Climate change into reverse gear – reversibility and legacies

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Research Article

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Abstract

As society appears determined to significantly reduce carbon emissions, the viable question arises how nature will follow. A simple model is applied to project atmospheric CO_2 concentration and near-surface temperature for emissions reductions up to 3 %/year. In result for anthropogenic efforts of 1.5-3 %/year emissions reduction, nature will return to the 1970's CO_2 concentration accompanied by a final industrial-eon temperature rise of 1.4-1.8 °C. For lower emissions reductions of e.g. 1 or 0 %/year, 22 % or 78 % of emissions need be technically removed per year to confine the temperature increase at 1.8 °C. Within this temperature regime, humankind's ocean heating is inferred to remain within natural variabilities and sea level to approximately rise by 6 m/°C at a pace of 0.2 m/century.

1. Introduction

Within broader society, there is wide-spread comprehension that the anthropogenic CO_2 emissions remain in the atmosphere virtually forever. On the other hand within science, it is undisputed that nature continuously removes a significant portion of the human emissions from the atmosphere. From observation on the industrial past, nature has removed on average 3%/year of the anthropogenic CO_2 emissions from the atmosphere [1]. This period has been characterized by ever-rising emissions. Now, society appears determined for the reverse, i.e. to steadily reduce emissions. This raises the viable question: Will nature continue on unchanged – reversible – path, i.e. still taking up 3%/year of the cumulated emissions, or have legacies built up inhibiting the return to previous states?

The present studies start from the presumption that humankind is dedicated to a – seemingly realistic – 3%/year emissions reduction. To size nature's reaction, the essential processes are entered into a simple modelling framework for CO_2 concentration, surface temperature, ocean heating, and sea level. The model framework serves as a handy tool for projections regarding future human emissions reductions. Since focusing on the driving terms, CO_2 is considered as the sole anthropogenic emissions.

2. What Happened Thus Far – Reading Nature From The Past

To understand nature's functioning, the look is devoted to the past – first to preindustrial times revealing undisturbed nature and second, to the industrial eon with significant anthropogenic contributions.

2.1 Atmospheric CO_2 concentration

During the preindustrial past 800 thousand years (ka), the atmospheric CO_2 concentration has followed temperature in the order of 20–25 ppmv/°C within the range of about 180–280 ppmv (ppmv, volume parts per million). – At preindustrial times, global waters have released 1.7 GtC/year into the atmosphere (cf. [2]). Apparently, terrestrial vegetation was prepared to consume these emissions leading to overall flux balance in first order. – During the industrial eon, the atmospheric CO_2 concentration has approximately evolved from 280 ppmv to 420 ppmv. These measured concentrations can be related to

the rather well known anthropogenic input if the latter is taken up by land and the oceans at a year-on-year rate of 3%/year [1].

2.2 Surface temperature

Also for the preindustrial past 800 ka, the temperature can be viewed determined by the atmospheric CO_2 concentration and direct temperature effects, the latter driven by the solar irradiation and snow/ice albedo alteration. The CO_2-temperature contribution is approximated by the 'Eocene relationship' with $T_{CO2} = \ln(pCO_2/22) * 6.68°C$ (T_{CO2}, surface temperature in °C; pCO_2, atmospheric CO_2 volume mixing ratio in ppmv) [3], here the data of [4] used for pCO_2. T_{CO2} comprises all related effects, e.g. from water vapor. When complemented by further driving forces, these are considered as correction terms, thus in turn also comprising all related effects. In the present studies, insolation is differentiated by the components eccentricity, obliquity, perihelion, flux at 65°N summer solstice, and global average [5]. Albedo is assumed proportional to sea level and in turn, sea level to seawater-$\delta^{18}O$ [4]. The temperature contributions from insolation and snow/ice albedo are determined by fit to the temperature measurements through the past ca. 800 ka [6]. At first, the subdivision between insolation and albedo is non-unique. In the present work, the relative contributions of albedo and CO_2 are constrained by consistency between energy budget [7] and absorber density dependencies [8]. In result, the effects from insolation and snow/ice albedo can be approximated by multiplying the CO_2-temperature contribution of the Eocene relationship with 1.4. This factor has proven its applicability in previous computations [8].

