



## Abstract

This study presents a new methodology, called temperature tagging. It keeps track of the contributions of individual processes to temperature within a climate model simulation. As a first step and as a test bed a simple box climate model is regarded. The model consists of an atmosphere, which absorbs and emits radiation and of a surface, which reflects, absorbs and emits radiation. The tagging methodology is used to investigate the impact of the atmosphere on surface temperature. Four processes are investigated in more detail and their contribution to the surface temperature quantified: (i) shortwave influx and shortwave atmospheric absorption (“sw”), (ii) longwave atmospheric absorption due to non-CO<sub>2</sub> greenhouse gases (“nC”), (iii) due to a base case CO<sub>2</sub> concentration (“bC”), and (iv) due to an enhanced CO<sub>2</sub> concentration (“eC”). The differential equation for the temperature in the box climate model is decomposed into four equations for the tagged temperatures. This method is applied to investigate the contribution of longwave absorption to the surface temperature (greenhouse effect), which is calculated to be 68 K. This estimate contrasts an alternative calculation of the greenhouse effect of slightly more than 30 K based on the difference of the surface temperature with and without an atmosphere. The difference of the two estimates is due to a shortwave cooling effect and a reduced contribution of the shortwave to the total downward flux: The shortwave absorption of the atmosphere results in a reduced net shortwave flux at the surface of 192 W m<sup>-2</sup>, leading to a cooling of the surface by 14 K. Introducing an atmosphere results in a downward longwave flux at the surface due to atmospheric absorption of 189 W m<sup>-2</sup>, which roughly equals the net shortwave flux of 192 W m<sup>-2</sup>. This longwave flux is a result of both, the radiation due to atmospheric temperatures and its longwave absorption. Hence the longwave absorption roughly accounts for 91 W m<sup>-2</sup> out of a total of 381 W m<sup>-2</sup> (roughly 25 %) and therefore accounts for a temperature of 68 K. In a second experiment, the CO<sub>2</sub> concentration is doubled, which leads to an increase in surface temperature of 1.2 K, resulting from a temperature increase due to CO<sub>2</sub> of 1.9 K, due to non-CO<sub>2</sub> greenhouse gases of 0.6 K and

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a cooling of 1.3 K due to a reduced importance of the solar heating for the surface and atmospheric temperatures. These two experiments show the feasibility of temperature tagging and its potential as a diagnostic for climate simulations.

## 1 Introduction

5 Whenever an extreme weather event happens, like the Russian heat wave in August 2010, the question is posed, whether this heat wave is a consequence of climate change. This questions has been addressed in various ways. Hansen et al. (2012) investigated the likelihood that such an event happened in a world without climate change and concluded that this event is a consequence of global warming since its “likelihood in the absence of global warming was exceedingly small.” On the other hand, Dole et al. (2011) showed that the Russian heat wave was primarily a consequence of a blocking event, a specific weather patttern not unusual for Russia. In ensemble simulations they showed that this blocking was not primarily caused by either greenhouse gases and sea surface temperatures and concluded that this specific weather event was solely caused by internal variability and that no anthropogenic influence was detected. The attribution techniques are different in both studies. However, what both studies have in common is that they compare on a statistical basis a world with climate change to a world without climate change (Hansen et al., 2012) or to a world with changed climate forcings (Dole et al., 2011). Here, a new methodology is introduced, which is not based on such statistical approaches, but deterministically attributes contributions of individual processes to the temperature: A temperature tagging methodology. Hence, with this method it is possible to answer the question: “How much of an observed heat wave is actually contributed by anthropogenic greenhouse gas emissions?”. It is a different question and not addressing the question, whether a heat wave would also have happened in a world without climate warming.

This methodology builds on tagging techniques developed in atmospheric chemistry (Grewe et al., 2010). These techniques enable to fully decompose a non-linear system

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and attribute chemical concentrations to emissions of gases. The principles of this technique are applied in this paper to the contribution of atmospheric absorption of radiation to the temperature in a very simple box climate model. It shows the feasibility and the potential of such a technique and should be seen as a first step towards a full temperature tagging method in climate or weather prediction models, with which the question of the contribution of anthropogenic greenhouse gas emissions to the temperature during an individual whether event can be answered.

The temperature tagging method in a simple climate box model is applied to investigate the contribution of atmospheric longwave absorption (greenhouse effect) to surface temperature and the temperature contribution from a doubling of the CO<sub>2</sub> concentration.

