Unified Theory of Climate

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Expanding the Concept of Atmospheric Greenhouse Effect Using Thermodynamic Principles: Implications for Predicting Future Climate Change

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1. Introduction

Recent studies revealed that Global Climate Models (GCMs) have significantly overestimated the Planet's warming since 1979 failing to predict the observed halt of global temperature rise over the past 13 years, (e.g. McKitrick et al. 2010). No consensus currently exists as to why the warming trend ceased in 1998 despite a continued increase in atmospheric CO_2 concentration. Moreover, the CO_2-temperature relationship shows significant inconsistencies across time scales. In addition, GCM projections heavily depend on the presence of positive feedbacks, while satellite observations indicate that the climate system is likely governed by strong negative feedbacks (Lindzen & Choi 2009; Spencer & Braswell 2010). At the same time, there is a mounting political pressure for Cap-and-Trade legislation and a global carbon tax, while scientists and entrepreneurs propose *geo-engineering* solutions to cool the Planet involving large-scale physical manipulation of the upper atmosphere. This situation calls for a thorough reexamination of the present climate-change paradigm; hence the reason for this study.

2. The Greenhouse Effect: Reexamining the Basics

According to the current theory, the Greenhouse Effect (GHE) is a *radiative phenomenon* caused by heat-trapping gases in the atmosphere such as CO_2 and water vapor assumed to *reduce* the rate of surface infrared cooling to space by *absorbing* the outgoing long-wave (LW) emission and *re-radiating* part of it *back*, thus increasing the total energy flux toward the surface. This is thought to boost the Earth's temperature by 18K—33K compared to a gray body with no absorbent atmosphere such as the Moon; hence making our Planet habitable. Figure 1 illustrates this concept using a simple two-layer system known as the Idealized Greenhouse Model (IGM). In this popular example, *S* is the TOA solar irradiance, *A* is the Earth shortwave albedo, T_s is the surface temperature, T_e is the Earth's *effective emission* temperature often equated with the mean temperature of middle troposphere, ϵ is emissivity, and σ is the Stefan-Boltzmann (S-B) constant.

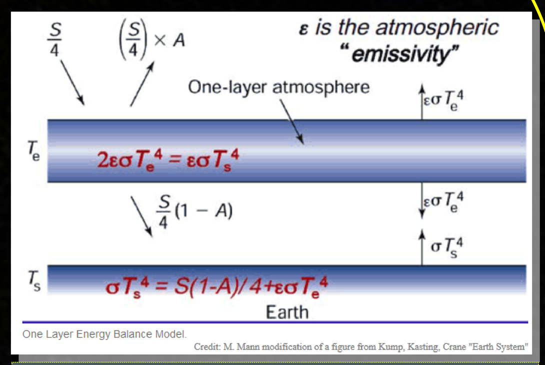

Figure 1. The *Greenhouse Effect* as taught at Universities around the World (diagram from the website of the Penn State University's Department of Meteorology).

2.1. Main Issues with the Current GHE Concept:

A) Magnitude of the Natural Greenhouse Effect. GHE is often quantified as a difference between the actual *mean* global surface temperature (T_s = 287.6K) and the planet's *average* gray-body (no-atmosphere) temperature (T_{gb}), i.e. GHE = $T_s - T_{gb}$. In the current theory, T_{gb} is equated with the emission temperature (T_e) calculated straight from the S-B law using Eq. (1). However, this is conceptually *incorrect* ! Due to Hölder's inequality among means in non-linear functions, T_e is *not* physically compatible with a *measurable* mean temperature of an airless planet.

$$T_e = \left[\frac{S_o(1-\alpha_p)}{4\epsilon\sigma}\right]^{\frac{1}{4}} \quad (1)$$

To be correct, T_{gb} must be computed via proper spherical integration of the planetary temperature field using Eq. (2), where μ is the cosine of incident solar angle at any point and c_s = 13.25e-5 is a small constant ensuring that T_{gb} = 2.72K (the temperature of deep Space) if S_o = 0.

$$T_{gb} = \frac{1}{4\pi}\int_0^{2\pi}\int_0^1 \sqrt[4]{\frac{(S_o+c_s)(1-\alpha_{gb})\mu}{\epsilon\sigma}}\,d\mu\,d\varphi = \frac{2}{5}\left[\frac{(S_o+c_s)(1-\alpha_{gb})}{\epsilon\sigma}\right]^{\frac{1}{4}} \quad (2)$$

Since $T_{gb} \ll T_e$ (T_{gb} =154.3K) in accordance with Hölder's inequality, GHE becomes *much larger* than presently estimated. According to Eq. (2), our atmosphere boosts Earth's surface temperature *not* by 18K—33K as currently assumed, but by 133K ! This raises the question: *Can a handful of atmospheric trace gases (< 0.5%) trap enough radiant heat to cause such a huge thermal enhancement at the surface ?* Thermodynamics tells us that this not possible.