The left part of Fig. 1 shows the measured temperatures (solid blue line) in comparison with the computation of the present work (dotted brown line). The measurement data are scaled to reflect a glacial-interglacial span of 4°C. The right part of Fig. 1 presents the decomposition into the CO_2-temperature relationship (solid blue line) and the contributions from insolation (solid yellow line) and albedo (dotted red line). The insolation contributions of Fig. 1 are obtained from 65°N summer solstice superimposed by the global average. As a result, insolation cannot be found to significantly contribute to the gross glacial-interglacial temperature pattern. Notwithstanding, it certainly plays a major role for the cyclic reversals. As complementary note, the discussed temperature contributions relate to equilibrium states. Upon a disturbance from equilibrium, e.g. the CO_2 concentration changing from a certain steady level to another, it takes in the order of $\gtrsim$ 1000 years until the temperature asymptotically reaches the new equilibrium temperature [8].

Conclusion

The temperature contribution from atmospheric CO_2 is considered well known from the Eocene relationship. For the present Late Quaternary, the second-next contribution originates from snow/ice albedo alteration, as rule of thumb amounting to 40% of the CO_2 contribution.

2.3 Ocean heat content (OHC)

The oceans are a prominent energy store and at the same time, exhibit strong inertia to Earth energy variabilities. Thus, the ocean heat content and its time pattern strongly influence the surface temperature evolvement.

The (total global) ocean heat content (OHC) during the past 2000 years can be subdivided into four sections (Fig. 2, solid blue line) [9]. – During the first 600 years, OHC increases almost linearly in time while temperature stays nearly constant (Fig. 2, dotted gray line [10]). Solar irradiance (Fig. 2, dashed red line) is in steady strong mode. – The period from years 600 to ~ 1000 is interpreted to reveal an equilibrated OHC state at about 1600 ZJ (1 ZJ = 10^{21} Joule). Insolation had left the stable high level. Constellations are such that surface temperature increases. – In the period 1000–1750, OHC decreases at about the same pace as it grew in the first period. Insolation variability is yet more pronounced than before. This time, temperature decreases together with OHC. – Since year 1750, OHC rises again, synchronously with temperature. Over the entire 2000-year period, OHC appears with a cyclic behavior posing a rising bias to the recent OHC development. – Since in absolute values, the slopes in the periods of years 0-600 and 1000–1750 are approximately equal, the indication may be inferred that the natural OHC trend (without anthropogenic influence) will extend to the future at the same pace, depicted with the dotted blue line in Fig. 2. During the industrial eon, ocean heat content has risen by 660 ZJ (solid blue line of Fig. 2) with the anthropogenic contribution estimated to 180 ZJ [8].

Conclusion

Most probably, natural processes bear a rising bias for the future OHC evolvement. A natural equilibrium state is interpreted existing at OHC in the order of 1600 ZJ.

2.4 Sea level

Between glacial and interglacial maxima for the preindustrial past about 400 ka, sea level has changed by roughly 100 m [4,12]. With an associated temperature span of 4°C, sea level has changed by 25 m per 1°C temperature change. During the recent glacial-to-interglacial transition, the pace reached the order of 1.3 m/century [12]. These relationships are highly non-linear, particularly when approaching the turning conditions of the glacial and interglacial maxima. At present, temperature and sea level have attained levels characteristic for an interglacial maximum, the sea level rise revealed at about 0.2 m/century for the recent 9 ka [12] – just what has been experienced to date during the industrial eon.

3. A Driving-term Model For Co Uptake And Temperature

The central aim of the present work is to unveil nature's proceeding in case anthropogenic CO_2 emissions will be reduced significantly. Would uptake of the anthropogenic atmospheric CO_2 continue at the previously experienced rate of 3%/year? How would temperature follow a decrease of atmospheric CO_2 concentration? This paragraph presents a driving-term model derived from the past, enabling straightforward projections into the future.

