Revisiting the greenhouse effect—a hydrological perspective

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Abstract Quantification of the greenhouse effect is a routine procedure in the framework of hydrological calculations of evaporation. According to the standard practice, this is made considering the water vapour in the atmosphere, without any reference to the concentration of carbon dioxide (CO_2), which, however, in the last century has escalated from 300 to about 420 ppm. As the formulae used for the greenhouse effect quantification were introduced 50-90 years ago, we examine whether these are still representative or not, based on eight sets of observations, distributed in time across a century. We conclude that the observed increase of the atmospheric CO_2 concentration has not altered, in a discernible manner, the greenhouse effect, which remains dominated by the quantity of water vapour in the atmosphere, and that the original formulae used in hydrological practice remain valid. Hence, there is no need for adaptation due to increased CO_2 concentration.

In God we trust; all others bring data.
(attributed to W. Edwards Deming, American engineer, statistician and management consultant)

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1 Introduction

According to Anders Ångström (1916), a pioneer of the measurement and modelling of radiation, the first observations relating to the problem of Earth's (longwave) radiation to space were made between the years 1780 and 1850. Ångström (1916, p. 65) cites some sporadic measurements by several researchers for the period 1887-1912. From these measurements and from experiments in the 19th century, it was understood that the major constituents of the atmosphere, i.e., nitrogen (N_2) and oxygen (O_2), are transparent to the longwave radiation. In contrast, some minor constituents, particularly water vapour (H_2O), carbon dioxide (CO_2) and ozone (O_3), absorb and reemit longwave radiation, thus being responsible for what has been called the *greenhouse effect*.

John Tyndall (1865) pioneered in understanding the dominance of water vapour in this process, as well as the importance of its presence for climate and life, which he expressed in the following manner:

> *We were led thus slowly up to the examination of the most widely diffused and most important of all vapours—the aqueous vapour of our atmosphere, and we found in it a potent absorber of the purely calorific* [longwave] *rays. The power of this substance to influence climate, and its general influence on the temperature of the earth, were then briefly dwelt upon. A cobweb spread above a blossom is sufficient to protect it from nightly chill; and thus the aqueous vapour of our air, attenuated as it is, checks the drain of terrestrial heat, and saves the surface of our planet from the refrigeration which would assuredly accrue, were no such substance interposed between it and the voids of space.*

Tyndall (1865) also understood the behaviour and the minor contribution of CO_2 in this effect:

> *Carbonic acid gas is one of the feeblest of absorbers of the radiant heat emitted by solid sources. It is, for example, extremely transparent to the rays emitted by the heated copper plate already referred to. There are, however, certain rays, comparatively few in number, emitted by the copper, to which the carbonic acid is impervious; and could we obtain a source of heat emitting such rays only, we should find carbonic acid more opaque than any other gas to the radiation from that source.*

Subsequently, the predominance of H_2O over CO_2 was confirmed by experiments, conducted to discern their relative influence on emissivity by using air free of one of the two constituents (Brooks, 1941; Elsasser, 1942, Figure 28). As a result, it was asserted that "any usual variations in CO_2 and O_3 will probably not cause much change, because of the predominance of the water-vapor radiation in the atmosphere" (Brooks, 1941).

Besides being more important as a greenhouse gas, water vapour has another big difference from CO_2: the fact that its quantity in the atmosphere varies substantially in time and in space, thus being an agent of perpetual change on all time scales. The change on fine time scales (e.g. hourly to daily) is easy to comprehend but change also occurs on annual, decadal, centennial scales and beyond. The understanding of the latter has been pioneered by Hurst (1951) and more recent studies confirm that the long-term change (also called Hurst-Kolmogorov behaviour) occurs in all processes related to water and the atmosphere (Koutsoyiannis, 2013, 2021, 2023a; Dimitriadis et al., 2021; O'Connell, P.E. et al., 2023).

In contrast, the temporal and spatial variation of CO_2 occurs at small rates and at large scales. This was understood by Ångström (1916), who stated:

> *the variations of the radiation in that part of the atmosphere* [the troposphere] *must depend almost entirely on the variations in the water-vapor element, the carbon-dioxide element being almost constant, as well in regard to time, as to place and to altitude. The probable slight influence of variations in the amount of ozone contained in the upper strata of the atmosphere, we may at present ignore.*
>
> On the other hand, Ångström (1916) also noted:

> *I think it very probable that relatively small changes in the amount of carbon dioxide or ozone in the atmosphere, may have considerable effect on the temperature conditions of the earth. This hypothesis was first advanced by Arrhenius, that the glacial period may have been produced by a temporary decrease in the amount of carbon dioxide in the air.*

And indeed, Svante Arrhenius, supported the idea that changes in atmospheric carbon dioxide concentration are the cause of the changes in temperature. Arrhenius (1896) stated:

> *Conversations with my friend and colleague Professor Högbom* […]*, led me to make a preliminary estimate of the probable effect of a variation of the atmospheric carbonic acid on the temperature of the earth. As this estimation led to the belief that one might in this way probably find an explanation for temperature variations of 5–10 °C, I worked out the calculation more in detail and lay it now before the public and the critics.*

However, recent studies, based on paleoclimatic and modern instrumental data, have questioned Arrhenius's hypothesis and suggested that the causality relationship between temperature and CO_2 could be opposite to this hypothesis, i.e. temperature variation could be the cause and CO_2 concentration variation could be the effect. A convincing explanation about why, in the long run, change in temperature leads and in CO_2 concentration follows has been given by Roe (2006) who demonstrated that in the Quaternary it is the effect of Milanković cycles (Milanković, 1935, 1941, 1998) rather than of atmospheric CO_2 concentration, that explains the glaciation process. Specifically, he found that

> *variations in atmospheric CO_2 appear to lag the rate of change of global ice volume. This implies only a secondary role for CO_2 —variations in which produce a weaker radiative forcing than the orbitally-induced changes in summertime insolation— in driving changes in global ice volume.*

(see also Koutsoyiannis, 2019; Koutsoyiannis and Kundzewicz, 2020; and references therein).

As for the recent changes, Koutsoyiannis et al. (2022a,b, 2023b) developed a stochastic methodology for detecting potential causal links and, using modern instrumental data of temperature and CO_2 concentration for the last 65 years, they concluded that temperature change is a potential cause of CO_2 concentration change while the opposite causality direction can be excluded as violating a necessary condition of causality. This result is opposite to the common belief that in the recent decades human CO_2 emissions are the cause of CO_2 and temperature increase. Yet, Koutsoyiannis et al. (2023b) showed that their result is consistent with the generally accepted global carbon budget as estimated by the latest (sixth) assessment report by the Intergovernmental Panel on Climate Change (IPCC) and depicted in Fig. 5.12 of Canadell et al. (2021).

Questions such as the above-mentioned causality direction need data to answer, as the human imagination and modelling capabilities are not adequate to provide sound and irrefutable answers. Likewise, the partial contributions of each of the two elixirs of life, H_2O and CO_2, to the greenhouse effect need data to quantify. By now, there is no shortage of such data. Perhaps the first who made systematic observations of Earth's longwave radiation and studied its variation with water vapour was Ångström. Specifically, he made several observations during an expedition in Bassour, Algeria, in 1912, and a second expedition in California, USA, in 1913 (Ångström, 1916). Dines and Dines (1927) and Robitzsch (1926) made their own observations in 1920s, which Brunt (1932) utilized to derive his celebrated formula for the calculation of the atmosphere's emissivity as a function of the water vapour pressure in the atmosphere. Now, we have systematic measurements of atmospheric radiation for about 110 years.

All these measurements quantify the greenhouse effect in terms of the influence of the water vapour in the atmosphere. The hydrological significance of this quantification cannot be overstated. In fact, since the introduction of Penman's (1948) equation for evaporation, which incorporates Brunt's (1932) formula, the quantification of the greenhouse effect has become part of the routine hydrological calculations for real-world problems. Here the notion of "real-world problems" is used to make the contrast with fictitious projections for the next hundreds, thousands or millions of years. The former are clearly part of science and technology while this may not be the case for the latter.[1]

Brunt's and Penman's equations, as well as many more equations of the same type (see section 2), describe the influence on longwave radiation of the amount of water vapour in the atmosphere. None of them contains any reference to the CO_2 concentration. The reason had already been explained by Ångström (1916) in the quotation given above: it was infeasible to quantify the effect of **"**the carbon-dioxide element" by means of measurements, as it was "almost constant" in the measurements of each individual researcher. However, with the over-century long accumulation of observations, in which the CO_2 concentration is no longer constant, one can study the effect of the latter, if any.

Hence, the research questions that are dealt with in this paper are the following two interrelated ones:

1. Has the increase of the atmospheric CO_2 concentration in the last century modified the greenhouse regime on Earth in a manner that is discernible from radiation measurements?

