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Preprint statement: This article is a preprint and has not been peer-reviewed, under consideration and submitted to ScienceOpen Preprints for open peer review.

Links to data: https://c.gmx.net/@797062368830953113/H_00zuerSK22tA3S5PCUog

Funder: No funding provided.

DOI: 10.14293/S2199-1006.1.SOR-.PPYDLMQ.v1

Preprint first posted online: 31 August 2020

Keywords: paleoclimate, climate modelling, atmospheric absorption, ocean-atmosphere interaction, ocean heat content, anthropogenic emission, energy consumption, risk assessment, climate projection, green growth

Simplified climate modelling to size economic boundaries

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Abstract

'Pencil-and-paper' climate modelling is extracted from the comprehensive previous research on the inherently complex natural processes. A major goal is to mediate between general scientific knowledge and the wide-spread scepticism by identifying the driving forces, seeking simple descriptions, uncovering reproducibility, and thus contributing to transparency. The results of the shortcut model are in outstanding agreement with earlier measurement data and simulation studies. Two observations are fundamentally novel requiring scrutinization by the natural sciences community: (1) near-proportionality of atmospheric infrared absorption to particle densities and (2), temperature impact from human energy consumption. Independently, the presented framework allows for straightforward climate projections and risk assessment. As result, future economic growth is demanded to zero, even in a renewables (Green Growth) world.

Keywords

paleoclimate; climate modelling; atmospheric absorption; ocean-atmosphere interaction; ocean heat content; anthropogenic emission; energy consumption; risk assessment; climate projection; green growth

23

24 1. Introduction

25 Earth presently receives on average 240 W/m^2 of insolation (planetary albedo taken into
26 account) [1], while the radiation from its surface amounts to 390 W/m^2 , given by its average
27 temperature of 15°C in the blackbody approximation (radiation synonymously termed for
28 density flux). Therefore, something must be delivering heat to the surface in addition to
29 insolation. When looking for the source, a hint comes from a well-known experience: clear-
30 sky nights exhibit relatively low Earth surface temperatures while cloudy nights remain
31 relatively warm. Thus, the atmosphere is contributing to the heat at the surface, with water
32 molecules as the dominant components.

33 However, the water content in the atmosphere is a passive reactant to otherwise driven
34 temperatures, acting as an amplifier. When looking for the temperature driving processes,
35 key candidates are the insolation (in particular the varying solar activity and modulation by
36 cosmic rays and planetary albedo), tectonic movements (e.g. with their impact on ocean and
37 wind currents), large volcanic activities, forms of life, extra-terrestrial events (bolide
38 impacts), and atmospheric composition beyond water content. Apparently through history,
39 all these components have played their role in driving Earth's near-surface atmospheric
40 temperature.

41 Regarding the atmospheric composition, CO_2 is recognized as a temperature driving agent. A
42 clear sign comes from the transmission spectrum of infrared radiation from Earth's surface
43 into space (cf. Fig. 15): It reveals strong absorption by atmospheric CO_2 which to all existing
44 knowledge, is contributing to the atmospheric heat. Thus, the wide-spread scepticism about

the climate-determining role of CO₂ cannot be directed towards its existence per se, rather towards its extent. The present analysis concentrates on the search for the empirically obvious related to the climate role of CO₂, by selecting from the – highly extensive and complex – previous observations and theoretical studies.

2. Puzzling the climate contribution of CO₂

2.1 Eocene, 50-35 Ma BP

First let us think of designing an experiment to measure the impact of the atmospheric CO₂ concentration onto the surface-air temperature. The CO₂ concentration needed to be changed and for each change, its value and the corresponding temperature recorded. Other temperature influences needed to be neglectable or well controlled. It turns out that Earth has performed such an experiment in the past. During the Eocene, in the period of 35 to 50 million years ago (Ma BP), atmospheric CO₂ has steadily been removed by sequestration while recording its concentration and the corresponding temperature via proxies. Other temperature influences are judged negligible, in particular from sea ice formation. The span of the CO₂ concentration has been from 1600 to 500 ppmv in the considered period, the temperature span from about 28 to 20 °C.

The ‘measurement’ data of this natural ‘experiment’ have previously been shown to well agree with computer simulations ([2], [3]). The present studies have revealed a simple relationship between the CO₂ concentration ($p\text{CO}_2$ in the unit ppmv, concentration synonymously termed for volume mixing ratio) and the entailed temperature (T_{CO_2}), in the further course referred to as the Eocene (CO₂-temperature) relationship:

67
$$T_{CO2} = \ln(pCO_2/22) * 6,679 \text{ (}^\circ\text{C)} \quad (1)$$

68 From the historical CO₂ concentrations of [3] (here used in course representation), the
 69 related temperatures are determined according to the preceding Eocene relationship. A
 70 slight correction is applied to account for the steady solar luminosity increase with time
 71 (ΔT_{sol}) by approximating [4] via

72
$$\Delta T_{sol} = -0,01514 * t \text{ (}^\circ\text{C)} \quad (2)$$

73 with t the time from present into the past in million years, and by applying 0.75 °C/(W/m²)
 74 for the radiative forcing-to-temperature sensitivity (see e.g. [3]).

75 In Fig. 1, the resulting $T = T_{CO2} + \Delta T_{sol}$ (smooth blue line) is compared with the data of [2]
 76 (orange wiggly line). The simple logarithmic function (equation 1) for the temperature
 77

78
 79 Fig. 1. Mean global annual near-surface air temperature trend for the Eocene as published by [2] (wiggly
 80 orange line) and computed from the Eocene CO₂-temperature relationship, $T = T_{CO2} + \Delta T_{sol}$, of the present
 81 work (smooth blue line); dotted bright-blue lines: boundaries for changes of factors in T_{CO2} by $\pm 1\%$

impact from the atmospheric CO₂ concentration is well able to reproduce the CO₂-temperature conditions in the considered period of 50 to 35 Ma BP and also beyond, extending to 60 Ma BP. As a sensitivity test, the two factors in T_{CO2} (equation 1) are changed by $\pm 1\%$ and the resulting temperature boundaries depicted in Fig. 1 by the dotted bright-blue lines.

Conclusion from the Eocene: As the primary change process, the atmospheric CO₂ concentration was steadily reduced in the period of 50 to 35 Ma BP. Roughly, a difference of 1100 ppmv in the CO₂ concentration is followed by a temperature difference of 8 °C. This causal relationship is well explained by simulation programs ([2], [3]). At the same time, the simple 2-parameter logarithmic function of equation 1, the Eocene relationship, is able to reflect the compound effect of all underlying processes.