Predominantly, the CO_2 uptake from the atmosphere is viewed determined by a four-fold matrix spanned by surface temperature and CO_2 concentration for the oceans and terrestrial vegetation. The construction of the present model follows a series of constraints, particularly given by (i) the data on the anthropogenic CO_2 emissions, here used from [13]; (ii) measurements on the atmospheric CO_2 concentration, the data here also from [13]; (iii) measurements on the atmospheric near-surface temperature trend during the industrial eon [14]; (iv) measurements and previous research results on the recent CO_2 uptake by the oceans [15]; (v) the preindustrial net primary production of the terrestrial vegetation at approximately 60 GtC/year, changing via the Keeling formula (a) with the atmospheric CO_2 concentration and (b), with the surface temperature via the growth factor in the formula; (vi) lower limit of the airborne fraction in the order of 15% [16]; (vii) upper limit of the ocean uptake about 5 times the atmospheric uptake (i.e. the preindustrial carbon content ratio between the oceans and the atmosphere, and accounting for the present Revelle factor); (viii) the ocean uptake dilution from temperature and CO_2 concentration in the order of 240 GtC for the period 2000–2100 in the IS92e scenario [17]. The analysis on the oceans is concentrated on a time horizon of $\gtrsim$ 100 years, thus on the upper ocean layer since the present studies focus on the first-order terms.

3.1 Ocean CO_2 uptake

The ocean uptake weakens with accumulation of CO_2. To emulate this effect, the 3%/year-uptake rate of the past is diluted for the future by $5 \bullet 10^{-4}/GtCO_2$ per cumulated CO_2. – The uptake temperature dependency is considered via CO_2 release from the oceans with an atmospheric concentration contribution of 20 ppmv/°C (see analysis on the past above), the temperature determined as outlined below. – While anthropogenic emissions and entailed atmospheric CO_2 concentration may be reduced in the future, the ocean carbon content first reflects the cumulated (strong) uptake from the past. To account for adaptation, the difference between the stronger uptake rate of the past to the lower uptake rate in the future is regarded as release from the oceans. The time lag is taken as 100 years according to the typical cycle time of the upper ocean layer. Slower ocean processes will take up additional 6–7% and yet further 3% on the 10,000-year and 100,000-year time scales for the considered emissions and concentrations [16], however neglected in the present analysis.

3.2 Terrestrial vegetation CO_2 uptake

Uptake of anthropogenic CO_2 by the terrestrial vegetation is regarded according to the Keeling formula, with 60 GtC/year of preindustrial net primary production, fertilized via $\ln(pCO_2/285)$, the preindustrial growth factor of 0.56 changing by -7.8 /°C with surface temperature as inferred from [18]. – Soil respiration principally changes with atmospheric CO_2 concentration and temperature. Since these variables strongly correlate, solely the dependency on the former is regarded. Assuming a base respiration level of 60 GtC/year, the dependency is taken to increase by 17.5 per 160 ppmv of pCO_2 elevation [19]. Care is taken not to release more than available soil carbon stock, the preindustrial amount regarded as 1,900 GtC. – Analogous to the oceans in case the atmospheric CO_2 concentration shrinks,

the excess between the stronger previous uptake relative to the lower actual uptake is considered as release to the atmosphere, here with a time lag of 30 years reflecting the typical cycle time of terrestrial vegetation [20,21]. – Among the results, the model yields an uptake ratio between land and oceans of 62:38 for the cumulated uptakes during the industrial eon (years 1850–2020).

3.3 Surface temperature

The temperature is derived from the atmospheric CO_2 concentration according to the Eocene relationship, multiplied by 1.4 for albedo effects – these equilibrium-related figures assumed realized during the industrial eon to 34% until the present and this ratio linearly changing in time, e.g. amounting to 42% in 100 years.

4. Projecting The Future: How Will Nature Follow Human Co Abatement?

Now with a practicable tool at hand, the look is devoted into the future for nature's reaction upon human emissions abatement. As humankind appears prepared for significant emissions reduction, 3%/year (year-on-year) represents the core of the present studies.

4.1 Atmospheric CO_2 concentration

For this abatement, the present estimation model points at a long-term steady atmospheric CO_2 concentration of 330 ppmv (Fig. 3, left, dashed red line) with a long-term accumulation share of 14%, 61%, and 25% between the atmosphere, the terrestrial vegetation, and the oceans, respectively. Atmospheric CO_2 concentration and airborne fraction are in good agreement with previous sophisticated studies on the role of the oceans [16].