In the next section, basic definitions, like tagging categories are defined (Sect. 2.1), the simple climate box model is introduced in Sect. 2.2, the temperature tagging methodology is presented in Sect. 2.3, and the experimental set-up is presented in Sect. 2.4. Results are presented in Sect. 3, first on the contribution of the greenhouse effect on the surface temperature (Sect. 3.1) and second the contribution of a doubling of the CO<sub>2</sub> concentration to the surface temperature (Sect. 3.2). A very brief outlook on how this methodology can be applied to a comprehensive climate model is given in Sect. 4, followed by conclusions.

## 2 Methodology

In this section a very simple climate box model is presented (Sect. 2.2), as it can be found in many meteorology text books (e.g. Andrews, 2010), used to test the idea of a temperature tagging (Sect. 2.3). This is a method to track changes in a model simulation induced by any regarded process, e.g. temperature changes induced by greenhouse gases. Depending on the scientific question there might be many possibilities to define temperature categories. Therefore Sect. 2.1 starts with the definition of the scientific question and the associated tagging categories.

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For this kind of tagging two aspects are important to be mentioned. Tagging has to be complete but not necessarily material. Completeness means that categories have to be defined in a way that the regarded physical quantity (here temperature) is totally split into individual parts without any remaining parts. Another way of looking at it is that the quantity is split into contributions and the sum of the contributions is again 100 %. Note that individual contributions might also be negative, e.g. for a cooling process. Hence, the tagged temperatures cannot be seen as physical temperatures, but as contributions to the temperature.

The second aspect is that tagging has mainly been used for chemical simulations, i.e. putting a tag to a material quantity, like ozone concentrations. This facilitates the tagging concept, but is physically or mathematically not necessary. Tags can be viewed as contributions of a process to any regarded quantity.

This tagging concept leads to a two-step approach within one simulated model timestep. First the normal physical system is solved (here described in Sect. 2.2) and afterwards a second set of differential equations is solved for the tagged quantities (Sect. 2.3).

## 2.1 Definition of tagging categories

The underlying scientific question, addressed here, is: “How large is the contribution of the absorption of longwave radiation caused by greenhouse gases to the surface temperature?”. Therefore, four different effects are of interest, which affect temperatures (Table 2). The first is the effect of the shortwave solar input and shortwave atmospheric absorption, tagged with the name “sw”. The transmitted solar radiation heats the surface and contributes thereby to the emission of longwave radiation, which in turn affects the atmospheric temperature by longwave absorption and feeds back to the surface temperature.

The other effects are related to the greenhouse effect, i.e. the longwave atmospheric absorption of radiation due to greenhouse gases and again their effects on surface and atmospheric temperatures. In order to study individual greenhouse gases, 3 groups are

defined: all non-CO<sub>2</sub> greenhouse gases, called “nC”, a base CO<sub>2</sub> concentration (here: 360 ppm), called “bC”, and an enhanced CO<sub>2</sub> concentration (“eC”) of either 0 ppm or 360 ppm, latter representing a CO<sub>2</sub> doubling.

This leads to four tagging categories: “sw”, “nC”, “bC”, “eC” (see also Table 2), which are physically defined in the following two sections.

## 2.2 A very simple climate model as a test bed

The basic concept of this climate box model is presented in Fig. 1. It consists of two domains: The first domain is the atmosphere with a temperature  $T_a$  and which absorbs radiation in the shortwave ( $a_s$ ) and longwave ( $a_l$ ). The second domain is the surface, characterised by the temperature  $T_s$  and the albedo ( $A$ ). Table 1 gives an overview on the chosen parameters.

At the top of the atmosphere (toa) the downward shortwave flux equals the solar radiation:

$${}^{\text{toa}}F_{\text{sw}}^{\downarrow} = S = 342 \frac{\text{W}}{\text{m}^2} \quad (1)$$

The atmosphere absorbs shortwave radiation and with the assumption of no reflection or scattering the downward flux at the surface (sfc) is

$${}^{\text{sfc}}F_{\text{sw}}^{\downarrow} = (1 - a_s) {}^{\text{toa}}F_{\text{sw}}^{\downarrow}. \quad (2)$$

