

Earth's balanced climates in view of their energy budgets

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Research Article

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Abstract

Earth's well-known energy budget scheme is subjected to variations representing changes of insolation and atmospheric absorption. The Charney Report variability cases of doubled atmospheric CO₂ concentration and insolation increase by 2 % are found reproducible. The planetary emissivity is revealed linear to surface temperature, conformant with measurements. Atmospheric water vapor with its characteristic concentration-temperature dependency appears as a major component in Earth's energy balancing mechanisms. From this, shift towards fewer and stronger rainfall events is prescribed for rising temperatures.

1. Introduction

A major aim of the present studies is the search for reproducibility on the results from sophisticated scientific research. Inherently, nature and climate are complex systems. Their understanding requires consideration of numerous aspects, each bound to coherently reflect the same system.

Earth's energy budget sorts the underlying processes by a rather transparent set of rules. The master rule is given by the observation that at any condition through history, Earth has managed to establish an energy-equilibrated state, thus avoiding endless runaway paths. Climate equilibrium states are characterized by balanced energy budgets, the entering energy flux equaling the emerging flux. This applies to the planetary Earth-space system (shortwave insolation entering, longwave radiation emerging to space) as well as to the subsystems of atmosphere and surface.

The energy budget appears like an accounting scheme.

- i. The energy flux received on Earth originates from the shortwave insolation at the top of the atmosphere (TOA), reduced by the reflections from the planetary surface. The emitted energy flux is composed of the radiation from clouds, the (cloud-atmosphere, and the surface in the atmospheric window.
- ii. The atmosphere receives energy from insolation absorption and from the surface via longwave absorption, evapotranspiration, and sensible heat; it emits radiation to the surface and into space from clouds and at clear sky.
- iii. The surface absorbs a fraction of the insolation and receives radiation from the atmosphere; it loses energy by radiation into space (in the atmospheric and into the atmosphere as well as by evapotranspiration and sensible heat. In addition, the surface (in this exchanges energy with the oceans; in an equilibrium state, the exchange is balanced, i.e. the ocean heat uptake is Earth surface emissivity is less than For simplicity when translating between radiation and temperature, ideal black-body with emissivity equal 1 is assumed through the present study.

2. Earth's Energy Budget – Variability Studies

The first three columns of Table 1 summarize the current energy budget [1]. Based on this reference data set, three variations are explored. In this procedure, three parameters are treated as fit variables: the longwave radiation from the atmosphere to the surface, the evapotranspiration & sensible heat component, and the longwave emittance to space from the clouds.

In variability case 1, the insolation at the top of the atmosphere is raised by 2 %. In case 2, the longwave atmospheric absorption is increased such that the surface temperature is raised by 3°C. In case 3, an additional longwave radiation of 3.2 W/m² is assumed to enter the atmosphere from below. The first two cases relate to variabilities studied earlier ([2] with further references): the first case addressing an insolation increase, the second case an increase in atmospheric CO₂ concentration. The third case relates to the anthropogenic energy consumption. The energy budget values of the three variability cases are computed from the reference data set as described in column 2 of Table 1.

Table 1

Earth energy budget: units W/m^2 , if not explicitly noted; bottom row: black body temperature related to planetary emittance. Column 1: Budget item; SW: shortwave; LW: longwave. Column 2: Item abbreviation and relationship; subscript R: value related to 3rd column; italics: item treated as free variable; σ : Stefan-Boltzmann constant; surface emissivity = 1. Column 3: data from [1], except italics; next columns with variations relative to column 3. Column 4: Variability case 1, insolation (TOA) + 2%. Column 5: Variability case 2, longwave absorption in the atmosphere such that surface temperature + 3°C. Column 6: Variability case 3, extra radiation from the surface with $3.2 W/m^2$.