4.2 Surface temperature

The temperature is inferred as explained by the following example. Let us imagine a maximum pCO_2 of 430 ppmv with a 1.3°C-temperature rise close to the present and a later reduction to steady 330 ppmv with an associated long-term equilibrium temperature gain of 1.4°C. In this case, the contemporary temperature has nearly reached the final equilibrium temperature, hence is expected to remain stable on the long-term future. These figures correspond to an emissions reduction of 3/%year (dashed red lines in Fig. 3, CO_2 concentration left, temperature right). If abatement was only 1.5 /year, the estimation model yields a long-term temperature gain of 1.8°C (dot-dashed red lines in Fig. 3). For comparison if emissions ceased at present, the future steady CO_2 concentration is indicated at 320 ppmv with an associated temperature gain of 1.2°C.

The precedingly outlined approach is a 'forward synchronization' between contemporary transition states and future equilibrium, i.e. both primarily directed by rising concentrations. If the new equilibrium state is

to exhibit reduced CO_2 concentrations (e.g. 290 ppmv from Carbon Capture and Storage, CCS), the further transition becomes 'down-forced' inverse-analogous to the industrial-eon past.

For a long-term temperature confinement of 1.8°C, the present estimation scheme indicates the following CCS requirements for various scenarios. (i) In case emissions reduction will be 1%/year or zero from the present, about 22% or 78% of present emissions needed be technically sequestered, respectively. (ii) In case these emissions reductions and CCS rates are commenced in 30 years from today and emissions remaining constant in the meantime, CCS is required in the order of 32–83% of present emissions for emissions reductions between 3 and 0%/year after year 2051. (iii) If humankind would even continue to increase emissions from the present, CCS is required to quickly approach 100% of emissions, for instance to sequester 98% of emissions for emissions growth of 0.5%/year.

Conclusion

Humankind is strongly advised to reduce carbon emissions at least by 1.5%/year on global level to benefit from nature's (low-cost, low-risk) offer to contribute towards viable temperature containment and to avoid the alternative serious climate impact or the demand for significantly larger mitigation effort and associated risk.

4.3 Ocean heating

With asymptotic ca. 1500 years-long evolvement of temperature from a certain equilibrium climate state to another upon equilibrium disturbance [8], the temperature trend is approximated by a tanh-function at this point. Then, the entire ocean heat uptake during the transition between the equilibrium states is given by the integral over 1-tanh. This – highly simplifying – approach leads to a total ocean heat uptake of 225 and 275 ZJ for final industrial-eon temperature gains of 1.4 and 1.8°C, the former case depicted by the dashed purple line in Fig. 2. Related to the natural upper turning point at about 1,600 ZJ, 14% or 17% are added in these two cases.

Conclusion

From the present estimation, anthropogenic ocean heating leaves nature rather undisturbed in case of sensible temperature containment.

4.4 Sea level

On one hand extrapolating from the past into the future, a sea level rise of about 25 m/°C (in dependence on surface temperature) is supported by an analysis of $\delta^{18}O$-data through the past 56 million years [25] (detailed description outside the present scope). On the other hand, Antarctic ice may exhibit noticeable inertia for industrial-eon warming up to about 2.5°C with a sea level rise in the order of 6 m/°C, this speeding up at higher temperatures towards total ice loss from further 2.5°C increase, sea level then roughly 70 m above present [26]. To first order, changes of ice volume and thus sea level can be regarded

reversible in their dependency on temperature [26]. Extrapolating the pace from the recent past, sea level gain of 0.2 m/century may serve as a viable indication for an industrial temperature rise up to 2.5°C.

Conclusion

Due to inertia in the reaction of Antarctic ice volume on rising temperatures, it appears realistic to anticipate the sea level to rise in the order of 6 m/°C for temperature gains below 2.5°C since preindustrial times, becoming realized on a horizon of several millennia.

5. Discussion

The central aim of the present studies has been to unveil basic insight how nature will react upon the intended reduction of anthropogenic CO_2 emissions. Will it follow the same path as in the previous century when emissions were continuously rising, or do legacies inhibit the return to past conditions?