A part of this radiation is reflected and the resulting upward directed flux is partly absorbed by the atmosphere before leaving the atmosphere:

$${}^{\text{sfc}}F_{\text{sw}}^{\uparrow} = A {}^{\text{sfc}}F_{\text{sw}}^{\downarrow} \quad (3)$$

$${}^{\text{toa}}F_{\text{sw}}^{\uparrow} = (1 - a_s) {}^{\text{sfc}}F_{\text{sw}}^{\uparrow}. \quad (4)$$

The temperature of the surface leads to an upward directed longwave radiation according to the Stefan-Boltzmann law:

$${}^{\text{sfc}}F_{\text{lw}}^{\uparrow} = \epsilon \sigma T_s^4. \quad (5)$$

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By using the Kirchoff's law, which states that the longwave emission equals the absorption, the atmosphere radiates with a longwave flux  $a_l\sigma T_a^4$ , which equals the downward longwave radiation at the surface:

$${}^{\text{sfc}}F_{\text{lw}}^{\downarrow} = a_l\sigma T_a^4, \quad (6)$$

5 and contributes to the longwave outgoing radiation in addition to the transmittance of the upward directed longwave surface flux:

$${}^{\text{toa}}F_{\text{lw}}^{\uparrow} = (1 - a_l) {}^{\text{sfc}}F_{\text{lw}}^{\uparrow} + a_l\sigma T_a^4. \quad (7)$$

In steady-state the fluxes are balanced. Hence the temperatures for the surface and the atmosphere can be deduced directly from:

$$10 \quad {}^{\text{toa}}F_{\text{net}} = -{}^{\text{toa}}F_{\text{lw}}^{\uparrow} + {}^{\text{toa}}F_{\text{sw}}^{\downarrow} - {}^{\text{toa}}F_{\text{sw}}^{\uparrow} \quad (8)$$

$$= 0 \quad (9)$$

and

$${}^{\text{sfc}}F_{\text{net}} = -{}^{\text{sfc}}F_{\text{lw}}^{\uparrow} - {}^{\text{sfc}}F_{\text{sw}}^{\uparrow} + {}^{\text{sfc}}F_{\text{lw}}^{\downarrow} + {}^{\text{sfc}}F_{\text{sw}}^{\downarrow} \quad (10)$$

$$= 0, \quad (11)$$

15 which gives:

$$T_s = \sqrt[4]{\frac{S(1 - (1 - a_s)(A(2 - a_s) - 1))}{(2 - a_l)\sigma}} \approx 286 \text{ K and} \quad (12)$$

$$T_a = \sqrt[4]{S - (1 - a_l)\sigma T_s^4 - A(1 - a_s)^2 S} \approx 255 \text{ K.} \quad (13)$$

The classical way to estimate the temperature caused by the greenhouse effect is to assume no atmosphere (i.e.  $a_l = 0$  and  $a_s = 0$ ), which results in a surface temperature (Eq. 12) of around 255 K. The difference of 31 K is then the effect of the atmosphere, i.e., the greenhouse effect.

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For non steady-state situations any flux imbalance leads to temperature changes following:

$$\frac{\partial T_a}{\partial t} = \frac{1}{c_p^{\text{air}} \rho^{\text{air}}} \frac{F_{\text{net}}^{\text{toa}} - F_{\text{net}}^{\text{sfc}}}{Z^{\text{air}}} \quad \text{and} \quad (14)$$

$$\frac{\partial T_s}{\partial t} = \frac{1}{c_p^{\text{sfc}} \rho^{\text{sfc}}} \frac{F_{\text{net}}^{\text{sfc}}}{Z^{\text{sfc}}}. \quad (15)$$

5 The respective parameters are set to represent realistic values and to give a 30 yr response time of this simple climate system. Changes in the concentration of carbon dioxide lead to a change in the absorption of longwave radiation. Therefore the absorption  $a_1$  is parameterised in a very simplified way to allow principle studies on the greenhouse effect and on a doubling of  $\text{CO}_2$ . The greenhouse gases are grouped (see  
 10 also Sect. 2.1) into non-carbon dioxide (“nC”; e.g. water vapour, methane, nitrous oxide), base case carbon dioxide (“bC”, here with a mixing ratio  $C_{\text{CO}_2}^{\text{bC}} = 360$  ppmv) and enhanced carbon dioxide (“eC”, e.g.  $C_{\text{CO}_2}^{\text{eC}} = 360$  ppmv for a doubling experiment). The absorptions are then defined as:

$$a_1 = a_1^{\text{sw}} + a_1^{\text{nC}} + a_1^{\text{bC}} + a_1^{\text{eC}}, \quad \text{with} \quad (16)$$

$$15 \quad a_1^{\text{sw}} = 0. \quad (\text{without atmosphere}) \quad (17)$$

$$a_1^{\text{nC}} = 0.61 \quad (18)$$

$$a_1^{\text{C}} = 0.2 - 0.04 \frac{360 \text{ ppm}}{C_{\text{CO}_2}} \quad (19)$$

$$a_1^{\text{bC}} = a_1^{\text{C}} \frac{C_{\text{CO}_2}^{\text{bC}}}{C_{\text{CO}_2}} \quad (20)$$

$$a_1^{\text{eC}} = a_1^{\text{C}} \frac{C_{\text{CO}_2}^{\text{eC}}}{C_{\text{CO}_2}} \quad (21)$$

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The absorption with respect to CO<sub>2</sub> depends on the total concentration  $C_{\text{CO}_2} = C_{\text{CO}_2}^{\text{bc}} + C_{\text{CO}_2}^{\text{ec}}$  (see also eq. 19) the individual contributions are then relative to the CO<sub>2</sub> contribution.

An instantaneous doubling of the carbon dioxide concentration (from 360 to 720 ppmv) results in an increase in the longwave absorption from 0.77 to 0.79. The resulting instantaneous radiative forcing ( $^{\text{toa}}F_{\text{net}}$ ) according to Eq. (8) is  $3.68 \text{ W m}^{-2}$  leading to a steady-state temperature increase of 3.1 K and hence a climate sensitivity of  $0.3 \text{ K (W m}^{-2})^{-1}$ . Applying the method of Gregory (Gregory et al., 2004) results in the identical value.

## 2.3 Temperature tagging

The temperature tagging aims at tracking temperature changes caused by any change in the climate system in every timestep of a simulation. In Sect. 2.1 the individual temperature categories are motivated. Here they are physically defined.

In the simple climate box model (Sect. 2.2) changes to the climate-system are introduced via changes in the absorption, which are parameterised depending on the carbon dioxide concentration (Eq. 16). That means that the individual contributions  $T_a^{\text{sw}}, T_a^{\text{nC}}, T_a^{\text{bC}}, T_a^{\text{eC}}$  to the total temperature  $T_a$  (and  $T_s$  in analogy) are dependent on and directly linked to the respective absorptions (Table 2).

The temperature equations are following Eqs. (14) and (15):

$$\frac{\partial T_a^i}{\partial t} = \frac{1}{c_p^{\text{air}} \rho^{\text{air}}} \frac{{}^{\text{toa}}F_{\text{net}}^i - {}^{\text{sfc}}F_{\text{net}}^i}{Z^{\text{air}}} \quad \text{and} \quad (22)$$

$$\frac{\partial T_s^i}{\partial t} = \frac{1}{c_p^{\text{sfc}} \rho^{\text{sfc}}} \frac{{}^{\text{sfc}}F_{\text{net}}^i}{Z^{\text{sfc}}}, \quad (23)$$

with  $i \in \{\text{sw}, \text{nC}, \text{bC}, \text{eC}\}$ . Hence the heart of the temperature tagging is to derive the appropriate fluxes associated with the absorption of the individual components.

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In this set-up, all shortwave fluxes are attributed to one component, only (“sw”, Table 2). Therefore, the tagged shortwave fluxes are straight forward:

$$\text{toa } F_{\text{sw}}^{\uparrow \text{SW}} = \text{toa } F_{\text{sw}}^{\uparrow} \quad (24)$$

$$\text{toa } F_{\text{sw}}^{\downarrow \text{SW}} = \text{toa } F_{\text{sw}}^{\downarrow} \quad (25)$$

$$\text{sfc } F_{\text{sw}}^{\uparrow \text{SW}} = \text{sfc } F_{\text{sw}}^{\uparrow} \quad (26)$$

$$\text{sfc } F_{\text{sw}}^{\downarrow \text{SW}} = \text{sfc } F_{\text{sw}}^{\downarrow} \quad (27)$$

whereas for all other categories the shortwave fluxes are zero.