Energy budget item	Notation	Reference data set	Variability case		
			1	2	3
			I + 2%	A + 3°C	EC
SW (insolation) TOA	SW_{TOA}	341	347.8	341	341
Planetary albedo	$\alpha_R = (79 + 23)/SW_{TOA}$	0,299			
SW absorption system	$SW_{Abs} = SW_{TOA} \cdot (1 - \alpha_R)$	239	244	239	239
SW absorption atmosphere	$SW_{AbsA} = SW_{AbsA,R} \cdot SW_{TOA} / SW_{TOA,R}$	78	80	78	78
SW absorption surface	$SW_{AbsS} = SW_{Abs} - SW_{AbsA}$	161	164	161	161
<i>LW radiation atmosphere to surface</i>	LW_{AS} (<i>free variable</i>)	333	<i>347.5</i>	<i>350</i>	<i>346.5</i>
<i>Evapotranspiration and sensible heat</i>	ES	97	<i>98</i>	<i>97</i>	<i>97</i>
Surface in	$SRF_{in} = SW_{AbsS} + LW_{AS}$	494	512	511	508
Temperature surface (K)	$T_S = ((SRF_{in} - ES) / \sigma)^{1/4}$	289.3	292.3	292.3	291.7
Atmospheric window fraction	$F_{window,R} = LW_{window} / (SRF_{in} - ES) = 40/396$	10.1 %			
LW radiation atm. wind.	$LW_{window} = F_{window,R} \cdot (SRF_{in} - ES)$	40	42	42	41
LW radiation from surface to atmosphere	$LW_{SA} = SRF_{in} - ES - LW_{window}$	357	372	372	372
Surface out	$SRF_{out} = ES + LW_{SA} + LW_{window}$	494	512	511	511
Surface equilibrium	$SRF_{out} - SRF_{in} = 0!$	1	1	1	3,2
Atmosphere in	$ATM_{in} = SW_{AbsA} + LW_{SA} + ES$	532	549	547	547
<i>Clouds radiation fraction</i>	F_{cloud} (<i>free variable, 5.65 % in [1]</i>)	<i>5.6 %</i>	<i>5.8 %</i>	<i>5.2 %</i>	<i>5.8 %</i>

Energy budget item	Notation	Reference data set	Variability case		
			1	2	3
			I+2%	A+3°C	EC
LW radiation clouds	$LW_{cloud}=F_{cloud} \bullet ATM_{in}$	30	32	28	32
LW radiation	LW_{atm}	169	170	169	169
Atmosphere out	$ATM_{out}=LW_{AS}+LW_{cloud}+LW_{atm}$	532	549	547	547
Atmosphere equilibrium	$ATM_{out}-ATM_{in}=0!$	1	1	1	1
LW emissions to space	$LW_{space}=LW_{window}+LW_{cloud}+LW_{atm}$	239	244	239	242
System equilibrium	$LW_{space}-SW_{Abs}=0!$	1	1	1	3,2
Planetary emissivity (pl. em.)	$\varepsilon_p = LW_{space}/(SRF_{in}-ES)$	0.602	0.589	0.578	0.590
Temperature pl. em. (K)	$T_p=(LW_{space}/\sigma)^{1/4}$	254.8	256.1	254.8	255.7

The solutions for the free parameter values (italics in Table 1) are non-unique. At first, their choice follows rather intuitive perception. At second, they may be adapted for consistency reasons, particularly related to the separately elaborated absorber density scheme [3]). Markable consistency is noted between the present energy budget and the absorber density scheme with water vapor as its dominant player.

Discussion on the variability cases: Variability case 1, insolation increase by 2 %. The temperature increase as given by the energy budget values is 3°C, the same as in [2] when applying there a sensitivity of 0.75°C/(W/m²). – The sensitivity defined as the ratio of surface temperature change to the TOA (longwave) emittance change, the same as the change in planetary shortwave absorption, hence $S = \Delta T_s / \Delta LW_{space} = \Delta T_s / \Delta SW_{Abs}$, the energy budget values of case 1 in Table 1 reveal a sensitivity of $S = 0.63^\circ\text{C}/(\text{W}/\text{m}^2)$ (case 1 versus reference data set, non-rounded). – The emissivity is decreased and the planetary emittance temperature slightly increased relative to the reference case. – The energy budget values are conformant with the separately presented ‘density scheme’ [3]: There, a temperature increase of 2.7°C is obtained (as compared to 3°C in the energy budget), with a radiation absorption rise of 14.7 W/m² comparing to the increase of atmosphere-to-surface longwave radiation (LW_{AS}) by 14.5 W/m² in the energy budget scheme of Table 1.