With this aim, the essentials of the atmospheric CO_2 uptake processes have been entered into a simple and thus readily transportable model. This model accounts for uptake dilution and respiration increase with rising surface temperature and carbon accumulation in the oceans and terrestrial vegetation, plus respiration from anthropogenic legacy when past uptake was higher than in the future with reduced emissions.

The outstanding agreement of the model with previous observations and sophisticated studies are viewed as confirmation that the driving terms have been identified correctly. The model enables projections in dependence on humankind's upcoming emissions. Since the present studies focus on the driving terms, CO_2 is considered as the sole anthropogenic emissions and error calculation as well as statistical analysis have been out of scope.

In brief, it is found that the CO_2 emissions reduction should amount to at least about 1.5%/year (year-on-year) to benefit from nature's support to confine temperatures at 1.8°C or lower, e.g. 1.4°C attainable with 3%/year emissions reduction. If humankind proves incapable of such emissions reductions, temperature containment in the same order is only achievable with – costly and environmentally risky – technical carbon capture and storage (CCS). The dependency of sea level on temperature can be extrapolated from the past with 6 m/°C as rule of thumb, probably becoming materialized at a pace in the order of 0.2 m/century.

Nature may follow an anthropogenic emissions reduction with a time lag of three centuries regarding the atmospheric CO_2 concentration. Society is advised to seriously strive for the mentioned reductions and closely track its realization, and to control the atmospheric CO_2 trend with appropriate time averaging – i.e. on decade rather than year level.

Declarations

Conflicts of Interest:

No conflict of interest is to be declared.

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Supplementary Materials

Supplementary Materials: All data and code are available: Simplified climate modelling.

Figures

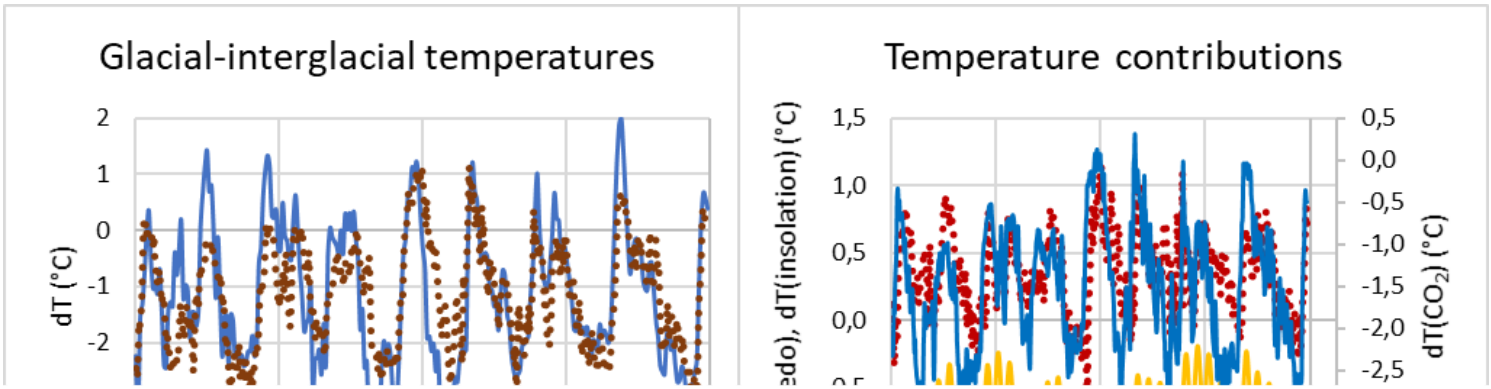

Figure 1

Temperature variabilities (dT) during the past 800 ka of glacial-interglacial cycles. Left: Measurements scaled to 4 °C glacial-interglacial span (solid blue line) [6] and computation based on the right figure (dotted brown line). Right: Computation contributions from atmospheric CO_2 concentration (solid blue line) according to the Eocene relationship, CO_2 data of [4]; from snow/albedo (dotted red line) scaled from seawater-$\delta^{18}O$ data [4]; and from insolation (yellow, offset -0.75 °C), data of [5].