The only non-trivial part of separation of fluxes into their contributions are the longwave components. To illustrate the main idea, which is following the tagging principle for chemical reactions (Grewe et al., 2010), the term  $(1 - a_1)^{\text{sfc}} F_{\text{lw}}^{\uparrow}$  as part of the flux  $\text{toa } F_{\text{lw}}^{\uparrow}$  is considered in more detail in the following. This is a typical example of a non-linear interaction of multiple categories, where both, the longwave absorption and the flux  $\text{sfc } F_{\text{lw}}^{\uparrow}$  have contributions from individual categories. This term can be written as:

$$(1 - a_1)^{\text{sfc}} F_{\text{lw}}^{\uparrow} = (1 - \sum_i a_1^i) \sum_i \text{sfc } F_{\text{lw}}^{\uparrow i} \quad (28)$$

$$= \sum_i \text{sfc } F_{\text{lw}}^{\uparrow i} + \sum_{i,j} a_1^i \text{sfc } F_{\text{lw}}^{\uparrow j} \quad (29)$$

$$= \sum_i (1 - a_1^i) \text{sfc } F_{\text{lw}}^{\uparrow i} - \sum_{i \neq j} a_1^i \text{sfc } F_{\text{lw}}^{\uparrow j} \quad (30)$$

$$= \sum_i (1 - a_1^i) \text{sfc } F_{\text{lw}}^{\uparrow i} - \frac{1}{2} \sum_{i \neq j} a_1^i \text{sfc } F_{\text{lw}}^{\uparrow j} - \frac{1}{2} \sum_{i \neq j} a_1^i \text{sfc } F_{\text{lw}}^{\uparrow j} \quad (31)$$

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$$= \sum_i \left[ (1 - a_l^i) \text{sfc} F_{lw}^{\uparrow i} - \frac{1}{2} a_l^i (\text{sfc} F_{lw}^{\uparrow} - \text{sfc} F_{lw}^{\uparrow i}) - \frac{1}{2} (a_l - a_l^i) \text{sfc} F_{lw}^{\uparrow i} \right] \quad (32)$$

$$= \sum_i \left[ \text{sfc} F_{lw}^{\uparrow i} - \frac{1}{2} \left( a_l^i \text{sfc} F_{lw}^{\uparrow} + a_l \text{sfc} F_{lw}^{\uparrow i} \right) \right] \quad (33)$$

The non-linearity in this term arises from  $\sum a_j F_j$ , the second term in Eq. (30), which describes the flux of category  $j$  absorbed by category  $i$ . For example, what happens when the radiation emitted at the surface associated with the “sw” radiation is absorbed in the atmosphere by the enhanced CO<sub>2</sub> concentration (“eC”)? The argument is that both processes are equally important and hence contribute equally by 50 % to the fluxes  $\text{sfc} F_{lw}^{\uparrow i}$  and  $\text{sfc} F_{lw}^{\uparrow}$  (Eq. 31). Note that this is the basic concept of this methodology. Whenever two processes or quantities are necessarily required then they are equally important and contribute by 50 % to non-linearities. Hence, we find a decomposition of the left hand side of Eq. (28) and can define the contribution of category  $i$  to the flux  $(1 - a_l) \text{sfc} F_{lw}^{\uparrow}$  by

$$(1 - a_l) \text{sfc} F_{lw}^{\uparrow} = \sum_i \underbrace{\text{sfc} F_{lw}^{\uparrow i}}_{\text{flux } i} - \underbrace{\frac{1}{2} a_l^i \text{sfc} F_{lw}^{\uparrow}}_{\text{total flux absorbed by } i} - \underbrace{\frac{1}{2} a_l \text{sfc} F_{lw}^{\uparrow i}}_{\text{flux } i \text{ absorbed by all}} \quad (34)$$

or alternatively

$$= \sum_i \text{sfc} F_{lw}^{\uparrow i} - \frac{1}{2} a_l \text{sfc} F_{lw}^{\uparrow} \left( \frac{a_l^i}{a_l} + \frac{\text{sfc} F_{lw}^{\uparrow i}}{\text{sfc} F_{lw}^{\uparrow}} \right) \quad (35)$$

The contribution from category  $i$  to the longwave flux at the top of the atmosphere resulting from the emission (Eq. 34) at the surface consist of 3 parts: (1) the contribution

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from category  $i$  to the emitted flux, i.e.  $^{\text{sfc}}F_{\text{lw}}^{\uparrow i}$ , (2) the reduction of this flux by the contribution of category  $i$  to the absorption and (3) the reduction of this flux by the total absorption of flux  $i$ . The factor  $1/2$  means that the other  $1/2$  of this contribution is assigned to another category (see also above). The terms (2) and (3) both include the

contribution  $a_1^{\text{sfc}}F_{\text{lw}}^{\uparrow i}$  by 50 % and hence provide together the total.