B) Role of Convection. The conceptual model in Fig. 1 can be mathematically described by the *simultaneous* Equations (3), where ν_a is the atmospheric fraction of the total shortwave absorption. Figure 2 depicts the solution to Eq. (3) for temperatures over a range of atmospheric emissivity (ϵ) using S_o = 1366 W m^{-2} and ν_a =0.326 (Trenberth et al. 2009). An increase in atmospheric emissivity does *indeed* cause a warming at the surface as stated by the current theory. However, Eq. (3) is *physically incomplete*, because it does *not* account for convection, which occurs *simultaneously* with radiative transfer. Adding a convective term to (3) (i.e. Eq. 4) dramatically alters the solution by collapsing the difference between T_s, T_a and T_e and virtually erasing the GHE (Fig. 3.)

$$\begin{cases} \frac{S_o}{4}(1-\alpha_p)(1-\nu_a)+\epsilon\sigma T_a^4-\sigma T_s^4=0 \\ \frac{S_o}{4}(1-\alpha_p)\nu_a+\epsilon\sigma T_s^4-2\epsilon\sigma T_a^4=0 \end{cases} \quad (3)$$

$$\begin{cases} \frac{S_o}{4}(1-\alpha_p)(1-\nu_a)+\epsilon\sigma T_a^4-\sigma T_s^4-c_p\rho(T_s-T_a)g_{bH}=0 \\ \frac{S_o}{4}(1-\alpha_p)\nu_a+\epsilon\sigma T_s^4+c_p\rho(T_s-T_a)g_{bH}-2\epsilon\sigma T_a^4=0 \end{cases} \quad (4)$$

This is because convective cooling is *many orders* of magnitude *more efficient* that radiative cooling. These results do not change with multi-layer models. In radiative transfer models, T_s increases with ϵ *not* as a result of *heat trapping* by greenhouse gases, but due to the *lack* of convective cooling, thus requiring a larger thermal gradient to export the necessary amount of heat. Modern GCMs do *not* solve *simultaneously* radiative transfer and convection. This *decoupling* of heat transports is the *core* reason for the surface warming projected by GCMs in response to increasing atmospheric greenhouse-gas concentrations.

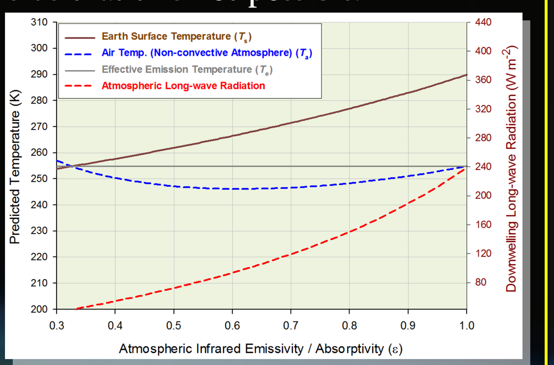

Figure 2. Solution to the two-layer model in Eq. 3 for T_s and T_a as a function of atmospheric emissivity assuming a *non-convective* atmosphere. Also shown is the predicted down-welling LW flux, $L_d \leq$ 239 W m^{-2}.

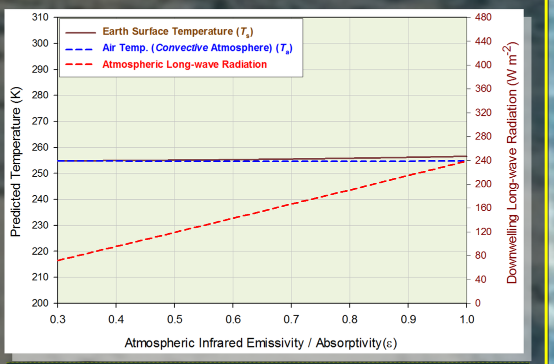

Figure 3. Solution to the two-layer model in Eq. 4 for T_s and T_a as a function of atmospheric emissivity assuming a *convective* atmosphere. Also shown is the predicted down-welling LW flux, $L_d \leq$ 239 W m^{-2}.

