison to the much lower heat capacity of the thermally-thin ground surface layer, also moderate those extremes. Despite any such extremes, the average temperature, according to the above analysis, should not depend on the presence or absence of an atmosphere per se.

At the other extreme is the "Hot Earth". For the Cold Earth, one had to assume that the ratio of absorptivity to emissivity was 0.633 / 1.00 = 0.633. For the Hot Earth, that ratio has to be inverted so that the absorptivity exceeds the emissivity. For the average albedo of 0.367 (corresponding to an absorptivity of 0.633) and a low emissivity of about 0.35 (which is about half the absorptivity), one obtains an average temperature of 50 C. That region is labeled in Fig. 1 as "The Hot Earth".

Clearly, this analysis shows that the Cold Earth Fallacy and the Hot Earth are unrealistic extremes, corresponding to emissivities that are too high and too low respectively, relative to Earth's absorptivity. As will be discussed shortly, between those two extremes lies a Moderate Earth in which absorptivity and emissivity are more closely matched.

4. COMPLEXITIES IN DETERMINING THE ABSORPTIVITY TO EMISSIVITY RATIO OF THE EARTH.

The problem of obtaining a realistic value for the absorptivity to emissivity ratio for all the entities at Earth's surface, and in its atmosphere, that participate in the radiative balance is a formidable task. The first and most difficult part of the problem is simply to locate the "surface" involved in the radiative-equilibrium process. Upon closer examination, one finds that the "surface" on which the incident solar irradiance is absorbed, and from which Earth radiates outward into Space , is not a simple surface at all. Most of Earth's albedo is caused by reflection of the incident solar flux from several surfaces: from the tops of clouds, from the surface of the oceans, from the surfaces of continents, and from the surfaces of dust particles in the atmosphere. There is also a scattering component to the albedo: from homogeneous gases and heterogeneous particulates in the atmosphere. Furthermore, the absorbed fraction of the solar flux is not only absorbed heterogeneously at those same surfaces, but also homogeneously by the gaseous components: water vapor mainly, with smaller contributions from other gases. That same distribution of homogeneous and heterogeneous absorbers emits the flux that is radiated from Earth to Space.

Those entities are distributed vertically throughout Earth's atmosphere: from the ocean surfaces at sea level, to the mountains at high altitudes, to continental depressions below sea level, and to the upper reaches of the atmosphere at the tops of clouds. Those same entities are distributed longitudinally and latitudinally from the equator to the poles. With what measured temperature are the calculated ones to be compared? Is it reasonable to expect that the calculated temperatures should be compared only with the air temperatures measured near Earth's topographic surface? How representative is such an average surface air temperature to the entire mass of the atmosphere involved in the radiative equilibrium processes? If the near-surface air temperature is not representative, is it realistically possible to measure the average temperature of the entire mass of absorbing and emitting entities with sufficient accuracy to make a meaningful comparison between the data and the predictions? One is asking for a definition of the mass of matter that constitutes Earth's surface, atmosphere, and oceans. How high in altitude should one go in the atmosphere to include it all? Similarly, how deep in the liquid fluid of the oceans should one go in order to include the mass below the ocean surface that influences the heat and mass transport processes near the ocean surface and in the atmosphere above it? How representative are near-surface temperatures of the average temperature of those vertically distributed, yet poorly defined entities. As difficult as those questions may be, they are nevertheless the ones which need to be answered in order to evaluate the validity of any models purporting to predict future conditions. It was indicated earlier that this was a *formidable* task; however, looking at the problem in depth, it may be more realistic to conclude that its resolution may be *unattainable* given our limited understanding of the complex processes involved, and the lack of data available for the current thermodynamic state of those entities.

5. KIRCHHOFF'S RADIATION LAW

Let us return to Eqs. (1) and (2) where we showed the possible extremes of a Cold Earth in which the emissivity markedly exceeded the absorptivity, and the Hot Earth in which the reverse was the case. Between those two extremes is the real or Moderate Earth, in which the emissivity and absorptivity are matched. In this case, the ensemble of entities would obey Kirchhoff's radiation law which gives:

$$(1 - \alpha) / \varepsilon = 1, \text{ and } T(e) = 278.9 \text{ K} = 5.7 \text{ C}.$$

Such a matched, moderate condition is normal for a system in thermal equilibrium with its radiation field: it is Kirchhoff's radiation law, which has been abundantly verified in controlled laboratory systems. But in dealing with Earth and its atmosphere, as discussed earlier, one has a complex, non-isothermal system that contains many components, and all three states of aggregation for its most dominant component - water. It is very likely that the earth-atmosphere system will depart somewhat from Kirchhoff's radiation law at specific times and in specific locations; however, the important question to be resolved is the extent to which it can depart from the law in the long run and averaged over its entire spatial extent. The issue of greenhouse warming can thus be posed in terms of the extent to which small changes in the composition of the minor gaseous components of the atmosphere can induce significant departures from Kirchhoff's radiation law in the earth-atmosphere system in such a way that its emissivity becomes significantly lower that its absorptivity over decades or centuries.

Let us look at the Vostok ice-core data [8], and assume that the measured temperature fluctuations recorded in that data are representative of those that were present in the entire earth-atmosphere system for the last 420,000 years. One sees four Glacial Coolings recorded with temperatures of about 7 C below current values, and five Interglacial Warmings with temperatures some 3 C above current levels. That corresponds to a 10 C temperature variation between Glacial Coolings and Interglacial Warmings. Referring to Fig 1, and neglecting for the moment the Milankovitch [9] variations in solar insolation that drive the Glacial/Interglacial alternation, it can be seen that for an albedo of 0.3 (a = 0.7) a 10 C temperature variation would be attained for an emissivity variation of at most $\Delta\varepsilon / \varepsilon = 0.1$, or only 10 %. Or alternatively, an albedo increase from $\alpha = 0.25$ to $\alpha = 0.35$, at a constant emissivity, could precipitate Glacial Cooling.