The alternative formulation (Eq. 35) shows that the tagged absorbed flux can also be written as a fraction of the total absorbed flux  $a_1^{\text{sfc}}F_{\text{lw}}^{\uparrow}$ . The fraction is the mean of the relative contribution of the tagged absorption and the tagged longwave upward flux at the surface.

The top of the atmosphere longwave flux  $^{\text{toa}}F_{\text{lw}}^{\uparrow}$  consists of two parts (see Eq. 7). The transmittance has just been discussed above and the flux emitted by the atmosphere is:

$$\frac{T_a^i}{T_a} a_1 \sigma T_a^4 = a_1 \sigma T_a^3 T_a^i. \quad (36)$$

Here the basic idea is that the total temperature is relevant for the radiation emission and that no contribution is more important than the other, which directly leads to a linear decomposition according to the individual contributions  $T_a^i$  to the atmospheric temperature  $T_a$ . Note that this is a different approach than considered in a perturbation approach, where a temperature change would be diagnosed for the case that the absorption is changed. This would give a temperature sensitivity, whereas the tagging provides consistent temperature contributions. This is often confused, but has to be distinguished, since both approaches differ significantly and address different questions (Grewe et al., 2010, 2012).

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Putting all this together, the tagged fluxes are

$$\text{sfc } F_{\text{lw}}^{\uparrow i} = \frac{T_{\text{s}}^i}{T_{\text{s}}} \text{sfc } F_{\text{lw}}^{\uparrow} \quad (37)$$

$$\text{sfc } F_{\text{lw}}^{\downarrow i} = \text{sfc } F_{\text{lw}}^{\downarrow} \frac{1}{2} \left( \frac{T_{\text{a}}^i}{T_{\text{a}}} + \frac{a_{\text{l}}^i}{a_{\text{l}}} \right) \quad (38)$$

$$\text{toa } F_{\text{lw}}^{\uparrow i} = \text{sfc } F_{\text{lw}}^{\uparrow i} - \frac{1}{2} a_{\text{l}}^i \text{sfc } F_{\text{lw}}^{\uparrow} \left( \frac{a_{\text{l}}^i}{a_{\text{l}}} + \frac{\text{sfc } F_{\text{lw}}^{\uparrow i}}{\text{sfc } F_{\text{lw}}^{\uparrow}} \right) + \text{sfc } F_{\text{lw}}^{\downarrow} \frac{1}{2} \left( \frac{T_{\text{a}}^i}{T_{\text{a}}} + \frac{a_{\text{l}}^i}{a_{\text{l}}} \right) \quad (39)$$

5 By definition, the sum of all tagged fluxes equals the total flux and hence the sum of the tagged temperatures equals the total temperature:

$$\sum_i T_{\text{a}}^i = T_{\text{a}} \quad \text{and} \quad (40)$$

$$\sum_i T_{\text{s}}^i = T_{\text{s}}. \quad (41)$$

10 This means that the definition of the categories leads to a complete decomposition of the temperature as required.

## 2.4 Experimental set-up

The climate box model is formulated in Fortran90, with a timestep of 1 day. The temperatures are initialised by the steady-state values and the tagged temperatures by equal shares of the respective temperatures. A spin-up of 1000 yr is regarded, before the actual experiment starts with a simulation length of 550 yr to again obtain an equilibrium situation.

15 For the greenhouse effect experiments, the absorption of the atmosphere is varied in steps of  $\alpha = 0.0, 0.1, \dots, 0.9, 1.0$ , i.e. a shortwave and longwave absorption of  $\alpha a_{\text{s}}$

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and  $\alpha a_1$  is taken into account. ( $a_1^{\text{bC}} = 0.16$  and  $a_1^{\text{eC}} = 0$ ).  $\alpha = 0$  and  $\alpha = 1$  refers to “no atmosphere” and “full atmosphere”, respectively.