C) Extra Kinetic Energy in the Troposphere. Observations show that the lower troposphere emits 44% *more* radiation toward the surface than the *total* solar flux absorbed by the *entire* Earth-Atmos. System (Pavlakis et al. 2003) (Fig. 4). Radiative transfer alone *cannot* explain this effect (e.g. Figs. 2 & 3) given the negligible heat storage capacity of air, no matter how detailed the model is. Thus, empirical evidence indicates that the lower atmosphere contains *more* kinetic energy than provided by the Sun. Understanding the origin of this *extra* energy is a key to the GHE.

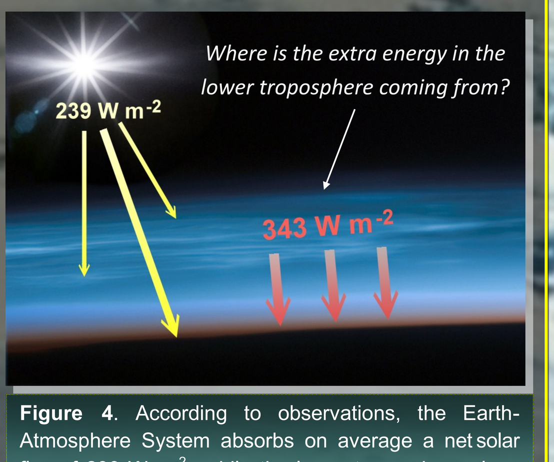

Figure 4. According to observations, the Earth-Atmosphere System absorbs on average a net solar flux of 239 W m^{-2}, while the lower troposphere alone emits 343 W m^{-2} thermal radiation toward the surface.

3. Atmospheric Thermal Enhancement (ATE)

Previous studies have noted that the term *Greenhouse Effect* is a misnomer when applied to the atmosphere, since real greenhouses retain heat through an entirely different mechanism compared to the free atmosphere, i.e. by physically trapping air mass and restricting convective heat exchange. Hence, we propose a new term instead, *Near-surface Atmospheric Thermal Enhancement* (ATE) defined as a *non-dimensional ratio* (N_{TE}) of the planet actual mean surface air temperature (T_s, K) to the average temperature of a Standard Planetary Gray Body (SPGB) with no atmosphere (T_{gb}, K) receiving the *same* solar irradiance, i.e. $N_{TE} = T_s / T_{gb}$. This new definition emphasizes the essence of GHE, which is the *temperature boost* at the surface due to the presence of an atmosphere. We employ Eq. (2) to estimate T_{gb} assuming an albedo α_{gb} = 0.12 and a surface emissivity ϵ = 0.955 for the SPGB based on data for Moon, Mercury, and the Earth surface. Using S_o = 1362 W m^{-2} (Kopp & Lean 2011) in Eq. (2) yields T_{gb} = 154.3K and N_{TE} = 287.6/154.3 = 1.863 for Earth. This prompts the question: *What mechanism enables our atmosphere to boost the planet surface temperature some 86% above that of a SPGB?*

3.1. Climate Implications of the Ideal Gas Law (IGL)

The average thermodynamic state of a planet's atmosphere can be accurately described by the Ideal Gas Law (IGL):

$$PV = nRT \quad (5)$$

where *P* is pressure (Pa), *V* is the gas volume (m^3), *n* is the gas amount (mole), *R* = 8.314 J K^{-1} mol^{-1} is the universal gas constant, and *T* is the gas temperature (K). Equation (5) has three features that are chiefly important to our discussion: *a)* the product $P\times V$ defines the internal *kinetic* energy of a gas that produces its temperature; *b)* the linear relationship in Eq. (5) guarantees that a *mean* global temperature can be *accurately* estimated from the planetary *averages* of surface pressure and air volume (or density), in sharp contrast to the non-linear relationship between temperature and radiant fluxes in Eq. (1) governed by Hölder's inequality of means; *c)* on a planetary scale, pressure in the lower troposphere is effectively *independent* of other variables in Eq. (5) and is only a function of gravity (*g*), total atmospheric mass (M_{at}), and surface area (A_s), i.e. $P_s = g\,M_{at}/A_s$. Hence, the near-surface atmospheric dynamics can safely be assumed to be governed (over non-geological time scales) by *nearly isobaric* processes on average, i.e. operating under *constant* pressure. This isobaric nature of tropospheric thermodynamics implies that the average atmospheric volume varies in a *fixed* proportion to changes in the mean surface air temperature following the Charles/Gay-Lussac Law, i.e. T_s/V= const. This can be written in terms of the average air density ρ (kg m^{-3}) as