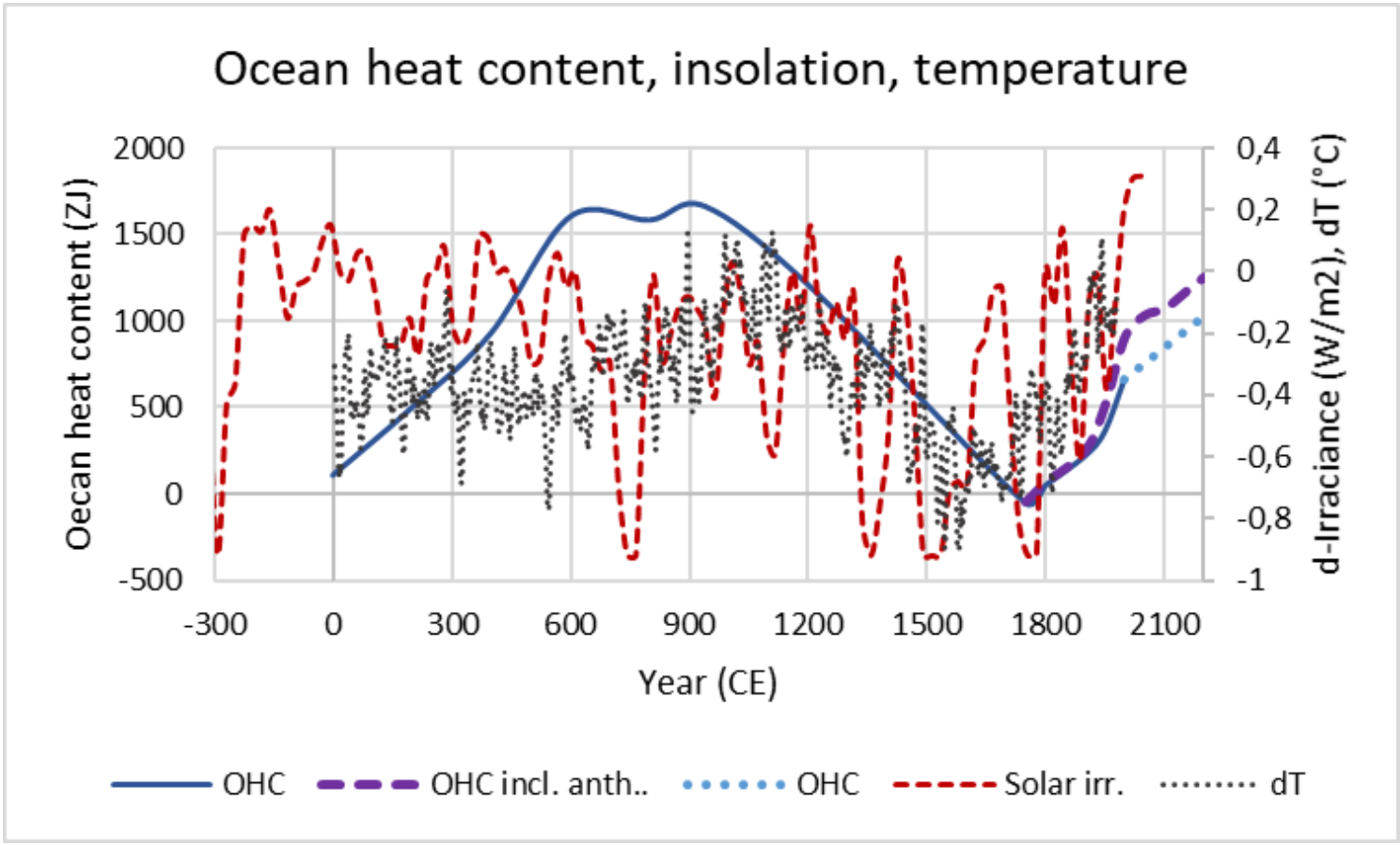

Figure 2

Ocean heat content and related observables for the past ca. 2000 years, with projections to the future. Solid blue line: Total global ocean heat content, reconstruction from [9]; dotted blue line: continuation into the future with the average slope of years 0-600; dashed purple line: adding the contribution from industrial-eon atmospheric longwave absorption increase to the blue lines (see text). Dotted grey line: surface temperature variability, smoothed from [10]. Dashed red line: solar irradiance variability [11].