For the CO<sub>2</sub> doubling experiments,  $C_{\text{CO}_2}^{\text{eC}}$  is set to 360 ppmv ( $a_1^{\text{eC}} = a_1^{\text{bC}} = 0.09$ ) after the spin-up period.

## 3 Results

### 3.1 The greenhouse effect

In Sect. 2.2 the greenhouse effect is defined as the difference in surface temperature for the cases with and without an atmosphere. Another explanation is given by IPCC (2007): “Greenhouse gases effectively absorb thermal infrared radiation, emitted by the Earth’s surface, by the atmosphere itself due to the same gases, and by clouds. Atmospheric radiation is emitted to all sides, including downward to the Earth’s surface. Thus, greenhouse gases trap heat within the surface-troposphere system. This is called the greenhouse effect.”

These are two definitions, which basically address the same physical properties of the atmosphere. However, they are inconsistent as will be shown in the following.

Figure 2a shows the increase in surface temperature when continuously increasing the atmospheric absorption (both sw and lw) from no atmosphere to the full atmosphere, reaching roughly 30 K, consistent with, e.g. Andrews (2010). Figure 2b shows the contributions to the surface temperature from the shortwave component (red), non-CO<sub>2</sub> greenhouse gases (green) and from CO<sub>2</sub> (blue). The contribution from greenhouse gases (red and blue) is 68 K and hence a factor of two larger than the classical calculation of the greenhouse effect (Fig. 2a).

One major difference is the different handling of the shortwave absorption of the atmosphere. In Fig. 2a the transition from no to a full atmosphere includes an increase in both the shortwave absorption and the longwave absorption, whereas in Fig. 2b, the temperature associated with greenhouse gases ( $T^{\text{nC}} + T^{\text{bC}} + T^{\text{eC}}$ ) is solely attributed

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to longwave absorption. Switching from no to a full atmosphere leads to an increase in the shortwave absorption and consequently to a decrease of the shortwave downward and upward radiation at the surface (Fig. 3a). The net surface shortwave radiation ( ${}^{\text{sfc}}F_{\text{sw}}^{\downarrow} - {}^{\text{sfc}}F_{\text{sw}}^{\uparrow}$ ) is decreasing by around  $50 \text{ W m}^{-2}$ . This decrease in the flux leads to a decrease of the surface temperature by roughly 14 K (Fig. 2b solid line). It can be easily determined by considering a surface flux balance for an atmosphere without a longwave absorption ( $a_l = 0$ ), but with a shortwave absorption, which gives a temperature of  $\sqrt[4]{(1 - A(1 - a_s)^2)S/\sigma}$ .

This shortwave cooling effect is largely compensated by an increased longwave absorption of the atmosphere. This can be shown in a simple experiment, where the longwave absorption is constant ( $a_l = 0.77$ ) and only the shortwave absorption varies (Fig. 2b, dashed line). The compensating effect leads to an increase in atmospheric temperatures and an increase in the longwave downward flux at the surface of more than  $200 \text{ W m}^{-2}$  (Fig. 3a, blue dotted line). The net longwave warming effect at the surface is largely over-compensating the shortwave cooling effect, leading to a positive total flux and an increase of the surface temperature (Fig. 4).

Therefore, during the transition from no atmosphere to a full atmosphere, the temperature associated with the shortwave radiation ( $T_s^{\text{sw}}$ ) decreases, since the shortwave cooling is, different to the surface temperature ( $T_s$ ), not over-compensated by longwave radiation (Figs. 3b and 4). The upward longwave radiation at the surface is attributed to the category “sw” by 100 % in the case of no atmosphere. Hence also the upward longwave flux at the top of the atmosphere and the downward flux at the surface are fully attributed to the category “sw”. The greenhouse gases (categories “nC” and “bC”) absorb longwave radiation and contribute considerably to the longwave atmospheric radiation leading to an increase in temperature of 68 K. Since the processes are identical for the categories “nC” and “bC” the results differ only in magnitude (Figs. 3c, d and 4).