Variability case 2, atmospheric absorption increase leading to a 3°C-surface temperature rise. For equilibrium, the system (i.e. planetary) emerging radiation (LW_{space}) must equal the temperature-effective incoming radiation (SW_{Abs}). – As of Table 1, the emissivity is further decreased, to be explained by the

absorber concentrations: the lowest concentrations relate to the reference case, mostly water vapor is added in case 1 (following the temperature proportionalities of H_2O and CO_2), then further CO_2 is added in case 2. – The energy budget consideration of Table 1 reveals an atmosphere-to-surface radiation gain (LW_{AS}) of 17 W/m^2 (case 2 vs. reference), as compared to an absorption increase of 16 W/m^2 in the density scheme, there with a 2.9°C -rise (as compared to 3°C here in the energy budget). In the density scheme, the 2.9°C - 16 W/m^2 -rise is reached at a CO_2 level of 440 ppmv opposed to 570 ppmv in [2], or 4°C with 510 ppmv opposed to 570 ppmv as more recently referred to (e.g. [4]).

Variability case 3, additional longwave emissions from the surface by 3.2 W/m^2 . Division of the 2.4°C -temperature increase (column 6 vs. column 3 for temperature in Table 1) by the extra radiation of 3.2 W/m^2 reveals a sensitivity of $0.75^\circ\text{C}/(\text{W/m}^2)$. – The equilibrium condition of Table 1 needs to be fulfilled for the atmosphere (see 'ok'-sign). For the surface and the planetary system, the outgoing radiation must equal the incoming ones plus the additional radiation of 3.2 W/m^2 to retain energy balance. – The density scheme [3] delivers 2.35°C as compared to the 2.4°C from the energy budget consideration.

Further variability cases (details not shown). Additional energy budget estimates have been performed on the zonal (polar vs. tropical) conditions, on the glacial-interglacial conditions [5], on atmospheric absorption increases effecting the surface temperature to rise by 10 and 20°C (as further variations of case 2), changing of the insolation by -4 % and + 5.5 % (as further variations of case 1), changing of the insolation by 4 % and simultaneously of the absorption with an additional 6°C -effect (coupling cases 1 and 2), and representing the faint young Sun conditions (low insolation, high surface temperature, high pCO_2 , low pO_2 , partly low continental coverage). – The energy budget estimates are again well reflected by the absorbing particle densities in the density scheme (i.e. to first order of H_2O and CO_2 , the former dominating by far).

For all variability cases, variations to the algorithms of Table 1 – i.e. altering albedo and atmospheric shortwave absorption in dependence on surface temperature – leaves the described results unchanged (details not shown).

Conclusion

The Charney Report variabilities, i.e. insolation and CO_2 concentration change, can be reproduced within the energy budget. Equilibrium requires TOA longwave emittance to change with absorbed shortwave irradiation in case of insolation change, and TOA longwave emittance to remain constant in case of absorber change (e.g. of CO_2 concentration). – Already inferring from case 1, emissivity is decreasing with increasing insolation and in turn increasing surface temperature. This indicates that water vapor is predominantly regulating emissivity with temperature, in view of water vapor being the major longwave absorber and at the same time, its concentration relatively strongly dependent on temperature.

3. Planetary Emissivity From The Energy Budget Variability Studies

In view of all variability cases, the planetary emissivity ε_p appears to well correlate with the surface temperature via $T_s = (-161 \cdot \varepsilon_p + 386)$ K, as summarized in Fig. 1. The zonal conditions (orange dotted) exhibit energy flux imbalances, while balances are given in all other cases. The linear relationship appears independent of the driving force (atmospheric longwave absorption and insolation examined here) and applies to a wide range of climate conditions (between -10 and $+20^\circ\text{C}$ from today's temperature). The relationship is revealed as an intrinsic property of the energy balancing mechanisms, largely originating from the atmospheric water vapor which is temperature-dependent in amount, itself significantly determining the surface temperature, and leaving the emittance to space rather slowly varying. Also clear-sky measurements reveal a linear relationship between outgoing longwave radiation (OLR) and near-surface temperature [6]. This is consistent with the present linear emissivity-temperature relationship if clouds contribute positively to OLR at cold and negatively at warm surface temperatures, of the order $+25$ and -55 W/m^2 at 200 and 300 K , respectively. This translates into a cloud feedback parameter of $0.8 \text{ W/m}^2/\text{K}$.