2.2 Late Quaternary, 420 ka BP until present

In order to explore the general applicability of the simple Eocene relationship, it is examined for a period with heavy disturbances to the pure CO₂ influence: the Late Quaternary with its waxing and waning sea ice, in cause alternating the surface albedo and thus, the absorbed surface insolation. The present study is based on the Vostok ice core data [5]. The herein reported CO₂ concentrations are used to derive the CO₂-effected temperature contributions according to the Eocene relationship (T_{CO2}). The albedo effect ($\Delta T_{ice-Quaternary}$) is approximated with help of the also reported $\delta^{18}O$ values [5] by adapting the linear sea level-albedo relationship of [3] via assumed proportionality between $\delta^{18}O$ (as temperature proxy) and sea level:

104
$$\Delta T_{ice-Quaternary} = (-3,73 * \delta^{18}O - 0,086) * 0.7 \text{ (}^{\circ}\text{C)} \quad (3)$$

105 with $\delta^{18}O$ in unit ‰ and the factor 0.7 representing the radiative forcing-to-temperature
 106 sensitivity (here treated as fit parameter, being close to the value of $0.75 \text{ }^{\circ}\text{C}/(\text{W}/\text{m}^2)$ used as
 107 standard in the present studies).

108 In Fig. 2, the resulting temperatures $T = T_{CO2} + \Delta T_{ice-Quaternary}$ are compared with the proxy-
 109 measured temperatures. The computed temperatures T (orange solid curve) are in good
 110 accordance with the measured temperatures (long-dashed dark blue from [5] and short-
 111 dashed bright blue from [2]).

112

113

114 Fig. 2. Surface temperatures for the Late Quaternary; ‘T (CO2, albedo)’: computed as $T = T_{CO2} + \Delta T_{ice-Quaternary}$
 115 in the present work (orange solid line); ‘T Petit’ (long-dashed dark blue line): course representation of [5]
 116 as derived from the Vostok ice core proxies, multiplied by 0.5 to transform local temperature anomalies
 117 into mean global values (as in [3]), plus a $14 \text{ }^{\circ}\text{C}$ offset to translate from anomalies into absolute
 118 temperature (treated as fit parameter to match the computed temperatures, and being approximately the
 119 pre-industrial surface temperature); ‘Ts (Hansen)’ (short-dashed bright blue line): temperature values of [2]

The two contributions to the computed temperature T , originating from CO_2 and ice albedo, are depicted in Fig. 3. Each, CO_2 and ice albedo, influences the surface temperature at similar size. The approximated albedo contributions $\Delta T_{\text{ice-Quaternary}}$ (solid grey curve) agree well with [3] (not shown).

Fig. 3. Surface temperature contributions to 'T(CO₂, albedo)' of Fig. 2; from CO₂: T_{CO_2} according to the Eocene relationship (dashed blue line, with an arbitrary offset for presentation purposes); from sea ice albedo: $\Delta T_{\text{ice-Quaternary}}$ (solid grey line)

Conclusion from the Late Quaternary, part 1: By switching on sea ice albedo as a massive second temperature determinant in addition to CO_2 , the observed temperatures are also well reproduced with help of the Eocene CO_2 -temperature relationship. The Eocene relationship is revealed as independent of other temperature-driving forces.

This raises the question about the CO_2 -temperature relationship in the other direction: It is well known that temperature is viably directing the atmospheric CO_2 concentration. On the

136 sceptics' side, there is remarkable supposition that the CO₂ concentration is predominantly
137 driven by temperature, rather than by human emissions during the industrial age. For an
138 examination, let us think of an experiment to measure the CO₂ concentration entailed by
139 different temperatures. Again, nature has done such an experiment: in the Late Quaternary.
140 By increasing and reducing sea ice coverage, albedo is being varied, by this the absorbed
141 surface insolation and in turn, the surface temperature. Temperature and CO₂ concentration
142 have been recorded via proxies deduced from ice cores (see before), the associated time via
143 the ice core depth. During the Late Quaternary, temperature is considered the predominant
144 CO₂ change agent, other CO₂-determining processes judged disregardable.

145 Looking at the Vostok ice core data [5], temperature has varied by about 10 °C between
146 glacial and inter-glacial maxima, and the CO₂ concentration by 100 ppmv. Thus, a change of
147 1 °C is followed by a change of 10 ppmv in CO₂ concentration. This is in good agreement with
148 theoretical research [6], where the CO₂ concentration (pCO_2) varies per 1 °C of temperature
149 change according to $pCO_2/27$ (ppmv). For pre-industrial pCO_2 , this roughly results in 10 ppmv
150 CO₂ concentration change caused by a 1 °C temperature change.

151 Application of this theoretical relationship to the temperature variabilities in the Vostok ice
152 core data [5] results in the CO₂ concentrations as depicted by the dashed orange curve in Fig.
153 4; the solid blue line shows the CO₂ concentrations as reported from the ice cores. The
154 comparison of the two curves reveals that the mentioned theoretical prescription can well
155 reproduce the CO₂ concentrations of the Late Quaternary. It needs to be noted that this
156 agreement requires the recent-most CO₂ concentration to be taken as 249 ppmv.

Fig. 4. Atmospheric CO₂ concentration in the Late Quaternary; solid blue line: course representation of proxy reconstruction [5]; dashed orange line: computed as caused by the temperature variabilities (of the proxy data [5]) according to theory [6], CO₂ concentration set to 249 ppmv for the starting point (pre-industrial times, right-most value)

Conclusion from the Late Quaternary, part 2: Nature reveals different CO₂-temperature relationships for either direction: (a) temperature driving CO₂, (b) CO₂ driving temperature. In direction (a), the atmospheric CO₂ concentration follows temperature changes by about 10 ppmv per 1 °C temperature change. In direction (b), a change of 10 ppmv in CO₂ concentration causes a temperature change of 0.07 °C. Regarding for instance a CO₂ concentration increase of 100 ppmv, the Eocene relationship indicates an induced temperature increase of 0.7 °C. Since this temperature increase, in turn, causes a concentration change of 7 ppmv, 7 % of the 100 ppmv-increase is to be attributed to the entailed temperature increase.

2.3 PETM, 56 Ma BP, and Devonian to Triassic, 400-200 Ma BP

So far, the Eocene CO₂-temperature relationship has proven applicable for two geological ages, the Eocene and the Late Quaternary. The next sections shall turn to other eons with yet different conditions. The first is the time of the Paleocene-Eocene Thermal Maximum (PETM), circa 56 Ma BP. In a previous computer simulation study [7], temperature and CO₂

Fig. 5. Surface temperature for PETM in dependence upon atmospheric CO₂ concentration, computation results as dots connected by straight lines; blue (solid connection): simulation results of [7]; black open circle: PETM condition [7]; orange (dashed connection): temperature following CO₂ concentration according to the Eocene relationship, corrected by ΔT_{sol} for 56 Ma (this work)

conditions have been analyzed by varying the CO₂ concentration up to 9 times pre-industrial levels. In Fig. 5, the results of the simulation study (blue dots connected by the solid line) are compared with the Eocene relationship results, corrected by ΔT_{sol} (equation 2) for 56 Ma

(orange dots connected by the dashed line); the black circle depicts the PETM condition according to [7].