$$\rho T_s = \text{const.} = P_s\,M\,/\,R \quad (6)$$

where P_s is the mean surface air pressure (Pa) and *M* is the molecular mass of air (kg mol^{-1}). Eq. (6) reveals an important characteristic of the average thermodynamic process at the surface, namely that a variation of global pressure due to either increase or decrease of total atmospheric mass will *immediately* alter *both* temperature and atmospheric density. What is presently unknown is the *differential effect* of a global pressure change on each variable. We offer a solution to this in & 3.3. Equations (5) and (6) imply that pressure *directly* controls the kinetic energy and temperature of the atmosphere. Under equal solar insolation, a higher surface pressure (due to a larger atmospheric mass) would produce a warmer troposphere, while a lower pressure would result in a cooler troposphere. At the limit, a zero pressure (due to the complete absence of atmosphere) would yield the planet's *gray-body* temperature.

The thermal effect of pressure is vividly demonstrated on a cosmic scale by the process of star formation, where gravity-induced rise of gas pressure boosts the temperature of an interstellar cloud to the threshold of a nuclear fusion. At a planetary level, the effect is manifest in Chinook winds, where an *adiabatically* heated downslope airflow raises local temperature by 20-30C in a matter of hours. This leads to a logical question: *Could air pressure be responsible for the observed thermal enhancement at the Earth surface presently known as a 'Natural Greenhouse Effect'?* To answer this we must analyze the relationship between N_{TE} factor and key atmospheric variables including pressure over a *wide* range of planetary climates. Fortunately, our solar system offers a suitable spectrum of celestial bodies for such analysis.

3.2. Interplanetary Data Set

We based our selection of celestial bodies for the ATE analysis on three criteria: 1) presence of a solid planetary surface with at least traces of atmosphere; 2) availability of reliable data on surface temperature, total pressure, atmospheric composition etc. preferably from direct measurements; and 3) representation of a wide range of atmospheric masses and compositions. This approach resulted in the choice of four planets - *Mercury, Venus, Earth,* and *Mars*, and four natural satellites - *Moon* of Earth, *Europa* of Jupiter, *Titan* of Saturn, and *Triton* of Neptune. Each celestial body was described by 13 parameters listed in Table 1.

Table 1. Planetary data used to analyze the physical nature of the Atmospheric Near-Surface Thermal Enhancement (N_{TE}). Information was gathered from multiple official sources using cross-referencing. The bottom three rows of data were estimated as part of this study using equations discussed in the text.