[1] Long-range predictions may contradict Karl Popper's (1983) falsifiability principle, i.e., "[a] statement (a theory, a conjecture) has the status of belonging to the empirical sciences if and only if it is falsifiable". In addition, the following quotation by Percy Williams Bridgman (1966) may hold: "A combination of words in the grammatical form of statement is only a 'pseudo-statement' when it purports to be about the future". More specific information about future climate predictions (also known as projections) can be found in Koutsoyiannis et al. (2008, 2011, 2023b) and Koutsoyiannis (2020).

2. Are the formulae used in hydrological practice, in particular those related to the longwave radiation, appropriate in their historical form, or do they need adaptation?

Naturally, the reply to the second question requires examination of radiation measurements at the surface, which are the only available for such a long period (110 years). One may thus say that, whatever the reply to the first question is, it only refers to the greenhouse effect at the surface, while for the radiative balance at the top of atmosphere the contribution of CO_2 is well-known and has been dominant in driving an enhancement in the atmosphere's greenhouse effect (Harries et al., 2001). However, macroscopically speaking, the question remains also valid for the top of the atmosphere. The energy exchange processes at the top of the atmosphere are not independent from, or inconsistent to, those at the surface, which additionally include sensible and latent heat flux, with a decisive role of water on the latter. In any case, the processes at the top of the atmosphere are not in the focus of this article, nor do we have rich enough data to study them in equal detail. Yet, we provide some indications of the consistency of what happens at the surface and at the top of the atmosphere in Appendix B, using satellite data available for the 21st century.

The approach we follow to study these questions is hydrological in two respects: first because the questions have a major hydrological dimension and second because we use data to study them, as is the standard hydrological practice. Other disciplines trust more models than data, but the tradition in hydrology has been to make inference based on data (observations), without refusing the usefulness of models, which provide the physical context to interpret observations. The fact that it is a tradition in hydrology is testified by Klemeš (1986), who, in proposing the famous split-sample scheme for optimally using data in building hydrological models, felt (and stated) that his "scheme contains no new and original ideas". In addition, Beven (quoted from Tchiguirinskaia et al., 2008), stated "we need those better measurements, and not necessarily better models", "the answer is in the data and a new theory alone would not be enough" and "the focus in the future should be oriented on new and more accurate measurement techniques". More recently, Koutsoyiannis and Montanari (2022a,b) have highlighted the role of data in adapting even bad models and at the same time assessing uncertainty, again based on data. As a counterexample of a discipline relying more on models, we may consider the so-called "climate science" (studying climate, which traditionally has been the subject of climatology). With reference to the development of climate models, Essex and Tsonis (2018) describe the preference for converging to each other, rather than to reality ("observed state"), in this way: "While the model results are all converging on a solution that solution excludes the observed state at a $p > 0.99$ level of confidence. This strongly hints at an emerging confirmation bias, with the models evolving to resemble each other ever more closely in each progressive model generation." At the same time, they illustrate (in their Fig. 2) that, despite convergence to each other, the disagreement between models and reality becomes wider rather than narrower.

Hence, while we appreciate the usefulness of climate studies based on models and simulations, pioneered by Manabe (Manabe et al., 1965; Manabe and Wetherald, 1967; see also Ramanathan, 1981), here we follow another path, that of inference based on observational data. Such data also provide the basis to confirm or refute models and simulations, and this is imperative in science (for example, Koutsoyiannis et al., 2023b, showed a disagreement between climate models and reality in terms of causality direction). While we recognize that regional characteristics of climate play a role (e.g., non-condensing greenhouse gas are expected to contribute more in cold climates where water vapour is less), and several contributions have emphasized these characteristics (e.g. Allan et al., 2009, for tropical ocean regions), here we follow a macroscopic approach, examining data from different regions of the globe simultaneously, irrespective of the regional climate. This is consistent with the hydrologic practice of using the same formulae for evaporation calculations over the globe. Our data sets are from a wide range of climates, humid and dry, and polar to hot, and are examined all together. Another difference of our study from climate studies is that we try to avoid assumptions that may contaminate the results with subjectivity (as a counterexample, Philipona et al., 2004, in an attempt to separate the influence of well mixed greenhouse gas changes on downward infrared radiation from the component from water vapour increases, corrected the radiation data for two thirds of the humidity increase considering that this is due to water vapour that stems from external warm air advection).

Historically, at the cradle of science (6th century BC), the first geoscientific question posed as such was purely hydrological—the flooding of the Nile (Koutsoyiannis and Mamassis, 2021). Thus, hydrology, has a long history and a broad domain (see its modern definition in UNESCO, 1964), yet it is susceptible to subordinating. In most part of the 20th century, hydrology was regarded as an appendage of hydraulic engineering (Yevjevich, 1968), useful to support the design of hydraulic structures, especially in estimating their design discharges. Whether in the 21st century it became an autonomous science, as many hydrologists of the 20th century had mandated, or developed other subordination links (perhaps related to funding opportunities), we leave to the reader to judge. It may be informative to note that Vit Klemeš, a pioneer of the autonomy mandate and President of the International Society of Hydrological Sciences from 1987 to 1991, later regretted the cutting of the link of hydrology with engineering and its replacement with other links, and addressed a plea to "hydrologists and other water professionals, to stand up for water, hydrology and water resource engineering, to restore their good name, unmask the demagoguery hiding behind the various 'green' slogans" (Klemeš, 2007; Koutsoyiannis, 2014b). Among these slogans, most determinant for hydrology's current status has been the "climate change", also renamed "climate emergency", "climate crisis" etc. (Koutsoyiannis et al., 2023a). In this respect, this paper, by delving into the greenhouse effect from a hydrological perspective and by highlighting the importance of water in it, may hopefully help to change the character of existing links of hydrology (particularly with climate), and strengthen its hypostasis as an autonomous scientific discipline.

2 Theoretical basis

The emission of longwave radiation, L, of a body (measured as energy per unit time and unit area, typically W m^{-2}) at temperature T (measured in kelvins) is described by the Stefan-Boltzmann law:

$$L = \varepsilon\sigma T^4 \tag{1}$$

where σ the Stefan–Boltzmann constant, $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}, and ε the emissivity of the body (dimensionless). For a black body radiator, $\varepsilon = 1$.

The Stefan–Boltzmann constant is a fixed physical constant as it is related to other physical and mathematical constants by

$$\sigma = \frac{2\pi^5 k^4}{15c^2h^3} \tag{2}$$

where π is the ratio of a circle's circumference to its diameter, k is the Boltzmann's constant, h is the Planck's constant, and c is the speed of light in vacuum. However, in the older publications referenced here (e.g. Pekeris, 1934; Swinbank, 1963), including the most celebrated and influential ones (e.g. Brunt, 1932, 1934), the value of this constant is taken higher by 1.7%, $\sigma = 5.77 \times 10^{-8}$ W m^{-2} K^{-4}. Dines (1920) uses a value smaller by 8.1%, $\sigma = 5.3 \times 10^{-8}$ W m^{-2} K^{-4} (originally in different units, here converted to SI), while he notes that "different authorities give different values". Indeed, Robinson (1947), attributes several values, such as those above, to different authors, while he adopts the value of $\sigma = 5.71 \times 10^{-8}$ W m^{-2} K^{-4}. Notably, though, Ångström (1916) used an almost accurate value of σ. Some authors, most notably Penman (1948), do not specify the value they used. For these reasons, attention must be paid when using old data sets, which we have attempted here, by adjusting the values of those data sets to ones corresponding the modern value of σ.

The net emission of the longwave radiation at the Earth's surface, L_n, is the difference between that emitted by the surface directed upward, L_s, and that emitted by the atmosphere directed downward, L_a, i.e.,

$$L_\mathrm{n} = L_\mathrm{s} - L_\mathrm{a} = \varepsilon_\mathrm{s}\sigma T_\mathrm{s}^4 - \varepsilon_\mathrm{a}\sigma T_\mathrm{a}^4 \tag{3}$$

where the subscripts 's' and 'a' refer to the surface (solid or liquid) and the atmosphere, respectively, and where a minor term of reflected upward longwave radiation has been neglected. The temperature of the surface, T_s, is well defined and the emissivity ε_s is close to 1, usually taken $\varepsilon_\mathrm{s} = 0.97$. However, in the atmosphere the temperature varies substantially and the quantity L_a is the integration of the radiation process across the entire atmosphere.