Conclusion from the PETM-study: The simple Eocene CO₂-temperature relationship is well able to reflect the comprehensive understanding of nature as implemented in simulation programs.

Fig. 6. CO₂ radiative forcing in the period 400-200 Ma BP; solid blue line: radiative forcing from [8] in course representation; dashed orange line: radiative forcing from the Eocene CO₂-temperature relationship (this work) with 1.2 °C/(W/m²) as sensitivity

In a further earlier study [8], the period of 400 to 200 Ma BP has been analyzed. Based on observed CO₂ concentrations [4], the related radiative forcings have been determined. In Fig. 6, these forcings (solid blue line) are compared to those given by the Eocene relationship (dashed orange line) by applying a sensitivity of 1.2 °C/(W/m²).

Conclusion from the 400-200 Ma-period: The pattern of the radiative forcing from earlier computer studies is well reproduced by the simple Eocene relationship. It is noted that a sensitivity of $1.2\text{ }^{\circ}\text{C}/(\text{W}/\text{m}^2)$ is required for the agreement, whereas the standard sensitivity in the present work is taken as $0.75\text{ }^{\circ}\text{C}/(\text{W}/\text{m}^2)$. At this point, no interpretation can be given on the sensitivity specifics of this case.

2.4 Late Paleozoic, 420 Ma BP until present

So far, the considerations have each focused on rather specific periods. In the various periods, the Eocene CO_2 -temperature relationship has proven as a viable tool to quantify the CO_2 -induced temperature variabilities. In this paragraph, the entire Late Paleozoic from about 420 Ma BP to present will be analyzed utilizing the Eocene relationship. The CO_2 data are taken from [4] (as in the previous 400-200 Ma study, context of Fig. 6), and the temperature data from [9]. Either data are judged state-of-the-art reconstructions of the paleo-conditions. Both data are shown together in Fig. 7, the blue (mostly upper) line for the temperature and the orange line for the CO_2 concentration.

From visual impression, the extremes exhibit rather consistent patterns: nearly the same CO_2 concentrations correspond to the respective temperatures at the minima and maxima (except at the maxima of 90 and 55 Ma BP). In between, CO_2 may lead temperature by circa 20 Ma (400-320 Ma BP) or lag by 20 Ma (280-220 Ma BP). From this, it is expected improbable to extract a statistically significant correlation between the two variables – if not artificially adapted for the 20 Ma time shifts. Since there is no explanation in sight for a potential time lead / lag, such statistical analysis is disregarded.

Fig. 7. Reconstructed surface temperatures (course reconstruction of [9]) and CO₂ concentrations [4] for the Late Paleozoic; blue (mostly upper) line: temperature, left scale; orange line: CO₂ concentration, right scale

Instead, the Eocene relationship is applied to the CO₂ concentrations. The resulting temperatures are depicted in Fig. 8 (dashed orange line) with a constant subtraction of 3 °C, and compared to the reconstructed (measured) temperatures (solid blue line). Besides the artificial 3 °C-offset, the agreement between the two curves is perceived remarkably good. One may infer that the Eocene relationship represents the major temperature driving force.

However, it is known that the absorbed insolation is subject to modulations with time. Significant variability is to be expected from the constantly increasing solar luminosity (see ΔT_{sol} of equation 2), from the cyclic cosmic ray intensities [10], and from surface albedo via sea ice coverage (e.g. regarding the Late Paleozoic icehouse at around 300 Ma). Further significant temperature influence is expected from tectonic changes (supercontinent Pangea

assembly to break-up covering the entire considered period).

Fig. 8. Surface temperatures; solid blue line: geologic reconstruction, as in Fig. 7; dashed orange line: temperature determined from the CO₂ concentrations [4] via the Eocene CO₂-temperature relationship minus 3 °C (this work)

The cosmic ray intensity $\varphi(t)/\varphi(0)$ is taken from [10] and its temperature influence approximated via fit by

$$\Delta T_{crf} = -4 * \varphi(t)/\varphi(0) \text{ (}^{\circ}\text{C)} \quad (4)$$

The resulting variability of $\sim 3 \text{ }^{\circ}\text{C}$ is found in consistency with [10] (not shown).

The tectonic changes are apparent in the paleogeographic evolvement; Fig. 9 shows a course reconstruction of [11]. The temperature impact is approximated via multiplying the coverages (in percent) of landmass, mountains, and ice sheets by $-0.2 \text{ }^{\circ}\text{C}/\%$, and the coverages of water (shallow waters and deep ocean) by $+0.2 \text{ }^{\circ}\text{C}/\%$, and applying a constant offset of $-7 \text{ }^{\circ}\text{C}$:

256
$$\Delta T_{tec} = \sum_i f_i * C_i - 7 \text{ (}^\circ\text{C)} \quad (5)$$

257 with i indicating the tectonic types and f_i the coverage-temperature impact described before,
 258 and C_i the respective coverages (Fig. 9).

259

260

261 Fig. 9. Paleogeographic evolvement with time; Earth coverages in % from top to bottom: deep ocean
 262 (dashed blue), landmass (solid brown), shallow waters (dashed bright blue), mountains (solid ochre), ice
 263 sheets (dotted violet)

264

265 This approach means for instance: In case, land gives 1 % to water, then 0.2 °C is contributed
 266 by the reduction of land coverage and another 0.2 °C by the simultaneous increase of the
 267 water area, in total 0.4 °C. Originally introduced to explore the tectonic influences, ΔT_{tec} in its
 268 given form is interpreted as reflecting albedo variabilities.

269 To put this into perspective, a 1 % land increase from today's tectonics – with ocean and
 270 land coverages 0.71 and 0.29, respectively, the ocean and land solar surface absorptions of

[1], and a sensitivity of $0.75 \text{ }^{\circ}\text{C}/(\text{W}/\text{m}^2)$ – results in a temperature reduction of $0.26 \text{ }^{\circ}\text{C}$. More qualitatively, the albedo of water clouds is about 10 % higher over land than over oceans, 0.46 versus 0.42 [13], contributing to higher surface insolation at oceans than at land. In conclusion, the albedo interpretation of ΔT_{tec} and the chosen parameter set are viewed as principally supported by separate studies. For instance in the Late Paleozoic icehouse at around 300 Ma BP, the ice sheet contribution to ΔT_{tec} is $-2.9 \text{ }^{\circ}\text{C}$ if the ice area is recruited from water areas.