	Mercury	Venus	Earth	Moon	Mars	Europa	Titan	Triton
Mean TOA Solar Irradiance (W m^{-2}), S_o	9,126.0	2,613.9	1,361.7	1,361.7	589.2	50.5	13.7	1.51
Bond Albedo α_p	0.12	0.75	0.30	0.11	0.18	0.67	0.22	0.76
Mean Gravity (m s^{-2}) g	3.700	8.836	9.798	1.622	3.690	1.314	1.352	0.779
Planet Surface Area (×10^{12} m^2) A_s	74.8	460.0	510.072	37.93	144.8	30.9	83.0	23.0
Atmospheric Mass above Unit Surface Area (kg m^{-2}) M_{at}/A_s	2.7 ×10^{-10}	1.0412 ×10^6	10,092.7	6.6 ×10^{-10}	185.7	1.284 ×10^{-7}	108,505.9	2.2
Mean Surface Pressure (Pa) P_s	10^{-9}	9.2×10^6	98,888.2	*1.069 ×10^{-9}	685.4	10^{-7}	146,700.0	1.7
Mean Surface Atmospheric Density (kg m^{-3}) ρ	0.00	65.00	1.20	0.00	0.02	*5.24 ×10^{-12}	*5.24	1.58 ×10^{-4}
Atmospheric composition (% of volume)	N/A	96.5 CO_2 3.5 N_2 0.02 SO_2	78.08 N_2 20.95 O_2 0.93 Ar 0.039 CO_2	N/A	95.3 CO_2 2.7 N_2 1.6 Ar 0.13 O_2	≈100 O_2	98.6 N_2 1.6 CH_4	98.0 N_2 2.0 CH_4
Molecular Mass of Air (kg mol^{-1}), M	N/A	0.0434	0.0290	N/A	0.0434	0.0320	0.0278	0.0278
Observed Mean Surface Temperature (K), T_s	248.2	737.2	287.6	154.3	182.0	73.4	93.7	36.8
Mean Surface Temperature from the Gas Law (K), T_s	0.0	738.8	287.4	0.0	182.0	73.4	93.7	*35.9
SPGB Mean Surface Temperature (K), T_{gb}	248.2	181.6	154.3	154.3	125.1	67.7	48.9	28.2
Near-surface Thermal Enhancement $N_{TE} = T_s/T_{gb}$	**1.000**	**4.068**	**1.863**	**1.000**	**1.455**	**1.084**	**1.918**	**1.276**

For planets with tangible atmospheres, i.e. Venus, Earth and Mars, the temperatures calculated from IGL agreed very well with observations. Note that, for extremely low pressures such as on Mercury and Moon, the Gas Law produces $T_s \approx$ 0.0. The SPGB temperatures were estimated from Eq. (2) using published data on solar irradiance and assuming α_{gb} = 0.12 and ϵ = 0.955. For Mars, global means of surface temperature and air pressure were calculated from remote sensing data retrieved via the method of radio occultation by the Radio Science Team (RST) at Stanford University using observations by the Mars Global Surveyor (MGS) spacecraft from 1999 to 2005. Since the MGS RST analysis has a wide spatial coverage, the new means represent current average conditions on the Red Planet much more accurately than older data based on Viking's spot observations from 1970s.

3.3. Physical Nature of ATE / GHE

Our analysis of interplanetary data (Table 1) found no meaningful relationships between ATE (N_{TE}) and variables such as total absorbed solar radiation by planets or the amount of greenhouse gases in their atmospheres. However, we discovered that N_{TE} was *strongly* related to total surface pressure with a nearly perfect regression fit (Fig. 5) via the following nonlinear function:

$$N_{TE}(P_s) = \frac{T_s}{T_{gb}} = \exp\left(0.233001\,P_s^{\,0.0651203} + 0.0015393\,P_s^{\,0.385232}\right) \quad (7)$$

where P_s is in Pa. The tight relationship signals a *causal* effect of pressure on N_{TE}, which is theoretically supported by the IGL (see & 3.1). Also, the P_s-N_{TE} curve in Fig. 5 strikingly resembles the response of the temp./potential temp. (T/θ) ratio to altitudinal changes of pressure described by the well-known Poisson formula derived from IGL (Fig. 6). Such a similarity in responses suggests that both N_{TE} and θ embody the effect of pressure-controlled *adiabatic* heating on air, even though the two mechanisms are *not* identical. This leads to a fundamental conclusion that the *'Natural Greenhouse Effect'* is in fact a *Pressure-induced Thermal Enhancement* (PTE) in nature.

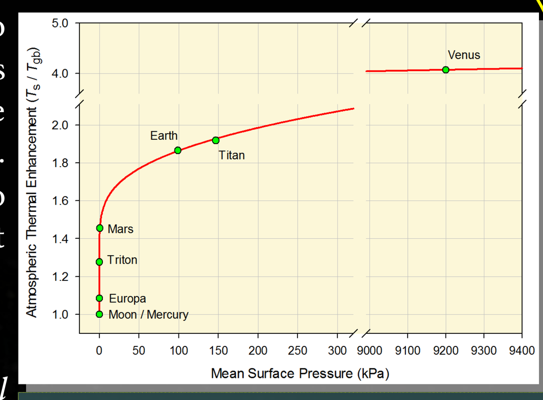

Figure 5. The Atmospheric Near-surface Thermal Enhancement (N_{TE}) as a function of mean surface total pressure (P_s) for 8 celestial bodies listed in Table 1. See Eq. (7) for the exact mathematical formula.