The theoretical basis for such integration is described by Goody (1964). Based on this theoretical basis and some assumptions on the atmospheric profiles (nearly standard atmosphere), Brutsaert (1975) was able to express analytically (by integration) the atmospheric radiation L_a near the surface for clear sky, and eventually find the effective emissivity as:

$$\varepsilon_\mathrm{a} = 1.24 \left(\frac{e_\mathrm{a}/\mathrm{hPa}}{T_\mathrm{a}/\mathrm{K}} \right)^{1/7} \tag{4}$$

with T_a taken as the atmospheric temperature at a level near Earth's surface (in K) and e_a being the partial pressure of water vapour (see below) at the same level (in hPa). He also proposed a simplification by fixing T_a to the average Earth's temperature near the surface, i.e. to 288 K, whence equation (4) becomes

$$\varepsilon_\mathrm{a} = 0.553 (e_\mathrm{a}/\mathrm{hPa})^{1/7} \tag{5}$$

A modification of the Brutsaert's equation (4) was proposed by Prata (1996) who constructed a physically based and observationally constrained clear-sky model of downward longwave radiation, expressed as:

$$\varepsilon_\mathrm{a} = 1 - (1 + w) \exp\left(-\sqrt{1.2 + 3.0w}\right), \qquad w \coloneqq 46.5 \frac{e_\mathrm{a}/\mathrm{hPa}}{T_\mathrm{a}/\mathrm{K}} \tag{6}$$

with w representing the atmospheric water content (most commonly known with the misnomer 'precipitable water'), found by linear regression on radiosonde data and expressed in cm. We may observe that for $e_\mathrm{a} = 0$, Brutsaert's equation (4) results in zero emissivity, while Prata's equation (6) has a nonzero minimum of $\varepsilon_\mathrm{a} = 0.67$ and, in this way, it describes the non-condensing greenhouse gas contribution to emissivity.

Decades earlier, empirical relationships of the same type (and with nonzero minimum) had been proposed, among which the earliest, most celebrated and most popular is that by Brunt (1932, 1934):

$$\varepsilon_\mathrm{a} = 0.526 + 0.065 \sqrt{e_\mathrm{a}/\mathrm{hPa}} \tag{7}$$

This was based on measurements by Dines and Dines (1927) at Benson. Furthermore, Brunt (1934) used additional data sets in which he fitted the same mathematical expression,

$$\varepsilon_\mathrm{a} = a + b \sqrt{e_\mathrm{a}/\mathrm{hPa}} \tag{8}$$

and found different values of the coefficients a and b. Namely, in addition to Benson data set, he also studied data from Bassour, Algeria (Ångström, 1916), Uppsala, Sweden (Asklöf, 1920), Lindenberg, Germany (Robitzsch, 1926), which he had also included in his original study (Brunt, 1932), Montpellier and Pic du Midi, France (Boutaric, 1928), and Poona (Pune), India (Ramanathan and Desai, 1932). Brunt provided individual pairs of a and b for each case, as well as an average fitting for all cases, which is

$$\varepsilon_\mathrm{a} = 0.44 + 0.08 \sqrt{e_\mathrm{a}/\mathrm{hPa}} \tag{9}$$

Subsequently, a large variety of similar empirical relationships were proposed by several researchers, critical reviews of which can be found in Carmona et al. (2014), Guo et al. (2019) and Wong et al. (2023), to mention the most recent.

It is reminded here that the partial pressure of water vapour e_a has a thermodynamic upper limit, the saturation water vapour pressure, which is a function of the temperature:

$$e(T_\mathrm{a}) = e_0 \exp\left(\frac{\alpha}{RT_0}\left(1-\frac{T_0}{T_\mathrm{a}}\right)\right)\left(\frac{T_0}{T_\mathrm{a}}\right)^{(c_\mathrm{L}-c_p)/R} \tag{10}$$

where (T_0, e_0) are the coordinates of the triple point of water, R is the specific gas constant of water vapour ($R = 461.5\ \mathrm{J\,kg^{-1}K^{-1}}$), $\alpha \coloneqq \xi R/k = \xi N_\mathrm{a}$ (with k the Boltzmann's constant, N_a the Avogadro constant and ξ the amount of energy required for a molecule to move from the liquid to gaseous phase), c_p is the specific heat at constant pressure of the water vapour and c_L is the specific heat of the liquid water. This is the celebrated Clausius-Clapeyron equation, which was recently rederived (Koutsoyiannis, 2014a, 2023) in a pure stochastic context by maximizing the entropy, i.e., the uncertainty, in a single water molecule. Notably, the maximization of uncertainty at the microscopic level yields a law that at the macroscopic level is nearly deterministic. By substitution of the various constants in (10), the following form of the equation is derived (first found in Koutsoyiannis, 2012):

$$e(T_\mathrm{a}) = e_0 \exp\left(24.921\left(1-\frac{T_0}{T_\mathrm{a}}\right)\right)\left(\frac{T_0}{T_\mathrm{a}}\right)^{5.06},\ T_0 = 273.16\ \mathrm{K}, e_0 = 6.11657\ \mathrm{hPa} \tag{11}$$

The equation can be analytically inverted to give T_a when e_a is known. The result is:

$$T_\mathrm{a} = \frac{4.925\,T_0}{-\mathrm{W}_{-1}\left(-4.925\exp(-4.925)\left(\frac{e_\mathrm{a}}{e_0}\right)^{\frac{1}{5.06}}\right)} \tag{12}$$

where the numerical value 4.925 is the ratio of the constants 24.921 and 5.06, and $\mathrm{W}_{-1}(z)$ is the Lambert W function of z (with W_{-1} being the non-principal real branch). Note that equations (11) and (12) are dimensionally consistent and also more accurate than other forms of the Clausius-Clapeyron equation (or approximations thereof) found in the literature.

A state in which the vapour pressure e_a is lower than the saturation pressure $e(T_\mathrm{a})$ is characterized by the relative humidity:

$$U \coloneqq \frac{e_a}{e(T_\mathrm{a})} = \frac{e(T_\mathrm{d})}{e(T_\mathrm{a})} \tag{13}$$

which serves as a formal definition of both the relative humidity U and the dew point T_d. If we know the temperature T_a and the dew point T_d, then the relative humidity is calculated as (Koutsoyiannis, 2023):

$$U = \exp\left(24.921\left(\frac{T_0}{T_\mathrm{a}}-\frac{T_0}{T_\mathrm{d}}\right)\right)\left(\frac{T_\mathrm{a}}{T_\mathrm{d}}\right)^{5.06} \tag{14}$$

If we know the temperature and the relative humidity, then the dew point $T_\mathrm{d} = e^{-1}\big(U\ e(T_\mathrm{a})\big)$, where $e^{-1}(\,)$, is inverse function of $e(\,)$, is found by the following analytical expression (Koutsoyiannis, 2023):

$$T_\mathrm{d} = \frac{4.925\ T_0}{-\mathrm{W}_{-1}\left(-\frac{4.925\ T_0}{T_\mathrm{a}}\exp\left(-\frac{4.925\ T_0}{T_\mathrm{a}}\right)U^{\frac{1}{5.06}}\right)} \tag{15}$$

At the equilibrium, the maximum U is 1, and T_d equals T_a, its upper limit .

Essentially, the above theoretical framework with its simple equations quantifies the greenhouse effect due to the presence of water vapour in the atmosphere. With Howard Penman's (1948) celebrated paper on natural evaporation from open water, bare soil and grass, this quantification became an essential part of hydrological practice in calculating evaporation, which represents a substantial component of the hydrological balance—and also the most intractable and difficult to measure. At the same time, evaporation calculations are most essential for agricultural irrigation practice.

Interestingly however, the way Penman chose to present the longwave radiation part in his equation may not inform hydrologists that the greenhouse effect is present in their evaporation calculations. Specifically, Penman's equation (7) presents the longwave radiation component for clear sky conditions as follows (after converting the vapour pressure, originally given as mmHg, to hPa):

$$\frac{L_\mathrm{n}}{\sigma T_\mathrm{a}^4} = 0.56 - 0.08\sqrt{e_\mathrm{a}/\mathrm{hPa}} \tag{16}$$

In other words, Penman did not make a distinction of the two components seen in equation (3). He quoted Brunt (1934) for this equation (actually, the 1939 edition of the book). Indeed, by comparing equation (16) with Brunt's equation (9) along with equation (3), it becomes evident that Penman assumed, as an approximation, that:

- $T_\mathrm{s} = T_\mathrm{a}$ (even though in other parts of his derivation he implied that $T_\mathrm{s} \neq T_\mathrm{a}$ as seen from his famous assumption that $\big(e(T_\mathrm{s}) - e(T_\mathrm{a})\big)/(T_\mathrm{s} - T_\mathrm{a}) = \mathrm{d}e(T_\mathrm{a})/\mathrm{d}T_\mathrm{a} =: \Delta$).
- $\varepsilon_\mathrm{s} = 1$.

Indeed, with these two assumptions, equations (9) and (3) yield (16).