In summary, the total temperature is determined by

$$T = T_{CO_2} + \Delta T_{sol} + \Delta T_{crf} + \Delta T_{tec} \quad (6)$$

The result is depicted in Fig. 10 by the dashed orange line and compared to the reconstructed (measured) temperatures (solid blue line). The agreement is perceived fair, particularly regarding the extensive period of about 400 Ma covering a large variety of disparate conditions. The pattern of the agreement remains principally unchanged (not shown) if considering an error band as given by the low and high CO_2 concentrations of [4] and by the temperature discussion of [9]. The agreement of the present high-level consideration with observations is seen as confirmation that the major temperature-determining components have been identified and that their respective contributions may be quantified by simple approximations. By nature of the approximations, the regarded contributions subsume all relevant underlying processes. This particularly applies to the Eocene CO_2 -temperature relationship comprising e.g. atmospheric water vapor variations with temperature, changing ocean-atmosphere interactions with varying atmospheric CO_2 concentrations and temperatures, and the temperature influence on the CO_2 concentration

(see above, Late Quaternary).

Fig. 10. Surface temperatures; solid blue line: geologic reconstruction, as in Fig. 7 and Fig. 8; dashed orange line: determined by equation (6) of this work based on the Eocene CO₂-temperature relationship

Certainly, the selective and simple driving-force consideration cannot cater for the entirety of all related processes. A major contribution to temperature variabilities is expected to arise from wind and ocean currents. The latter may be the cause for the deviations between about 50 and 30 Ma BP in Fig. 10 which decreases by circa -4 °C during this period. Such additional cooling may well be ascribed to changes in the ocean currents [14], [15].

From comparison of Fig. 10 with Fig. 8, the summed effect of luminosity increase (ΔT_{sol}), cosmic rays (ΔT_{crf}), and tectonics (ΔT_{tec}) roughly acts as a constant temperature reduction of 3 °C. The single temperature contributions to T (equation (6), Fig. 10) are depicted in Fig. 11.

Fig. 11. Surface temperature contributions to dashed orange line of Fig. 10: T_{CO_2} (solid blue) with 14 °C-subtraction for presentation purposes, ΔT_{sol} (dotted gray), ΔT_{crf} (dash-dotted green), ΔT_{tec} (dashed orange)

Conclusion from the Late Paleozoic: The attempt is perceived successful to describe the fundamental climate determinants by simple means. The Eocene CO_2 -temperature relationship is revealed to be applicable throughout (at least) the past 400 Ma, revealing CO_2 with the major impact. The second major influence comes from the absorbed insolation as modulated by the planetary albedo (via tectonics in Fig. 10 and Fig. 11), cosmic rays, and the sun's luminosity. The Milankovitch-cycles turn out to play a subordinate role for understanding the climate variabilities on the high level pursued in this study. However, there is room for other important contributions, particularly from ocean currents. At the very least, the benefit of the present analysis is to have a handy tool for estimates, particularly to quickly size risk from the CO_2 -temperature relationship.

3 Eocene CO₂-temperature relationship and absorbing-molecule densities

From absorption characteristics and atmospheric mixing ratios, it is readily understood that H₂O absorbs more longwave radiation than CO₂ and that both are the main absorbing media for Earth's radiation. To explore the interrelation between the particle densities and temperature, the working assumption is examined that absorption be proportional to the molecule (number) densities in the atmosphere.

The number density (q) is set proportional to the volume mixing ratio (p), corrected by a small factor for the general density-temperature dependence. The starting point for the volume mixing ratios (p_0) is 0.3 % for H₂O and 179 ppmv for CO₂ (to represent the last glacial maximum), accordingly for the number densities (q_0). For H₂O, the volume mixing ratio is positively correlated with temperature by 7 %/°C which is multiplied by a fit factor (δ). For CO₂, the volume mixing ratio is multiplied by an attenuation fit factor (γ) to cater for absorption saturation effects. The starting point for the absorbed infrared radiation is a fit parameter (Q_{A0}) and for the surface temperature 14 °C with 385.5 W/m² in surface radiation (Q_{S0}) (which is 3 °C below pre-industrial level in the Eocene relationship). Absorption is scaled proportional to the summed number densities of H₂O and CO₂ ($\Delta Q_A = \Delta q/q_0 * Q_{A0}$) and added to the radiation starting point ($Q = Q_{S0} + \Delta Q_A$), then transformed into temperature based on the blackbody assumption.

The analysis has been performed for a temperature interval of 13 °C. In result, the Eocene relationship is reproduced (at deviations below 9 ‰) with $Q_{A0} = 57 \text{ W/m}^2$, $\delta = 1.02$ (corresponding to a H₂O concentration increase with temperature of 7.14 %/°C close to the generally given 7 %/°C) and $\gamma = -0.004/(100 \text{ ppmv})$ (meaning a deviation of -4 ‰ per 100

345 ppmv from direct proportionality in the CO₂-absorption relationship as a measure for
346 saturation effects). If ΔQ_A is subjected to the atmospheric window with 10 % direct
347 transmittance, Q_{A0} shows as 63.4 W/m² with all other results retained. The present studies
348 will be continued with the above value $Q_{A0}=57$ W/m².

349 It is noted that the revealed density proportionality of the Eocene relationship reflects how
350 temperature and particle densities are established in concert. It does not express
351 temperature to solely follow the densities; instead, temperature may have other major
352 determinants.

353 In summary, with the portion of 57 W/m² from Earth's radiation considered for atmospheric
354 absorption on H₂O and CO₂ at a reference situation (given by p_0 and Q_{S0}), the Eocene
355 relationship reveals a strong proportional dependency of the absorbed radiation on the
356 molecule densities. In search for the interpretation, the absorption line intensities are
357 divided into three groups. To the first group, the very strong absorption lines are assigned,
358 where the temperature impact from absorption is insensitive to density increases. The
359 second group contains the medium-strong absorption lines, where the absorbed radiation
360 changes with the number of molecules available for absorption. The third group contains the
361 weak absorption lines which have a negligible share of the totally absorbed radiation at the
362 given molecule densities.

363 With rectangular approximation of the absorption lines from [16], the Planck distribution for
364 Earth's spectral exitance gives the following coverages of Earth's radiant exitance by the line
365 groups: Assigning line intensities $> 10^{-22}$ (line intensity in unit cm⁻¹/(molecules * cm⁻²)) to the
366 first group and intensities between 10^{-22} and 10^{-23} to the second group, the lines cover a

radiant exitance of 94 W/m^2 in the first (strong) group and of 61 W/m^2 in the second (medium-strong) group. This result supports the interpretation that the above 57 W/m^2 may be attributed to the medium-strong absorption lines where absorption is proportional to the number densities of the absorbing molecules.

Conclusion: The Eocene CO_2 -temperature relationship is nearly reproduced by proportional dependency of the absorbed flux density on the number densities of atmospheric H_2O and CO_2 ; a CO_2 saturation effect shows as 4 ‰ per 100 ppmv. The absorption-density proportionality acts on a defined portion of Earth's infrared radiation, i.e. on 57 W/m^2 of the radiant exitance at reference conditions.