For equilibrium states, the predominant role of water vapor demands its atmospheric residence time to roughly scale with the concentration dependence on the surface temperature. This is necessary to bring the relatively high concentration variability (exponential on temperature according to the Clausius-Clapeyron relation) in line with the relatively stable evapotranspiration and precipitation energy contributions (amounting to ca. 83 % of ES in Table 1; changing by the order of $0.5 \text{ \%}/^\circ\text{C}$ in the energy budget estimates, details not shown). As a result, mean precipitation remains rather unchanged. On the other hand, a simultaneous increase of water vapor concentration and residence time prescribes increase of low-efficiency rainfall and frequency decrease of higher-intensity rainfall with rising intensity per event.

Conclusion

The natural temperature-regulated provisioning of water vapor to the atmosphere is a major component in Earth's maintenance of the energy flux balance. Prerequisite is the residence time of atmospheric water vapor to roughly scale with its concentration temperature dependency, from the energy budget estimates with ca. $8 \text{ \%}/^\circ\text{C}$ (details not shown). Consequently, mean precipitation remains rather temperature-independent while rainfall shifts to fewer and more intense events with increasing temperatures. – Emissivity to space is prescribed to inverse-linearly vary with the surface temperature. – The simple energy budget estimates support the absorption-density relationship of [3].

4. Discussion

It appears interesting that the simple energy budget consideration reveals important intrinsic characteristics of nature: emissivity inverse-linearly following surface temperature, this independent of the temperature-driving agent; water vapor as a dominant component in Earth's energy balancing mechanism, controlled by the characteristic temperature dependency of its concentration; the strongly varying water vapor concentration in combination with the weakly varying evapotranspiration prescribing

rainfall pattern changes with temperature. The prominent role of water vapor, with CO₂ in conjunction, is confirmed by a density-based description [3].

The energy budget study is viewed complementary to the radiative forcing-concept. For completed transitions between equilibrium states, it avoids situations where the feedback parameter (in its typical definition) is predetermined to zero (in case of longwave absorber change: TOA radiation constant while surface temperature changing), which is equivalent to infinite sensitivity and undefined temperature change in the frequently presented formalism. Within the transitions between equilibrium states (transient climate), potential (TOA) radiation imbalance is supposed to be dominated by the ocean heat uptake (perceived as common knowledge).

The forcing concept's starting point of TOA longwave radiation changing with surface temperature by T³ (Planck feedback) is put into perspective. For equilibrium states, the energy budget reveals an intrinsic linear behavior, i.e. changing via a constant instead of T³, in line with observations. This is fundamentally attributed to atmospheric water vapor with its absorption and concentration-temperature properties. For the transient regime, a first look is to be directed at the atmosphere-ocean interplay.

The energy budget scheme may serve as shortcut to cumbersome regression analysis of sophisticated simulation results. A handy tool is provided for quick insight in appropriate cases.

Supplementary Materials

All data and code are available: [Simplified climate modelling](#).

Declarations

Conflicts of Interest: No conflict of interest is to be declared.