Since its introduction, Penman's (1948) equation, whose complete form is not reproduced here, has been the basis for routine calculations of the evaporation from water surfaces. Modified versions of the original equation have been common, including those with different parameters a and b in equation (8) (see review by Batchelor, 1984). Most influential was that by Goss and Brooks (1956), which, based on measurements of longwave radiation in California, USA, suggested the values $a = 0.66$ and $b = 0.039$.

In another historical contribution, Monteith (1965) adapted Penman's method to estimate water requirements of crops, thus shaping what has been called the Penman-Monteith method. Montieth did not adapt the part of Penman's method referring to longwave radiation, even though in earlier publications he had studied it. Specifically,

Monteith and Szeicz (1962) had suggested $a = 0.53$ and $b = 0.065$. Subsequently the Penman-Monteith method became a standard of the Food and Industry Organization (FAO), initially in the version by Doorenbos and Pruitt (1977; FAO Irrigation and Drainage Paper 24) and later in the version by Allen et al. (1998; FAO Irrigation and Drainage Paper 56). In both versions, the net longwave radiation is calculated as

$$\frac{L_\mathrm{n}}{\sigma T_\mathrm{a}^4} = 0.34 - 0.044\sqrt{e_\mathrm{a}/\mathrm{hPa}} \tag{17}$$

Clearly, this formula is influenced by Goss and Brooks (1956) and predicts a lower L_n by about 40% compared to Penman's formula in equation (16). In turn, it reflects a higher intensity of the greenhouse effect.

In the public perception[2] of present day, it is the carbon dioxide (CO_2) that determines the greenhouse effect on Earth. However, the above theoretical framework clearly demonstrates the dominance of water vapour, even without considering the additional effect of the clouds, which increases the downward radiation of the atmosphere by up to 25% for nimbostratus clouds or for fog (Brutsaert, 1991, p. 143).

A recent study by Schmidt et al. (2010) attributes 19% of the longwave radiation absorption to CO_2 against 75% of water vapour and clouds, a ratio of 1:4 (cf. Koutsoyiannis, 2021). CO_2 is followed by O_3, whose contribution is estimated by Schmidt et al. between 2.7% and 5.7%. However, there may be an overestimation of the relative contribution of CO_2. Specifically, in an example given by Brooks (1952), the contribution of the CO_2 bands is about 1:8 compared to water vapour, without considering the clouds. In addition, van Wijngaarden and Happer (2020; corroborated in de Lange et al., 2022) using a detailed model of the radiation in the atmosphere (validated by satellite data) concluded that a doubling of CO_2 concentration (from 400 to 800 ppm) would result in a 3 W/m^2 decrease of radiation flux in the top of the atmosphere. The same study (in its Table 5) estimates a temperature increase at the surface for a doubling of CO_2 concentration of the order of 2 K (interestingly, not different from that estimated by Manabe and Wetherald, 1967). If this is translated to black body radiation, it results in an increase of about 3%. If this result is correct, given that in the time span of our study there was an increase of its concentration of the order of 30% (rather than doubling), one would

[2] Samples are the following quotations: (a) "Carbon dioxide is Earth's most important greenhouse gas" (U.S. National Oceanic and Atmospheric Administration—NOAA, Climate.gov: Science & information for a climate-smart nation, https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide; (b) "Carbon dioxide is widely reported as the most important anthropogenic greenhouse gas" (U.S. Environmental Protection Agency—EPA, Report on the Environment, https://www.epa.gov/report-environment/greenhouse-gases; notice here the adjective "anthropogenic", which wildly contrasts the fact that only 4% of the carbon dioxide emissions are anthropogenic, with 96% being natural; Koutsoyiannis et al., 2023b); (c) "For climate change, the most important greenhouse gas is carbon dioxide, which is why you hear so many references to 'carbon' when people talk about climate change." (Massachusetts Institute of Technology—MIT, Climate Portal, https://climate.mit.edu/explainers/greenhouse-gases); (d) "Carbon dioxide (CO_2) is the most significant greenhouse gas" (Britannica, https://www.britannica.com/science/greenhouse-gas). (All linked sites were accessed on 15 October 2023).

not expect a discernible change in the greenhouse effect on the surface. On the other hand, if the CO_2 contribution is indeed 19% (according to Schmidt et al., 2010, or even more, according to the dominant perception), one would expect that the observed change in the CO_2 concentration by 30% would have a discernible effect on the greenhouse effect. This will be told by the analysis of the observational data in the next sections.

3 Data

To investigate the two research questions posed in the introduction, we use eight data sets. The first is the earliest data set by Ångström (1916), and is followed by two data sets used by Brunt (1932) to propose his formula (Dines and Dines, 1927; Robitzsch, 1926). Then we have three data sets from 1950s, 1960s and 1970s (Stoll and Hardy, 1955; Swinbank, 1963; Aase and Idso, 1978), two of which were also used by Brutsaert (1991). Finally, we have two data sets of the 21st century (Carmona et al., 2014; Li et al., 2017), in which the atmospheric CO_2 concentration was much higher than in the other six data sets. The timeline of the observation periods of the eight data sets is shown in Figure 1, along with the global atmospheric CO_2 concentration.

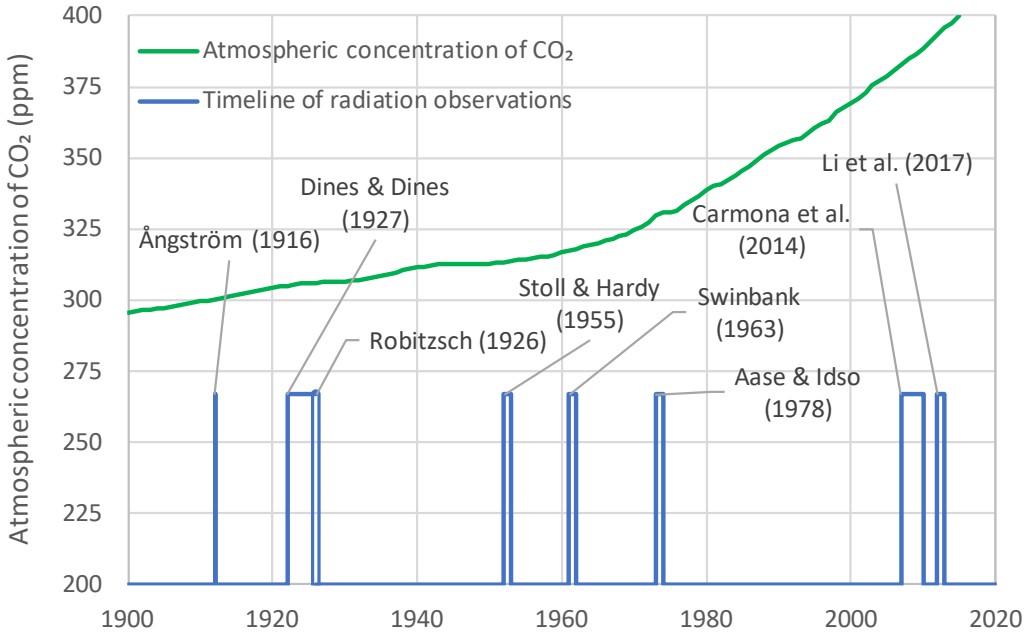

Figure 1 Timeline of the observation periods of the eight data sets (not to scale) and atmospheric CO_2 concentration according to Meinshausen et al. (2020). The CO_2 concentration data were downloaded from https://gmd.copernicus.org/articles/13/3571/2020/gmd-13-3571-2020-supplement.zip (accessed 25 August 2023); from the Excel file provided, the data from the column "CO2 ppm World" of the tabs "T2 – History Year 1750 to 2014" were retrieved.

The details of the data sets are given in Table 1. All data sets used are for clear sky conditions, which is most appropriate for our purpose as they exclude any interference from clouds. In addition to the eight data sets, the measurements by Goss and Brooks (1956), which were the basis of the FAO Penman-Monteith method, were also retrieved, by digitization of their Fig. 4, and analyzed, but they were not included in Table 1 as the information provided was not enough to make even a rough reconstruction.

Table 1 Details of the eight data sets used in the study and information about their retrieval.