4 Applying the temperature-density relationship to the anthropogenic energy consumption

In this section, the general applicability of the preceding absorption-to-particle density dependence shall be tested regarding the anthropogenic energy consumption. The energy consumption represents an additional radiation from Earth's surface (ΔQ_{EC} in W/m^2). 10 % of this additional radiation is directly emitted into space (fraction e_d) [1], 90 % is processed by nature with a resulting temperature contribution according to Earth's sensitivity (S) of temperature to radiation change. The sensitivity expresses the temperature change upon a radiation change as the compound result of all participating natural processes. It has been subject to numerous earlier studies (e.g. [2], [3]), and $0.75 \text{ }^\circ\text{C}/(\text{W/m}^2)$ is taken as standard in the present analysis. The temperature contribution from the energy consumption (ΔT_{EC}) by the end of a given year is:

$$\Delta T_{EC}(\text{year}) = \Delta T_{EC}(\text{year}-1) + (1 - e_d) * \Delta Q_{EC}(\text{year}) * S \quad (7)$$

with the industrial era starting at year 1750, $\Delta T_{EC}(1749) = 0$ °C, ΔQ_{EC} for the period since 1800 determined according to [17] (in consistency with [18]), and ΔQ_{EC} for the years 1750-1800 scaled proportional to population [19].

This temperature determination is compared to a derivation based on atmospheric H₂O and CO₂ molecule densities. For this derivation, starting point for year 1749 is $p_0\text{H}_2\text{O} = 0.4$ % and $p_0\text{CO}_2 = 285$ ppmv, an absorption of $Q_{A0}=57$ W/m² at these concentrations, and a temperature of 14 °C with an associated radiant exitance of $Q(1749) = 385.5$ W/m². The radiation corresponding to each year's energy consumption, $(1 - e_d) * \Delta Q_{EC}$, is translated into its temperature contribution via the blackbody assumption. This temperature contribution, in turn, leads to a concentration increase: for H₂O according to the preceding chapter (7.14 %/°C); for CO₂ according to the earlier 10 ppmv/°C (see context of Fig. 4), approximated by 3.7 % $p\text{CO}_2$ change per 1 °C temperature change. The absorption change (ΔQ_A) is taken proportional to the concentration change. The flux density at the end of a given year (Q) and the corresponding temperature (T) are

$$Q = Q_{EC} + \Delta Q_A, \quad Q_{EC}(\text{year}) = Q(\text{year}-1) + (1 - e_d) * \Delta Q_{EC}(\text{year}), \quad T = (Q/\sigma)^{1/4},$$

$$\Delta Q_A = \Delta p(T_{EC}) / p_0 * Q_{A0}, \quad p = p\text{H}_2\text{O} + p\text{CO}_2 \quad (8)$$

with σ the Stefan-Boltzmann constant, partly generic variable definition, and starting at year=1750. (If ΔQ_A was subjected to e_d as ΔQ_{EC} , all results were retained with $Q_{A0}=63.4$ W/m², compare remark in the previous chapter.)

The trends of the temperature contribution from the anthropogenic energy consumption are depicted in Fig. 12: for the sensitivity consideration of equation (7) by the solid orange line

and for the density consideration of equation (8) by the dashed grey line. Both methods deliver nearly identical patterns. By year 2018, the temperature contribution from the energy consumption is estimated to about 1.1 °C with a deviation of $\pm 6\%$ for the two

Fig. 12. Temperature contribution from the anthropogenic energy consumption by given year; solid orange line: computed by applying a sensitivity of $0.75\text{ }^{\circ}\text{C}/(\text{W}/\text{m}^2)$ to the radiation caused by the energy consumption (equation 7); dashed grey line: computed based on absorption by atmospheric H_2O and CO_2 , their concentrations increasing with temperature as caused by the energy consumption and the absorption proportional to the concentrations (equation 8)

methods. Extrapolation with an annual energy consumption growth rate of 1.6% /year leads to an estimated temperature contribution of $4.8\text{ }^{\circ}\text{C}$ by year 2100, with $\pm 9\%$ difference for the two methods (not shown).

The increase of the CO_2 concentration as caused by the temperature increase of $1.1\text{ }^{\circ}\text{C}$ is 11 ppmv from pre-industrial times to the present (see context of Fig. 4). As additional

information, a sensitivity of $0.66\text{ }^{\circ}\text{C}/(\text{W}/\text{m}^2)$ in equation (7) renders the two curves of Fig. 12 indistinguishable (instead of the used $0.75\text{ }^{\circ}\text{C}/(\text{W}/\text{m}^2)$).

In the next step, the temperature contribution based on absorption proportional to the trace gas concentrations (equation 8) is put into perspective with results from sophisticated computer simulations [20]. Fig. 13 shows the temperature change versus time in years from the starting point of quadrupling (upper red data set) and doubling (lower blue data set) the CO_2 concentration, with quadrupling through the first 140 years and doubling through the

Fig. 13. Temperature evolution with time upon quadrupling and doubling of CO_2 concentration, quadrupling and doubling with constant annual increase through the first 140 and 70 years, respectively, and constant concentrations afterwards. From simulation results, reproduced from [20]: quadrupling (upper dashed red lines) and doubling (lower dashed blue lines), respectively; equilibrium temperatures after 2000-3000 years indicated by horizontal lines to the right. Temperature change according to the Eocene relationship (this work) by respective dots. Corresponding temperatures from the concentration-proportionality of equation (8): dotted red and solid blue lines

first 70 years, both at constant annual rate and the concentration kept constant afterwards. The simulation results are depicted by dashed lines, with the equilibrium temperatures – as established after 2000-3000 years – indicated on the right side by horizontal lines. The dots mark the corresponding temperatures according to the Eocene relationship. The left dotted red and solid blue lines show the temperature results according to the absorption-concentration proportionality of equation (8).

The temperatures of the Eocene relationship and the equilibrium simulation results are in good agreement, as inherently without surprise since the Eocene relationship always reflects the equilibrium state. The concentration-proportionality scheme (dotted red and solid blue lines left in Fig. 13) leads to temperatures near the simulation results during the time of CO₂ concentration increase (the first 70, respectively 140 years), however to temperatures lower than expected for the equilibrium states. Thus with CO₂ as the change causing agent, the transient states are well reproduced by the density proportionality while the equilibrium state temperatures are underestimated.

Conclusion: Two methods have been applied to explore the climate impact from the energy consumption during the industrial age. The first method is based on Earth's sensitivity to radiation change. The second method is based on proportionality of the atmospheric absorption to the – temperature dependent – H₂O and CO₂ concentrations. From either method, the temperature contribution due to the anthropogenic energy consumption has accumulated to ca. 1.1 °C during the industrial era until year 2018 – caused by the energy release itself without effects from anthropogenic CO₂ emissions. Implicit presumption is that every radiation perturbation leads to a new stable state. The explanation from the concentration-proportionality scheme (equation 8) is that radiation increase leads to

temperature increase, this in turn to (predominantly) higher H₂O concentration, in turn to sustained higher absorption and thus temperature. Deriving a temperature contribution from the energy consumption is a novel approach and requires scientific discussion before further application.