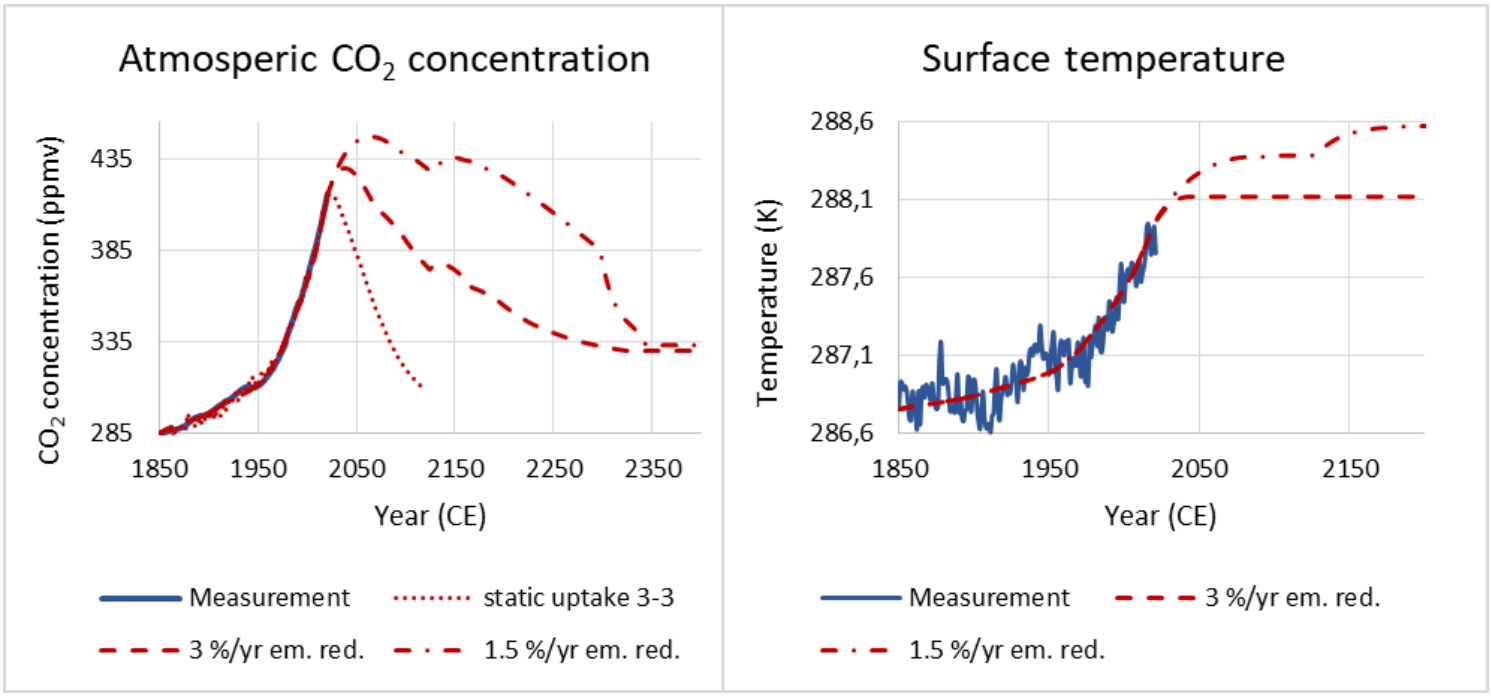

Figure 3

Nature's reaction upon anthropogenic carbon emissions observed in the past and projected for future emissions reductions. Left, atmospheric CO_2 concentration: measurement (solid blue line) [22,23]; computed with 3 %/year uptake rate for atmospheric anthropogenic content and 3 %/year CO_2 emissions reduction (dotted red); computed with the present driving-term model for emissions reductions of 3 (dashed red) and 1.5 (dot-dashed red) %/year. Right, near-surface air temperature: measurements (solid blue line), [24] plus 287 K; computed with the present model for emissions reductions of 3 (dashed red) and 1.5 (dot-dashed red) %/year.