No.	Observation year [CO_2 concentration], References	Notes
1	1912 [300 ppm] Ångström (1916)	This is probably the earliest record of systematic measurements of L_n (38 in total), conducted by Ångström in Bassour, Algeria, during July-September 1912. The results of all measurements are tabulated in his publication. No preprocessing of the data was necessary except converting to SI units.
2	1922–26 [305 ppm] Dines and Dines (1927), Brunt (1932, 1934), Swinbank (1963)	This data set was the basis of the celebrated Brunt's formula, equation (7). The publication by Dines and Dines (1927) contained tables with observations of radiation, including longwave, at Benson, Oxfordshire, UK, during 1922–26. The tables, which according to Raman (1935) contained 12 monthly mean values, were not found. However, it was possible to make a useful reconstruction of the data set (ranges rather than individual values), based on the facts that: (a) Brunt (1932, 1934) reports a near perfect correlation with respect to equation (7), with a correlation coefficient of 0.97; (b) Brunt (1932, 1934) gives the range of e at 7-14 hPa; (c) Swinbank's (1963) Figure 1, shows that L_a ranged between 237 and 326 W m^{-2}.
3	1926 [306 ppm] Robitzsch (1926), Brunt (1932, 1934), Pekeris (1934)	The original publication by Robitzsch (1926), which contained the measurements, was not found, but his measurements (11 grouped means from 1350 observations taken on 30 clear nights at Lindenberg) were reproduced in tabulated form by Brunt (1932, 1934) and Pekeris (1934). The tabulated data were used here after converting e from mmHg to hPa and recovering from the incorrect value of σ. Note though that Raman (1935) criticized the measurements as possibly influenced by systematic errors.
4	1952-53 [314 ppm] Stoll and Hardy (1955), Satterlund (1979)	The observations by Stoll and Hardy (1955) were made in Alaska and included some measurements for temperatures below 0 °C (down to –55 °C). Satterlund (1979; Fig. 1), followed by Brutsaert (1991; Fig. 6.7), provided these data in graphical form, including in the same convention followed here (see section 4), i.e., R_a calculated by the Brutsaert formula (equation (4)) vs. measured. Satterlund's figure was digitized, and the units were converted to SI, i.e., from langleys per day (Ly d^{-1} = cal cm^{-2} d^{-1}) to W m^{-2}.
5	1961-62 [318 ppm] Swinbank (1963)	Swinbank (1963) conducted and presented in tabulated form measurements in Australia during 1961-62, namely Aspendale and Kerang (86 and 5 measurements, respectively), as well as in the Indian Ocean (6 measurements in 1962). The tabulated data were ready for use after the necessary conversion to SI and recovering from the incorrect value of σ.
6	1973-74 [330 ppm] Aase and Idso (1978)	Aase and Idso (1978) conducted 65 measurements of longwave radiation at Sidney, Montana, USA (39 for temperatures above 0 °C, up to 27 °C, and 26 for temperatures below 0 °C, down to –30 °C). They provided the data in tables, from which they were taken here after conversion from Ly d^{-1} to W m^{-2}. In addition, Satterlund (1979; Fig. 1), followed by Brutsaert (1991; Fig. 6.7) provided these data in graphical form, which was crosschecked here and found to agree with the original data.

No.	Observation year [CO_2 concentration], References	Notes
7	2007-10 [385 ppm] Carmona et al. (2014)	Carmona et al. (2014) collected data from Tandil in the central-southeastern area of the Buenos Aires province, Argentina, at eight measurement campaigns. The measurements, taken over 840 days, included 3 443 hourly observations for clear sky conditions. As shown in their Fig. 2, L_a ranged between 200 and 450 W m^{-2}, T_a between 0 and 36 °C, and U between 0.1 and 1. The data are provided in graphical form, including in the same convention followed here (see section 4), i.e., R_a calculated by the Brutsaert formula (equation (4)) vs. measured. The related graph (Carmona et al., 2014, Fig. 3d) was digitized and the resulting values, which were originally in SI units, were ready for processing. It is expected that, because of the large size of the data set, some of the data points were not identified by the automatic digitization software, but the resulting cloud of points looks identical to that of the original graph.
8	2012-13 [395 ppm] Li et al. (2017)	Li et al. (2017) processed data from 7 SURFRAD (Surface Radiation Budget Network) stations over the contiguous USA covering different climatic conditions and an altitude span from 98 m to 1689 m. Their comprehensive data set includes 17 127 and 14 052 measurements for clear sky conditions for 2012 and 2013, respectively. Because of the huge number of data, their plots illustrate only a random subset to improve the readability of the figures. Therefore, recovering of the data by digitization of their figures was impossible. However, it was possible to make a representative reconstruction of the data set (ranges rather than individual values), based on the facts that: (a) Li et al. provide a near perfect recalibration of the Brutsaert formula (equation (4)) on their data, with relative bias –0.6% and root mean square error (RMSE) 4.5%; the recalibrated parameters are 1.168 and 1/9, replacing 1.24 and 1/7, respectively; (b) their Fig. 2 indicates that L_a ranged between 170 and 450 W m^{-2}; (c) their Table 1 provides interquartile ranges for T_a, L_a and U. Details of the reconstruction method are given in the Appendix A.

4 Results

The method we use to deal with the two research questions is simple, intuitive and graphical. Specifically, for each data set, we plot the calculated values of the downward longwave radiation L_a against the measured values. The plots for all eight data sets are shown in a single graph, Figure 2, which allows comparison of each data set with the equality line (calculated L_a equal to measured) as well as intercomparisons of the behaviours of the different data sets.

To find the calculated values we use a single reference model, namely Brutsaert's formula (equation (4)) with its original parameters, so that we have the same reference for all data sets. The reasons we chose this formula are the following: (a) it has a strong theoretical background; (b) in the study by Carmona et al. (2014), which among other things compared six methods (with their original parameters) against their set of observations (data set No. 7 in Table 1), it was ranked first in terms of performance; (c)

in the study by Guo et al. (2019), which compared five methods against ground measurements collected from 71 globally distributed sites, Brutsaert's formula was found to perform most uniformly with respect to altitude, having the largest coefficient of determination and lowest bias for high altitudes (> 3000 m, in which temperatures are lower); (d) it was deemed most relevant from a hydrological perspective (Wilfried Brutsaert is a hydrologist).

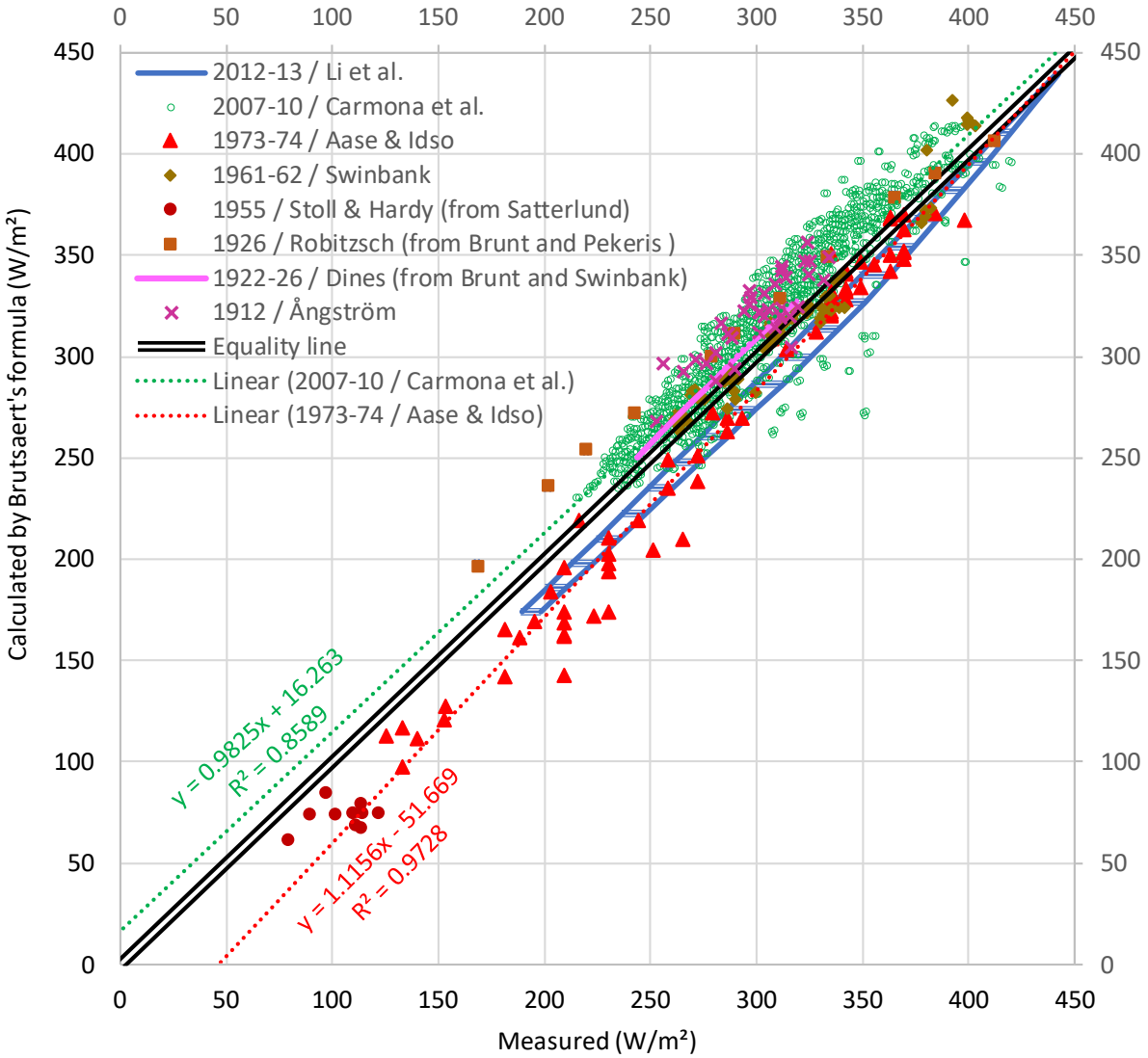

Figure 2 Plot of downward radiation of the atmosphere L_a calculated by the Brutsaert's formula with its original parameters (equation(4)), vs. measured L_a in all eight data sets. The points correspond to individual measurements, while the lines correspond to reconstructions by envelopes, as described in Table 1 and Appendix A. For the two data sets with the largest number of points, Aase and Idso (1978), and Carmona et al. (2014), the linear regression lines are also shown in the figure, along with their equations.