Overall, Fig. 13 may be interpreted that the proportionality of absorbed energy to trace gas concentrations (dotted red and solid blue lines) represents a driving force to the air-surface temperature.

The Eocene relationship relates well with the equilibrium results from sophisticated computer simulations.

5 Zonal atmospheric emittance

Turning from atmospheric absorption to emission into space, it is known that the poles are net emitters: the infrared emission to space is larger than the insolation absorption at the surface, see dotted-green line and solid-red line in Fig. 14, respectively [21]. The equatorial region, to the contrary, is a net absorber: the absorbed radiation outweighs the radiation emitted to space. This zonal pattern is found to exhibit the following characteristics.

According to Earth's energy budget (here [23] for its subdivision), 235 W/m² are on average received from the sun after planetary albedo taken into account (insolation *I_S*, solid-red curve in Fig. 14). 40 and 30 W/m² are emitted into space through the atmospheric window and from clouds, respectively. It turns out that the residual atmospheric infrared emission

Fig. 14. Zonal mean radiation; insolation absorbed by Earth (solid red) and emissions into space (dotted green) from measurements (reproduced from [21], general pattern consistent with early measurement data [22]); emissions into space from the approximation of this work (see text, dashed orange)

of 165 W/m^2 may be decomposed into a constant part of 114 W/m^2 , and a variable part proportional to IS with 51 W/m^2 for $IS = 235 \text{ W/m}^2$ – with the emissions through the atmospheric window and from clouds also being treated proportional to IS . The resulting infrared emissions to space are depicted in Fig. 14 by the dashed orange line. As can be seen, the simple approximation with a radiation component of 51 W/m^2 proportional to absorbed insolation (IS) and a constant component of 114 W/m^2 can well reproduce the zonal cooling-warming pattern between the poles and the equator.

It is interesting how CO_2 contributes to the constant emissions part with the strong CO_2 absorption band around wavenumber 667 cm^{-1} . As clearly visible in Fig. 15, the emissions of this band originate from a nearly constant altitude (expressed by the corresponding

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Fig. 15. Infrared emission spectra for three cases, from top to bottom: hot desert, intermediate over water, and extremely cold; blackbody radiances at several temperatures superimposed; from [24]

506 blackbody temperature of about 210 K) independent of the surface temperature, thus
507 independent of the radiant exitance from ground. This is interpreted as follows.

508 An absorbing CO₂ molecule close to the surface cannot de-excite via radiation to space for
509 two major reasons. (A) An emitted photon is being re-absorbed by a nearby CO₂ molecule;
510 only as the CO₂ density sufficiently decreases with the altitude gradient, a spontaneously
511 emitted photon has the change to escape to space. (B) The average lifetime of the excited
512 CO₂ molecule from spontaneous emission is of the order of several 100 msec, to about 50%
513 between 300 and 800 msec [16]. On the contrary, the lifetime from relaxation via collisional
514 V/R-T (vibrational and rotational to translational) energy transfer is of the order of few μ sec
515 near Earth's surface.

516 The latter may be estimated from research results related to the $\nu_2/667.5\text{ cm}^{-1}$ vibrational
517 state of CO₂. With a volume mixing ratio for water vapor (H₂O) of 0.4 % near the surface and
518 the given collisional transfer rates ([25], [26], [27]), H₂O plays the dominant role before N₂ as
519 collision partner, the H₂O relaxation time being estimated to roughly 2 μ sec. This is more
520 than 5 orders of magnitude lower than the lifetime from spontaneous emission (see above)
521 so that the latter has a negligible probability to occur. At the altitude of 20 km, the situation
522 changes. From mixing ratios and collisional transfer rates, N₂ is the dominant relaxation
523 partner. With the temperature dependence of the collisional rate constant (roughly a
524 decrease by a factor of 10 from ground level to 20 km altitude, [25] and [28]) and with the
525 given densities at 20 km altitude, the lifetime from N₂ collision relaxation is estimated at 3
526 msec. From this – first order – consideration, emission to space from the given CO₂ band is
527 not expected below 20 km altitude.

528 The emissions spectra (Fig. 15) give a hint on the effective emission altitude: The 'needle' in
529 the center of the CO₂ emissions valley emits at higher temperatures than the surrounding
530 'valley bottom'. According to HITRAN [16], the lifetimes in the 'needle' are about half of the
531 lifetimes in the surrounding 'bottom'. Thus, the 'needle' is less sensitive to collisional V/R-T
532 transfer and could emit from lower altitudes, which above 20 km means lower temperatures
533 due the positive stratospheric temperature gradient. Since the data reveal the opposite for
534 the 'needle', i.e. higher emissions temperature than the surroundings, collisional energy
535 transfer seems to be subordinate at the relevant altitudes.

536 On the other hand again from HITRAN [16], the absorption line intensities in the 'needle' are
537 about a factor of 2 larger than the neighboring line intensities. Thus the 'needle' lines need a
538 correspondingly lower density for the spontaneously emitted photons to escape re-
539 absorption by CO₂, in turn they need a higher altitude to emit to space. Since higher
540 altitudes mean higher temperatures (see before), the emissions spectra (Fig. 15) reveal a
541 higher temperature for the 'needle' lines than for the surrounding 'valley' lines.

542 Conclusion: Regarding the zonal variability of the radiation budget, the infrared radiation to
543 space may be considered composed by two component types: a set of components radiating
544 proportional to the absorbed solar irradiation, and a constant component independent of
545 the absorbed insolation.

546 Absorption of Earth's infrared radiation by the strong lines of the atmospheric CO₂ is
547 comprehended as being processed via translational energy transfer, which is equivalent to
548 the transformation of radiation energy into heat. Starting at altitudes of the lower
549 Stratosphere, absorption by CO₂ can lead to emission to space and thus cooling of the

atmosphere. The higher the atmospheric CO₂ concentration, the higher the region from which CO₂ effectively radiates to space (due to the mentioned density dependence).

6 Anthropogenic carbon emissions and atmospheric CO₂ concentration

It is well known that mankind have undertaken significant CO₂ emissions into the atmosphere, added 'extra' to the equilibrated natural source and sink mechanisms. For the present estimates, the data for carbon emissions from fossil fuel burning and cement production [29] is multiplied by a factor of 1.2 to account for CO₂ input from land use change and in addition, is incremented by 200 Mt CO₂/year to consider volcanic activities.