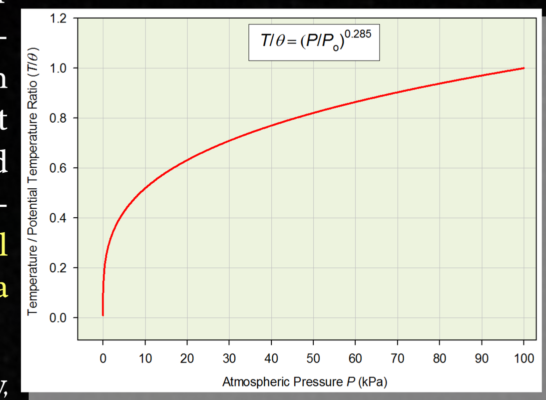

Figure 6. Temperature / potential temperature ratio as a function of atmospheric pressure according to the Poisson formula based on the Gas law (P_o = 100 kPa.) Note the striking similarity with the curve in Fig. 5

N_{TE} should *not* be confused with an actual energy, however, since it only defines the *relative* (*fractional*) increase of a planet's surface temperature above that of a SPGB. Pressure by itself is *not* a source of energy! Instead, it *enhances* (*amplifies*) the energy supplied by an external source such as the Sun through density-dependent rates of molecular collision. This relative enhancement *only* manifests as an *actual* energy in the presence of external heating. Thus, Earth and Titan have similar N_{TE} values, yet their absolute surface temperatures are *very* different due to vastly dissimilar solar insolation. While pressure (*P*) controls the magnitude of the enhancement factor, solar heating determines the average atmospheric volume (*V*), and the product $P\times V$ defines the *total kinetic energy* and *temperature* of the atmosphere. Therefore, for particular solar insolation, the N_{TE} factor gives rise to *extra* kinetic energy in the lower atmosphere *beyond* the amount supplied by the Sun. This *additional energy* is responsible for keeping the Earth surface 133K warmer than it would be in the absence of atmosphere, and is the source for the observed 44% extra down-welling LW flux in the lower troposphere (see &2.1 C). Hence, the atmosphere does *not* act as a *'blanket'* reducing the surface infrared cooling to space as maintained by the current GH theory, but is *in and of itself* a *source* of extra energy through pressure. This makes the GHE a *thermodynamic* phenomenon, *not* a radiative one as presently assumed!

Equation (7) allows us to derive a simple yet robust formula for predicting a planet's mean surface temperature as a function of only *two* variables – TOA solar irradiance and mean atmospheric surface pressure, i.e.

$$T_s = 25.3966\,(S_o + 0.0001325)^{0.25}\,N_{TE}(P_s) \quad (8)$$

Equation (8) almost *completely* explains the variation of T_s among analyzed celestial bodies, thus providing a needed function to parse the effect of a global pressure change on the dependent variables ρ and T_s in Eq. (6).

4. Implications of the new ATE Concept

The implications of the above findings are numerous and paradigm-altering. These are but a few examples:

A) Global surface temperature is *independent* of the down-welling LW flux known as *greenhouse* or *back* radiation, because both quantities derive from the *same* pool of atmospheric kinetic energy maintained by solar heating and air pressure. Variations in the downward LW flux (caused by an increase of tropospheric emissivity, for example) are *completely* counterbalanced (offset) by changes in the rate of surface convective cooling, for this is how the system conserves its internal energy.

B) Modifying chemical composition of the atmosphere *cannot* alter the system's total kinetic energy, hence the size of ATE (GHE). This is supported by the IGL and the fact that planets of vastly different atmospheric composition follow the same P_s-N_{TE} relationship in Fig. 5. The lack of impact by atmospheric composition on surface temperature is explained via the compensating effect of convective cooling on *back* radiation discussed above.

C) Eq. (8) suggests that the planet albedo is largely a *product* of climate rather than a driver of it. This is because the bulk of the albedo reflects the amount of kinetic energy supplied by the Sun and the atmospheric pressure. However, independent small changes in albedo do occur due to 1%-3% secular variations of cloud cover most likely driven by solar activity. These cloud changes cause ± 0.7C semi-periodic fluctuations of global temperature on a decadal to centennial time scale as indicated by recent satellite observations (Fig. 7) and climate reconstructions for the past 10,000 years.