As seen in Figure 2, deviations from the equality line are visible and reflect: (a) differences in the local conditions as the data sets are observations from different parts of the world with different climates; (b) differences in the temperature lapse rate and water vapour profile at different times, even for the same location; (c) differences in aerosols in the atmosphere; (d) different measurement errors as the measuring devices have not been the same during the century-long period; and (e) imperfections of

Brutsaert's formula, which is based on several assumptions about the profiles of atmospheric variables—assumptions that may not always hold.

Actually, these very deviations constitute the conceptual basis of our method. Our aim is to investigate if they follow a systematic pattern, with respect to the time period of the measurements, and hence the CO_2 concentration, which has been systematically increasing in time. With reference to Figure 2, if a particular data set indicates enhanced greenhouse effect, the measured values would be higher than the calculated as the latter refer to the standard reference conditions. Therefore the data points will be aligned on the right of the equality line. In contrast, a weaker greenhouse effect will be seen as an alignment of the points on the left of the equality line. An enhancement of the greenhouse effect, due to increasing CO_2 concentration, through the years would be seen as a gradual displacement of the points from left to right with the progression of time.

However, the alignment of points of the different data sets does not show a gradual displacement from left to right. Rather it shows alternation in both directions. This means that the effect of the direct CO_2 emission at the surface is smaller than the side effects (listed as (a) to (e) above) causing the variability seen in Figure 2, and thus it is impossible to discern. For the two data sets with the larger number of points, Aase and Idso (1978) for 330 ppm CO_2, and Carmona et al. (2014) for 385 ppm CO_2, the linear regression lines have also been drawn in the figure. These are aligned opposite to the expectation of displacement, i.e., the older set lies on the right of the equality line and the newer on the left.

The measurements by Goss and Brooks (1956), which were the basis of the FAO Penman-Monteith method, were also analyzed, assuming several alternatives of U for the individual measurements, as there was no hint about the values of U or T in the paper. These alternatives resulted in large differences among them, yet in all of them the resulting points were aligned very close to the equality line (closer than most of the other data sets).

Generally, the Brutsaert's formula (equation (4)), which is mapped as the equality line in the figure, represents well all data sets, irrespective of time or CO_2 concentration. Additional factors such as those listed above (points (a) to (e)) can influence the greenhouse effect and thus cause differences in L_a, which are not captured by Brutsaert's formula or other ones.

A recent development has given water an additional role in this respect, which needs to be explored. Specifically, according to the standard assumptions, the concentration of H_2O above the troposphere is very small, of the order of 1 ppm (van Wijngaarden and Happer, 2020, Fig. 1), and hence its contribution to the greenhouse effect is negligible in the upper strata of the atmosphere. However, following the Hunga Tonga-Hunga Ha'apai submarine volcanic eruption (15 January 2022), an enormous H_2O injection was observed, which penetrated even into the mesosphere (Millán et al., 2022). As a result, H_2O concentrations in the upper strata of the atmosphere increased even by two orders of magnitude, up to the order of 100 ppm (Fig. 3 of Millán et al.), while in the stratosphere

the water mass increased by 13% relative to climatological levels (Khaykin et al., 2022). Millán et al. (2022) asserted that the excess stratospheric H_2O will persist for years, and may lead to surface warming due to the radiative forcing from the excess stratospheric H_2O.

5 Conclusions

The various sets of observations of Earth's atmospheric (longwave) radiation, spanning a period of a century, allow us to draw the following conclusions, which answer the research questions posed in the introduction:

1. The observed increase of the atmospheric CO_2 concentration from 300 to more than 400 ppm has not altered, in a discernible manner, the greenhouse effect, which remains dominated by the quantity of water vapour in the atmosphere.
2. The original formulae used in hydrological practice, in particular those related to the longwave radiation in the framework of evaporation calculations, remain valid and they do not need adaptation due to increased CO_2 concentration.

Apparently, this does not mean that further research is unnecessary, or that we have reached a "settled science" (a popular term, which may be interpreted as a euphemism for unsettled—cf. Koonin, 2021). Rather, the results of this study suggest that this further research should move the focus from the influence of carbon dioxide on climate to that of water. The recent incident of the submarine volcanic eruption, which caused enormous increase in the water concentration in the upper atmosphere, also highlights the necessity of studying the multifaceted role of water in the greenhouse effect.

Appendix A: Reconstruction of the Li et al. data set

Here we provide details for the reconstruction of the Li et al. (2017) data set for the purpose of comparing it with other data sets in Figure 2. We stress that this reconstruction is made in terms of envelope curves rather than individual values, which would be impossible. We interpreted the values resulting from the recalibrated parameters of Brutsaert's formula by Li et al. as measured values and we used the original parameters to find the calculated values of L_a. Obviously, this method does not capture the (likely random) error around Li et al.' recalibrated model (RMSE = 4.5%) and therefore the term envelope used is not meant in its precise sense, but after removing the error. Certainly however, the method captures the general tendency of the data.

If M is the "measured" atmospheric radiation, which corresponds to the calibrated parameters of Brutsaert's formula by Li et al. (2017) and C is the calculated atmospheric radiation, which corresponds to the standard Brutsaert's formula (equation (4)), then

$$M = 1.168\left(\frac{e_\mathrm{a}}{T_\mathrm{a}}\right)^{0.111}\sigma T_\mathrm{a}^4, \qquad C = 1.24\left(\frac{e_\mathrm{a}}{T_\mathrm{a}}\right)^{0.143}\sigma T_\mathrm{a}^4 \tag{A1}$$

where all quantities are expressed in the usual SI units (M and C in W m^{-2}, T_a in K, e_a in hPa). Assuming that the temperature T_a is specified, we eliminate e_a from these two equations and after algebraic manipulations we find

$$C = 1.015\, M^{1.287} (\sigma T_\mathrm{a}^4)^{-0.287} = 122 \frac{M^{1.287}}{T_\mathrm{a}^{1.148}} \tag{A2}$$

Alternatively, in the case that the relative humidity $U = e_\mathrm{a}/e(T_\mathrm{a})$ is specified, we have

$$M = 1.168 \left(\frac{U\, e(T_\mathrm{a})}{T_\mathrm{a}}\right)^{0.111} \sigma T_\mathrm{a}^4, \qquad C = 1.24 \left(\frac{U\, e(T_\mathrm{a})}{T_\mathrm{a}}\right)^{0.143} \sigma T_\mathrm{a}^4 \tag{A3}$$

These two equations again define a relationship between M and C, which however is implicit as it involves T_a, which is not specified. Nonetheless, the relationship between M and C is well defined and can be evaluated numerically.

Now, for the reconstruction we assumed L_a between 170 to 450 W m^{-2} and we constructed three envelope curves. For the upper curve shown in Figure 2 (the one that is almost a straight line) we assumed $U = 1$ (the upper physical limit) and used equations (A3) to determine C from M. The lower curve is in fact a concatenation of two parts. The low part corresponds to $U = 0.1$ (a reasonable minimum of relative humidity, smaller than the lower quantile in the most arid station, which is 0.134) and was again calculated using equations (A3). The high part corresponds to $T_\mathrm{a} = 30$ °C (a reasonable maximum of temperature, greater than the upper quantile in the most arid station, which is 27.1 °C) and was calculated using equation (A2).