The measured atmospheric CO₂ concentrations ([30], [31]) can be reproduced by applying an

Fig. 16. Atmospheric CO₂ concentrations for the industrial era; blue solid line: measurement data ([30], [31]); dashed red line: computed data based on emissions [29] with 3 %/year uptake rate of the added emissions; dotted orange and dot-dashed orange lines: uptake rate reduced and increased by 1%, respectively

annual removal (uptake) rate of 3 %/year to the extra CO₂ emissions, as shown in Fig. 16. The emissions-derived concentrations (dashed red line) agree well with the measured concentrations (solid blue line). As sensitivity check, the uptake rate has been changed by ± 1 %; the results are depicted via the dotted (upper) and the dot-dashed (lower) orange lines. While the removal of 3 %/year gives a coherent description of the past, there is no scientific base for its use in projections. The 3 %/year uptake rate relates to a lifetime of approximately 35 years for the extra (mainly anthropogenic) CO₂ contributions. To the current knowledge, this is too low given the time spans of the relevant underlying natural processes. In consequence, it needs to be anticipated that the annual removal rate may significantly decrease in the future and thus the atmospheric concentrations to evolve larger than determined by the 3 %/year uptake rate. Nevertheless, the estimate scheme applied for Fig. 16 appears appealing due to its simplicity and good measurement agreement. It may serve as a useful tool for projections, however always recalling that the optimistic boundaries are being explored.

Conclusion: The impact of anthropogenic carbon emissions onto the atmospheric CO₂ concentration may be approximated based on a 3 %/year uptake rate for the added emissions. This is derived from past patterns and may be used for projections with the restriction that conclusions are to be located at the optimistic end. Projecting with this scheme, the concentration may be contained within 500 ppmv if the present emissions were held constant for the future, i.e. establishing a growth rate of zero. For comparison, past carbon emissions growth rates were 3 %/year.

7 Relationship between anthropogenic activities and temperature

The Eocene CO₂-temperature relationship points to a temperature increase of 2.3 °C from the anthropogenic CO₂ emissions during the industrial era until present – with an actual atmospheric CO₂ concentration of approximately 400 ppmv. Additional (at least) 1.1 °C are to be expected from the energy consumption (see above). Roughly $\frac{1}{3}$ of this total temperature increase is being experienced at present. The difference may be explained if about 45% of the anthropogenic annual radiation (from energy consumption and CO₂ absorption, with H₂O as amplifier) is taken up by the oceans each year – leaving its footprint in the accumulated ocean heat content.

Fig. 17 shows the resulting ocean heat contents for the years 1950-2010 (dashed orange line), subtracted by the 1950-value of $3.7 \cdot 10^{22}$ J for presentation purposes. These computed results are compared to observations for the mean global ocean heat content in the upper 700 m ocean depth: The blue lines in Fig. 17 depict the upper and lower boundaries of the 95 % confidence level [32]. It is noted that for year 2010, the observation for the upper 1500 m ocean layer lies approximately $1.8 \cdot 10^{23}$ J above the level of 1970 [32] which roughly corresponds to $1.8 \cdot 10^{23}$ J for year 2010 in Fig. 17. This is regarded as indication that the contributions for the dashed orange line are not overestimated.

Overall, the agreement of Fig. 17 is interpreted to confirm as driving force mechanism: Energy consumption and the extra CO₂ emissions cause the air-surface temperature to rise, at the same time with strong uptake of the additional radiation by the oceans. This uptake turns out as an initial effect, as seen next.

Fig. 17. Annual mean globally integrated upper 700 m ocean heat content for the years 1950-2010; solid blue lines: observations, upper and lower boundaries for the 95 % confidence level, reproduced from [32]; dashed orange line: computation results (this work), 45 %/year ocean heat uptake of contributions from energy consumption (see context of Fig. 12) and carbon emissions (Eocene relationship applied to CO₂ concentrations of Fig. 16), subtracted by $3.7 \cdot 10^{22}$ J (value of 1950) for ease of comparison.

In course of the present work, the temperature contribution from a CO₂ concentration increase may be determined via the Eocene relationship. By nature of its derivation, the Eocene relationship always reflects Earth's equilibrium states – in consistency with computer simulations (Fig. 13). As mentioned for the present CO₂ concentration, the Eocene relationship prescribes a temperature of 2.3 °C above preindustrial levels – which by its equilibrium nature, Earth will establish at some point in time. In other words, the energy taken up by the oceans will eventually be redistributed such that the entire 2.3 °C will be experienced above surface. Presumably, the same will occur with the temperature contribution from the energy consumption.

In a scenario where future CO₂ emissions would yield a concentration of 500 ppmv (see before), a further warming contribution of 1.5 °C is to be expected, the CO₂ contribution totaling to 3.8 °C. If the global energy consumption will grow by 1.6 %/year until 2100, a 4.8 °C contribution will be the result. In this case, the industrial age will finally yield an 8.6 °C temperature increase. As noted for the methods of the CO₂ concentration determination (see context of Fig. 16) and the temperature derivation from energy consumption (see context of Fig. 13), the given temperatures are to be positioned on the optimistic side. On the other hand, the contribution from energy consumption follows a novel approach and requires scientific discussion before further usage. So far, Fig. 17 is viewed in support of the approach.

Conclusion: The anthropogenic temperature contribution from carbon emissions and energy consumption need to be projected to (at least) 8.6 °C - with CO₂ emissions held constant at the present level and energy consumption growing by 1.6 %/year until 2100. For the present, 1/3 of the anticipated temperature increase is being experienced as air-surface temperature. This diminution is interpreted to result from the energy uptake by the oceans. However, from nature's prescription via the Eocene relationship and confirmed by computer simulations, the entire anticipated temperature will at some point emerge as air-surface temperature.

8 Growth potential from the transition to renewables

In this paragraph, only the temperature contribution from the atmospheric CO₂ concentration will be considered. As mentioned, the concentration will remain below 500

648 ppmv if the present emissions were kept constant in the future. This raises the question:
649 Which economic growth rate will be possible from the intended transition to renewables?
650 To pursue a calculational example, the constant emissions scenario is considered as target.
651 Furthermore, the total CO₂ emissions are considered as originating from fossil material
652 usage, land use change, and cement manufacture. Land use change and cement
653 manufacture are estimated to contribute with 17 % and 6 % to the total emissions,
654 respectively. Additional contributions from volcanoes are negligible and therefore
655 disregarded. Furthermore, natural intake and uptake of atmospheric CO₂ are presumed to
656 be in unchanged balance since pre-industrial times.

657 Regarding details on the world energy consumption, the present studies are based on [33]
658 and [34], the CO₂ allocations on [29]. For year 2020, the total globally delivered energy is
659 estimated at 119,000 TWh per year, with a share of 23 % in electric energy and 77 % in direct
660 primary energy (Fig. 18). The latter comprises the fossil material usage for other applications
661 than electricity generation. Of the electric energy, 65 % is generated from fossil fuel and 35
662 % by the further technologies, i.e. particularly hydropower, nuclear energy, wind, biomass,
663 photovoltaics, and geothermics. The present growth rate of annual energy demand is of the
664 order of 1,6 % per year.