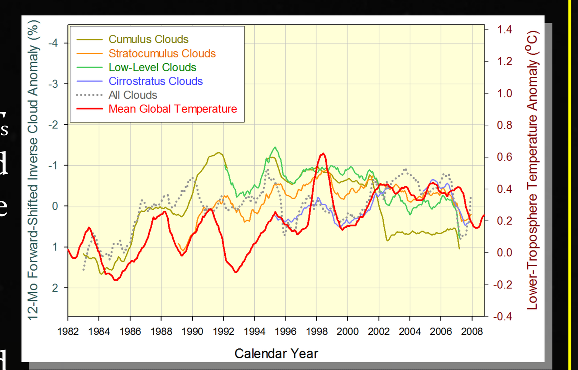

Figure 7. Dynamics of global temperature and 12-month forward shifted cloud cover types from satellite observations. Cloud changes appear to have been the cause for temperature variations during the past 30 years (Nikolov & Zeller, manuscript).

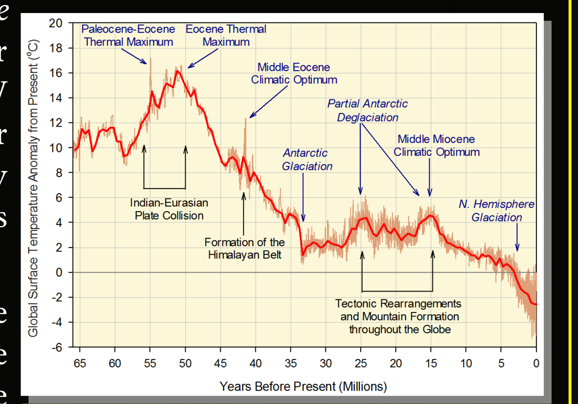

Figure 8. Dynamics of global surface temperature during the Cenozoic Era reconstructed from ^{18}O proxies in marine sediments (Hansen et al. 2008).

D) Large climate shifts observed in the paleo-record such as the 16C *directional* cooling of the Globe for the past 51 million years (Fig. 8) can now be explained through changes in atmospheric mass and surface pressure caused by geologic variations of Earth's tectonic activity and mantle degasing (Fig. 9).

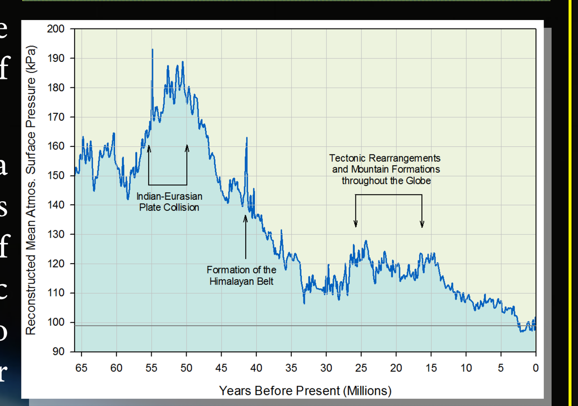

Figure 9. Dynamics of mean surface atmospheric pressure during the Cenozoic Era reconstructed from the temperature record in Fig. 8 by inverting Eq. (8).

5. Unified Theory of Climate (UTC)

Results from our research can help rectify physical inconsistencies in the current GHE concept and assist in the development of a Unified Theory of Climate based on a deeper and more robust understanding of various climate forcings and the time scales of their operation as proposed in Fig.10.

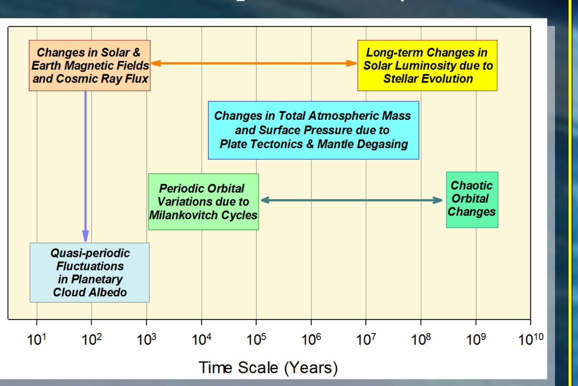

Figure 10. Global *climate forcings* and their time scales of operation according to the hereto proposed Unified Theory of Climate (UTC). Arrows indicate process interactions.