To crosscheck the performance of the method of reconstruction by envelopes, we also applied it to the data set of Carmona et al. (2014), for which the entire data series is available. In addition, Carmona et al. also recalibrated Brutsaert's formula. The fitted parameters in both studies are shown in Table A1, along with the original parameters. The resulting envelopes for $U = 1$, $U = 0.1$ and $T_\mathrm{a} = 36$ °C (cf. Table 1, data set No 7) are shown in Figure A1, along with the individual points and, for comparison, to the envelopes for the Li et al. (2017) data set.

The envelopes for the Carmona et al. data set are well aligned with respect to the spread of the individual points (also plotted in the figure), but, as expected, they do not capture the entire scatter of the data. Nonetheless, they capture the tendency of the data to lie on the left of the equality line, while the reconstruction by Li et al. data lies on the right of the equality line. Interestingly, in both studies, both fitted parameters are smaller than in the original formula (Table A1) and one would intuitively expect a similar behaviour for the two data sets. However, the smaller value of b given by Li et al. results in opposite alignment of the envelopes with respect to the equality line (Figure A1).

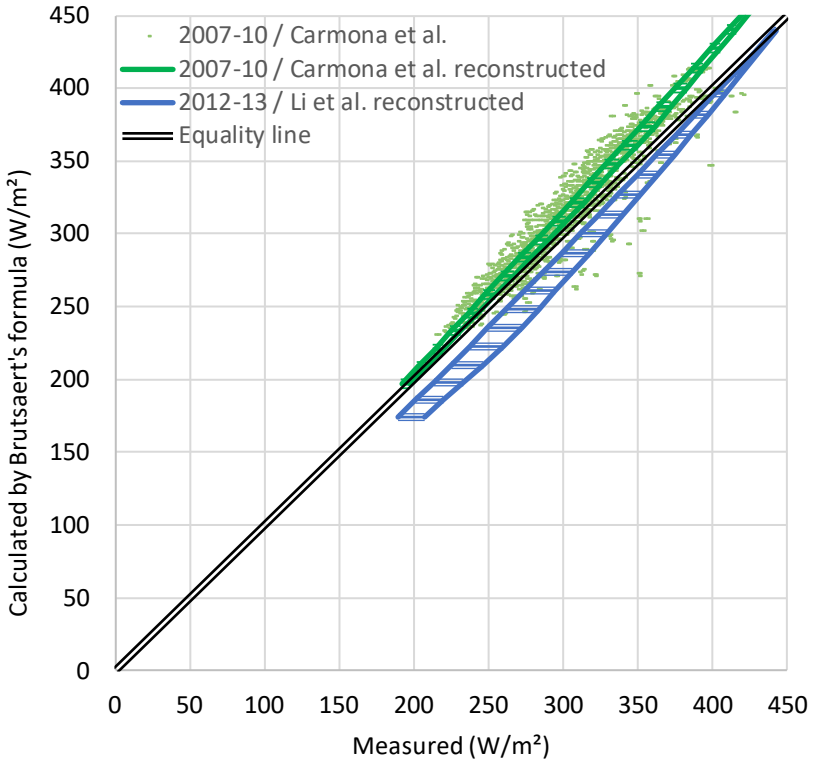

Figure A1 Cross-check of the reconstruction by envelopes based on the Carmona et al. (2014) data set, for which both the original points and the envelopes are shown. The reconstruction of the Li et al. (2017) is also shown for comparison. The graph is similar to that of Figure 2, showing the downward radiation of the atmosphere L_a calculated by the Brutsaert's formula with its original parameters (equation(4)), vs. measured or reconstructed L_a, but only for the two indicated sets. The points correspond to individual measurements, while the lines correspond to reconstructions by envelopes.

Table A1 Parameters a' and b' of a generalized Brutsaert's formula, $\varepsilon_a = a'(e_a/T_a)^{b'}$, as recalibrated by Carmona et al. (2014) and Li et al. (2017), and resulting relative RMSE of the fitting as reported in these publications.

	Original, Brutsaert (1975)	Carmona et al. (2014)	Li et al. (2017)
a'	1.24	1.11	1.168
b'	1/7 = 0.143	0.123	1/9 = 0.111
Relative RMSE		4%	4.5%

Appendix B: Radiation data in the top of the atmosphere

Harris et al. (2001) analysed the difference between the spectra of the outgoing longwave radiation of the Earth as measured by orbiting spacecraft in 1970 and 1997 and found differences in the spectra that point to long-term changes in atmospheric CO_2 and other gases related to the greenhouse effect. Their study considered the profiles of atmospheric temperature and water vapour, but did not give any hint about the relative contribution (and importance) of water vapour in comparison to these gases. In a macroscopic approach, as the one followed in this paper, it is the total longwave radiation flux, rather than the changes in the spectrum for particular frequencies, that counts most.

In the 21st century, radiation fluxes at the top of the atmosphere (TOA) have been estimated from satellite instruments. Specifically, this was done in the ongoing project Clouds and the Earth's Radiant Energy System (CERES), a part of NASA's Earth Observing

System, designed to measure both solar-reflected and Earth-emitted radiation from the TOA (in CERES defined at the altitude of 20 km) to the surface. The data are available online (https://ceres-tool.larc.nasa.gov/ord-tool/jsp/SSF1degEd41Selection.jsp) and were retrieved here as global averages for the monthly timescale and for their entire time span, which is from March 2000 to date for the Terra platform and from July 2002 to date for the Aqua platform.

The CERES TOA time series of longwave radiation fluxes for clear sky and all sky conditions are shown in Figure B1. The graphs also show the linear trends in the two cases, which were estimated for full years only (i.e., 23 years for the Terra platform and 20 years for the Aqua platform, leaving out a number of values exceeding a multiple of 12). The linear trends are very small. What is more interesting is that, while they are slightly negative for clear sky, they become slightly positive for all sky. This does not suggest that they are linked to CO_2 changes. Rather a link to atmospheric water is more likely, as it can be conjectured that they reflect changes in the temperature and water vapour profiles in the atmosphere and hence in the formation and vertical profiles of clouds.

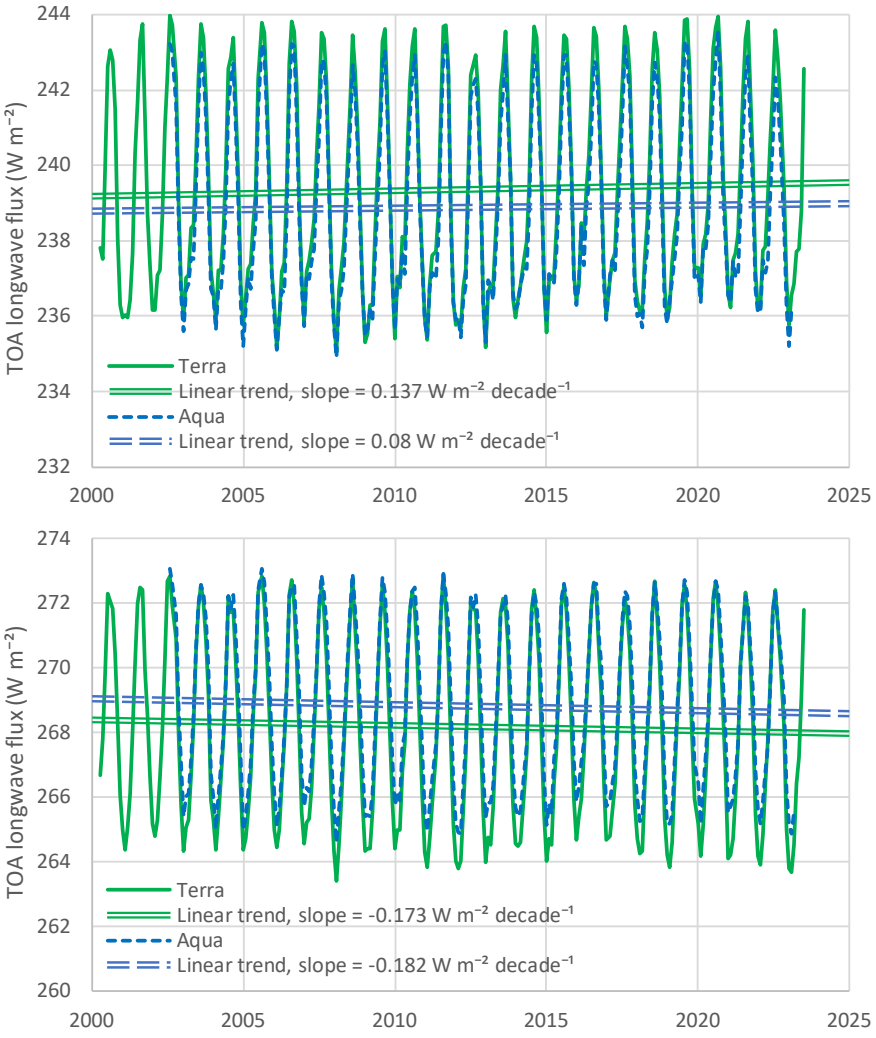

Figure B1 TOA time series of longwave radiation fluxes, as provided by NASA's CERES, along with linear trend, for (upper) all sky and (lower) clear sky.