665 As renewables scenario, it is assumed that all electricity generation from fossil fuel is being
666 replaced by renewable technologies at constant pace within 25 years. Taking CO₂
667 investments for provisioning of the renewable equipment into account, the CO₂ emissions
668 typically are reduced by 43 % within the first 25 years, and by 95 % afterwards. These figures
669 are derived for average total CO₂ emissions of 30 g CO₂ per renewables-generated electric

kWh. This emissions value has exemplary character, representing the actual low end for photovoltaics and 1.5 times the anticipated conditions for wind power. The renewables electricity generation is taken continuous, disregarding the need of a buffering system. Within this parameter set, the implicit optimistic and conservative biases are expected to be balanced.

Fig. 18. Global annual energy supply, estimate for year 2020, based on [33] and [34]. Direct primary energy refers to direct use of primary energy e.g. in heating, as opposed to transformation of primary energy into electric energy before consumption. Brackets: fractional contributions to total global carbon emissions

At present, 27 % of the total annual global CO₂ emissions originate from fossil fuel electricity generation. The above-mentioned emissions reduction of 95 % in this sector corresponds to a reduction of 26 % with respect to the total emissions. On a time horizon of 100 years, this reduction corresponds to an annualized reduction rate of 0.3 %/year. In result, the transition

685 from fossil fuel to renewables in electricity generation opens an overall growth allowance of
686 the order of 0.3 %/year.

687 Due to the efficiencies of fossil fuel usage in electricity generation, about 2.8 times the
688 generated energy needs to be provided by the raw material. In applications others than
689 electricity generation, this efficiency factor is highly specific to the particular process,
690 rendering its explicit consideration inappropriate for an order-of-magnitude view; hence, the
691 delivered energy is taken as the energy contained in the raw material. On this base, the
692 residential and commercial sectors are estimated to contribute 7 % to the total CO₂
693 emissions. If – to explore the extreme – all these emissions were eliminated and this
694 regarded on a 100-years horizon, it would translate to an annualized reduction rate below
695 0.1 %/year relative to the total present emissions.

696 Presently, 66 % of the total energy consumption originate from the non-electricity
697 applications in the sectors industry and transportation, corresponding to 43 % of the total
698 CO₂ emissions. Replacement of fossil techniques by low-emission ones appears less
699 straightforward than in other application areas. As indication, we know of the difficulties to
700 size the real CO₂ footprint of electric vehicles. Also, new technologies in heavy
701 transportation are hardly in sight yet, and the ship engines are just at the verge of a first
702 transformation stage. In the industry sector, e.g. existing process heat techniques may need
703 to be migrated to new methods which is to be considered challenging.

704 Assuming 30 % of the CO₂ emissions in these two sectors (industry and transportation) can
705 be reduced within 30 years – perceived as achievable – this corresponds to a reduction of

0.4 %/year relative to the total emissions, bearing an overall growth allowance of the same size.

Since 23 % of emissions originate from cement manufacture and land use change (see above), reductions in these areas can add valuable additional growth allowances. A detailed elaboration is disregarded in lack of currently imaginable reduction mechanisms.

Fig. 19. Potential CO₂ reduction scenario, fractions relative to present total CO₂ emissions after reduction. 95 % reduction in electricity generation leading to a residual emissions contribution of 1 %, reduction in the sectors residential and commercial taken as 100 % with a residual of 0 % contribution, reduction in the sectors industry & transportation 30 % from present levels leading to a residual of 30 % CO₂ emissions contribution, contributions from cement manufacture and land use change retained from the present due to the lack of prognosis quality, total reduction of CO₂ emissions 46 %

The thus described transition to renewables leads to carbon emissions reductions as summarized in Fig. 19, relative to the present emissions. The residual emissions from electricity production as well as in the sectors residential and commercial nearly vanish; the

723 sectors industry and transportation retain 30 % of current levels; emissions from cement
724 manufacture and land use change are carried forward from the present as reasoned; 46 %
725 are considered as feasible reduction relative to the present.

726 Conclusion: A total economic growth window of 0.8 %/year may be opened by the migration
727 from fossil material usage to new techniques. This growth allowance represents the upper
728 boundary of 'Green Growth', first due to the optimistic translation from carbon emissions
729 into atmospheric CO₂ concentration. Second, the upper limit of 500 ppmv for the future CO₂
730 concentration has exemplary character; the temperature projected for this concentration
731 may need to be judged too high as a target to aim for.

732 Of the total growth window, about 40 % is anticipated from the renewables migration in
733 electricity generation. To 50 %, the growth allowance is attributed to migration efforts in the
734 sectors of industry and transportation. This reveals that transitions in these sectors are an
735 important key if mankind is to continue their abiding striving for economic growth.
736 Regarding the existing societal mechanisms, globally homogeneous taxation of CO₂
737 emissions appears as a viable tool to stimulate potential transformations.

738

739 9 Interpretation

740 Methodologically, the present study is based on the principle that the determining forces of
741 a natural phenomenon are (1) few and (2), clearly visible. The focus has been the search for
742 the clearly visible on nature dealing with the extra anthropogenic input into the natural
743 processes.

744 With this focus, a sophisticated error calculation is regarded subordinate. Remarks on error
745 consideration are included (Late Paleozoic, ocean heat content) and sensitivity studies
746 performed (Eocene relationship, emissions-to-CO₂ concentration relationship). In general,
747 the presented studies are based on long-term trends. The approach presumes that the
748 degree of agreement between approximation and observation is clearly visible in the long-
749 term patterns. In case detailed error calculations are required before further application of
750 the results, they need to be scoped for separate studies.

751 The major goal, reproduction of the results from the comprehensive scientific research in an
752 80:20 approach by simplistic means, is considered achieved. The importance of CO₂ for
753 Earth's climate is crystallized. Either direction in the temperature relationship – CO₂ or
754 temperature in the driver's seat – is quantified by simple means. From the presented
755 analyses, it seems difficult to argue that the CO₂-temperature relationship reflects a spurious
756 correlation. At the very least with societal responsibility, the risk must be assumed that
757 nature treats any atmospheric CO₂ concentration according to the Eocene relationship.

758 Furthermore, the role of CO₂ is put into perspective with other major climate determinants,
759 particularly those causing insolation variabilities (solar luminosity, cosmic rays, planetary
760 albedo), with a note to the anticipated role of the ocean currents. The hope is that this will
761 facilitate differentiation in the discussions.

762 Two results of the present work are fundamentally novel. First, the natural CO₂-to-
763 temperature impact may reveal proportionality to the absorbing air molecule densities,
764 predominantly from H₂O and CO₂. Second from applying general understanding of nature
765 (particularly expressed by the term sensitivity), energy consumption during the industrial era

may yield an accumulated temperature increase of approximately 1.1 °C until present. Either result requires confirmation before being applied beyond the current presentation.

In summary, handy tools are provided to easily quantify climate impact from human activities. From the nature of their derivation, these tools allow for projections at the optimistic boundary. In the very brief conclusion, it is hard to anticipate compatibility of further economic growth with climate change confinement, even assuming the potential transition from fossil material usage to renewables. The presented framework shows viable reference points when regarding geoengineering solutions.

Data Availability

Data and code are entirely provided [here](#).

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