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Figures

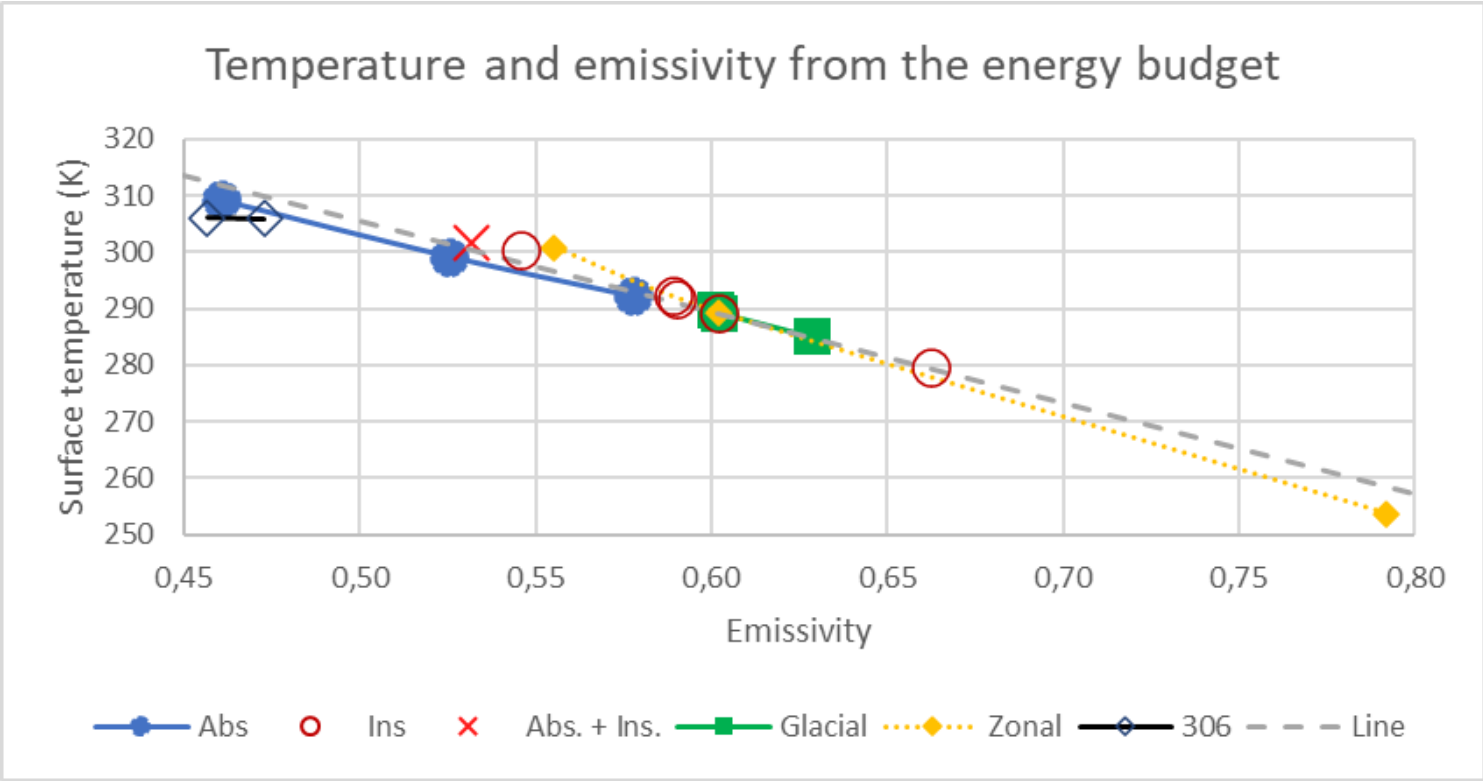


Figure 1

Surface temperature versus planetary emissivity as obtained by the present energy budget studies for different variability cases relative to the current budget [1] (see Table 1 and text), symbol connections for visibility purposes. Blue filled circles, solid line: atmospheric absorption varied such that surface temperature +3, +10, +20 °C; red open circles, no line: insolation -4, ±0, +2, +5.5 %, and surface radiation +3.2 W/m2; red cross: insolation +4% and absorption leading to further +6 °C; green filled squares, solid line: conditions of glacial and interglacial maxima in the Late Quaternary; orange diamonds, dotted line: conditions of poles and equator, the only case with energy flux imbalance per symbol; black open diamonds, solid line: surface temperature 306 K, pCO₂ 3,600 (right) and 30,000 ppmv (left), representing faint young Sun conditions; gray dashed line: linear fit through the value points (zonal cases, orange, exempted), deviation boundaries of fit-line temperatures to energy budget values ±2 %.