To better assess a possible connection with water and, in particular, its form in clouds (which are opaque to shortwave radiation), we also examine the time series of shortwave radiation, whose temporal evolution is shown in Figure B2. The latter figure indicates a falling trend, which is clearer and a multiple of that of clear sky longwave radiation (Figure B1). Note that the decreasing trend in total outgoing TOA radiation flux is consistent with increased atmospheric temperature (decreased total outgoing radiation flux means that more energy is stored on Earth). From the numerical values of the trends in the two figures we find that the total decrease of outgoing radiation in the 23 years of data availability is (0.649 – 0.137) × 23 / 10 = 1.18 W/m^2. This is greater than the average imbalance (net absorbed energy) of the Earth, which, if calculated from the ocean heat content data, is about 0.4 W/m^2 (Koutsoyiannis, 2021). This decrease of outgoing radiation can hardly be attributed to increased CO_2 concentration. Rather, it can be related to water vapour and cloud profiles (and aerosols), given that other greenhouse gases such as CO_2 and CH_4 are well mixed.

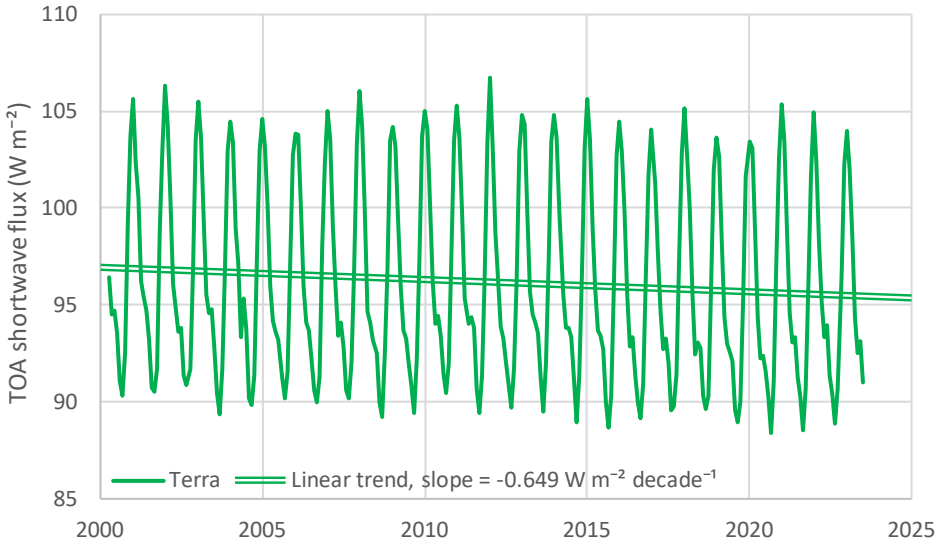

Figure B2 TOA time series of shortwave radiation flux, as provided by NASA's CERES, along with linear trend, for all sky.

On the other hand, in view of a general tendency to blame every phenomenon on the commonly assumed causal chain "fossil fuel emissions → CO_2 concentration rise → global warming", typically followed by an assertion of intensification of the hydrological cycle, it would not be a surprise if someone attributed the trends in Figure B1 and Figure B2 to some agent related to hydrological impacts of CO_2. However, as shown by Koutsoyiannis (2020) the IPCC assumptions on the intensification of the hydrological cycle due to CO_2 increase do not stand. Additional support on this is provided by Figure B3, where macroscopically no increasing trend (actually no trend at all) is seen in the atmospheric water content.

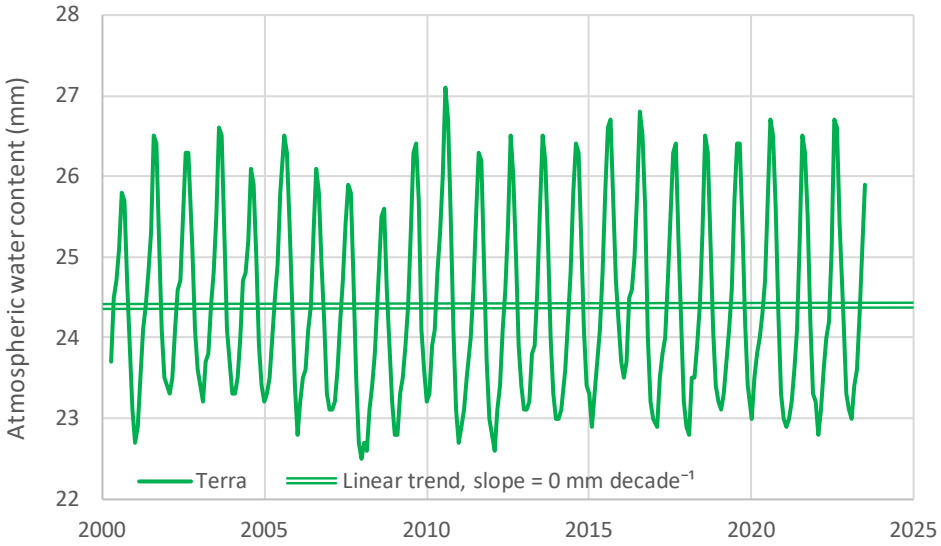

Figure B3 Atmospheric water content (precipitable water), as provided by NASA's CERES, along with linear trend (which in this case does not exist).

In contrast, as shown in Figure B4, decreasing trends appear in the total cloud area fraction. This is consistent with the above conjecture that changes in the shortwave radiation are related to changes in clouds; those in the longwave radiation are more difficult to explain and would need to study the profiles and geographical distribution of temperature, water vapour and clouds.

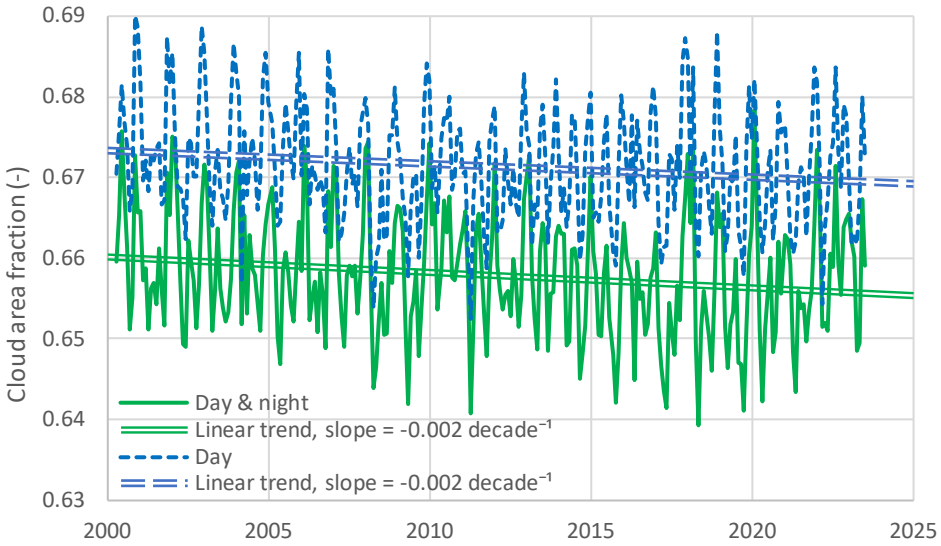

Figure B4 Total cloud area fraction, as provided by NASA's CERES, along with linear trends.

The above information cannot give conclusive results as the period of measurements is short and the processes too complex to allow for a simple interpretation. Yet all indications suggest that at the macroscopic level (global fluxes) the changes observed are related to water, while nothing related to CO_2 is discerned. This suggests a minor role of CO_2, as substantiated by van Wijngaarden and Happer (2020) and de Lange et al. (2022), and also expressed by Smirnov and Zhilyaev (2021) in their statement "water molecules in the atmosphere may be responsible for the observed heating of the Earth", which is in

"contradiction with the results of climatological models in the analysis of the Earth's greenhouse effect". The difference in the conclusions of Harris et al. (2001) on the one hand and the last three studies on the other hand, must rely in the fact the latter investigated the entire range of longwave frequencies from 0 to 2500 – 2600 cm^{-1}, while the former examined frequencies in the range of 700 to 1400 cm^{-1}. Interestingly, the frequencies left out in Harris et al. (2001) (i.e. < 700 cm^{-1} and > 1400 cm^{-1}) are precisely those fully dominated by water molecules.

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Funding information: This research received no funding but was conducted for scientific curiosity.

Data availability: This research uses no new data. The data sets used have been retrieved from the sources described in detail in the text.

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