The above calculation overestimates the albedo changes required to sustain a Glacial or an Interglacial. The initiating mechanism for either involves the Milankovitch mechanism of increased or decreased solar insolation in the Northern Hemisphere brought about by the changes in Earth's orbital parameters. Those involve temporal and spatial changes in the factor, I, in Eq. (1). The Milankovitch insolation variations are the main driving mechanism, and thus more modest albedo changes than those calculated above would serve to amplify the temperature variations.

It is interesting to speculate whether such a change in albedo can realistically be attained by changes in the areas of ice and cloud cover that might be expected during Glacials and Interglacials. As Glacial Coolings are initiated by the Milankovitch mechanism of reduced solar insolation in the Northern Hemisphere, and ice advances on the Northern Hemisphere land masses, there is an increase in albedo which accelerates the advance of ice, and hence the cooling associated with increasing albedo. Eventually, as the oceans cool during that Glacial, there is a reduction in ocean temperature in the tropical latitudes and the Southern Hemisphere. The decreasing ocean temperature results in decreasing cloudiness, and a reduction in the albedo in those regions; and leads to warming. That warming counteracts the acceleration of the advancing ice and limits its extent.

As the process begins to reverse via the Milankovitch mechanism of increasing solar insolation in the Northern Hemisphere, the extent of ice-cover diminishes, and there is a decrease in the Earth's albedo. That decrease accelerates the rate at which the ice retreats, uncovering more land whose albedo is lower than that of ice - resulting in an increase in Northern Hemisphere warming. Eventually, as the oceans continue to warm, there is an increase in sea-surface temperature in the tropical latitudes and the Southern Hemisphere, resulting in an increase in cloudiness. That increasing cloudiness increases Earth's albedo, resulting in a cooling which diminishes the rate of retreat of continental ice.

Such a negative feedback loop between northern latitudes of the Northern Hemisphere and the rest of the Earth could thus play a role in moderating the magnitude of the temperature fluctuations between the Glacial Coolings and the Interglacial Warmings after they are initiated by the Milankovitch mechanism.

One final speculation: the ocean like the atmosphere, has a significant vertical dimension. Density gradients play an important role in the transport of sensible heat in that vertical dimension and also horizontally between northern and southern latitudes.

Pure water reaches its maximum density at 4 ^{0}C, whereas saline ocean water reaches its maximum density at its freezing point which is slightly below 0 ^{0}C. Those density differences, caused by temperature and salinity variations between the polar latitudes and lower latitudes, generate ocean circulations. It is at the temperature of its maximum density that the largest mass of oceanic water accumulates by gravity into an insulated storage realm of enormous mass in the lowest regions of the ocean depths below the thermocline. Near its maximum density state, that large mass is effectively insulated from the temperature variations of the warmer surface waters in the equatorial and subtropical latitudes. Those higher temperature waters remain floating on the surface while the lower temperature mass sinks by gravity to accumulate below in a storage realm with an enormous capacity for the accumulation of sensible heat. The heat and mass transport from that enormous ocean reservoir to the atmosphere are the dominant factors in determining temperatures and weather conditions over the entire globe.

It is intriguing to note that for the Moderate Earth - which obeys Kirchhoff's radiation law with an absorptivity that was equal to its emissivity - the equilibrium temperature was T (e) = 5.7 ^{0}C. Now, the average temperature of the ocean's surface waters is about 17.6 ^{0}C [10]; however, as one descends below the surface to the thermocline and below, one soon reaches the higher density water in that enormous storage realm whose temperature is nearly constant at about 3 ^{0}C. If one takes a mass weighted average of the surface water temperature of 17.6 ^{0}C and that much larger subsurface mass at 3 ^{0}C, one obtains an average ocean temperature that is close to the 5.7 ^{0}C temperature required by Kirchhoff's radiation law. Is that really a coincidence? Or is it simply a reflection of the fact that Earth is in radiative equilibrium with the Sun, with its absorptivity and emissivity in balance on the longest of time scales. It should be no surprise that balance is maintained by the one entity that meteorologists and climatologists have long known to be the major determinant of Earth's weather - the oceans.

6. CONCLUSIONS

This analysis of the radiative equilibrium balance between Sun and Earth shows that the average temperature of the "surface" of the Earth, which perforce includes all the entities in its physical surface plus its oceans and atmosphere, is controlled by the ratio of its absorptivity to emissivity. It is shown that modest changes of at most one to two percent in the Earth's albedo brought about by modest changes in cloud cover, are sufficient to account for the observed average temperature changes of the last century - provided that those changes in absorptivity are not counterbalanced by comparable changes in emissivity. Several mechanisms are suggested to account for the imbalance in the absorptivity to emissivity ratio. However, those suggested mechanisms by no means exhaust the possibilities.

Nevertheless, the analysis suggests that, in the long run, the emissivity to absorptivity ratio is generally near unity, as required by Kirchhoff's radiation law. That requirement insures a moderate average Earth temperature of about 5.7 ^{0}C for the entities involved in that radiative equilibrium - in fair agreement with the observed mass-average temperature of those entities. That mass-average is dominated by the ocean's mass.

Except for the influence of cloud albedo, this analysis makes no assumptions regarding the detailed composition of the atmosphere. Nor are any such assumptions needed in explaining the observed variations in 20th Century temperatures, or the larger, longer-term variations of Glacial Coolings and Interglacial Warmings. This refined analysis supports this author's earlier conclusion [1] that:

It is implausible to expect that small changes in the concentration of any minor atmospheric constituent such as carbon dioxide, can significantly influence that radiative equilibrium.

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