Figure 5 summarises the results by comparing the net shortwave flux and the downward longwave flux. Their sum has to be balanced by the emitted longwave radiation

at the surface temperature (Eq. 11). Without an atmosphere (left) the surface temperature (255 K) is determined by the net shortwave radiation (see also above). With an atmosphere, which absorbs only in the shortwave, this shortwave flux is reduced and leads to a surface temperature of 241 K. With an atmosphere (second right) the longwave downward flux is adding to the net shortwave flux by approximately the same amount and increases the surface temperature to 286 K. Hence the contribution of the net shortwave flux and longwave flux to the surface temperature are 144 K and 142 K, respectively. However this is not yet the temperature associated with the shortwave and longwave processes, since a large fraction of the longwave radiation, which is emitted by the surface is actually caused by shortwave radiation. This radiation is absorbed by the atmosphere and contributes to the longwave downward radiation. Hence the total longwave downward radiation of  $189 \text{ W m}^{-2}$  has a contribution of  $98 \text{ W m}^{-2}$  due to the radiation emitted by the surface (the part, which was heated by solar radiation) and a second contribution of  $91 \text{ W m}^{-2}$  due to absorption of longwave radiation by greenhouse gases (right part of Fig. 5). This attribution is shown in more detail in Fig. 6. The temperature increases highly non-linearly (4th square root) with the surface flux. In the situation of an atmosphere absorbing only in the shortwave the surface flux of  $192 \text{ W m}^{-2}$  leads to a temperature of 241 K (red). The temperature to flux ratio (solid line) is much lower in the situation of a full atmosphere and the  $381 \text{ W m}^{-2}$  lead to a temperature of 286 K. Due to this lower ratio, the flux of  $192 \text{ W m}^{-2}$  leads to a much lower contribution to the surface temperature of 144 K (red) in the situation of a full atmosphere. The flux originating from the solar heating of the surface and the subsequent longwave radiation and atmospheric absorption amounts to  $98 \text{ W m}^{-2}$  and thus leading to 74 K (green). The remaining greenhouse effect, the absorption of longwave radiation due to greenhouse gases accounts for a flux of  $91 \text{ W m}^{-2}$  and hence 68 K (blue).

Therefore, the two different ways to calculate the contribution of the greenhouse effect to the surface temperature of 31 K and 68 K largely differ. The surface temperature without an atmosphere is 255 K (Fig. 5). The surface fluxes are reduced, if only an atmosphere is considered, which only absorbs in the shortwave. The surface temperature

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decreases by 14 K to 241 K. The surface flux increases by a factor of two because of the longwave absorption, if a full atmosphere is regarded. This leads to a reduction of the contribution of the shortwave influx to the surface temperature from 100 % to 75 %, when changing from an atmosphere which only absorbs in the shortwave to a full atmosphere. This contribution of roughly 75 %, which represents a flux of  $290 \text{ W m}^{-2}$ , leads to a temperature  $T_s^{\text{SW}}$  of 218 K and a temperature associated to the greenhouse effect of  $T_s^{\text{nC}} + T_s^{\text{bC}} = 68 \text{ K}$ .

### 3.2 Effects of a CO<sub>2</sub> doubling

Figure 7 shows the top of the atmosphere flux, surface and temperature changes for the CO<sub>2</sub> doubling experiment. After the spin-up time, the radiation flux responds immediately to the change in the longwave absorption. The atmospheric temperature shows an immediate drop. This drop is caused by the different response times of the atmosphere and the surface. Shortly after the change in the absorption, the surface fluxes are almost unaffected, but the atmospheric temperatures reacts quickly. Hence the atmospheric longwave emission increases, leading to a radiative cooling. Then the surface temperature slowly increases due to the increasing flux emitted from the atmosphere caused by the increased absorption, which in turn also leads to a warming of the atmosphere.

The contribution of the greenhouse gases to the surface temperature is shown in Fig. 8. The largest contribution with 218 K is arising from the incoming shortwave radiation heating the surface ( $T_s^{\text{SW}}$ ) as already discussed in Sect. 3.1. The non-CO<sub>2</sub> greenhouse gases contribute with additional 55 K ( $T_s^{\text{nC}}$ ) and the background CO<sub>2</sub> concentration with around 15 K ( $T_s^{\text{bC}}$ ). The change in CO<sub>2</sub> concentration leads to changes in the surface temperature  $T_s$ , which largely can be explained by the change in the temperature associated with the CO<sub>2</sub> change ( $T_s^{\text{bC}} + T_s^{\text{eC}}$ ) (Fig. 9). The temperature of the individual CO<sub>2</sub> contributions  $T_s^{\text{bC}}$  and  $T_s^{\text{eC}}$  are identical with around 8 K when reaching steady-state for the CO<sub>2</sub> doubling experiment. They have to be identical, since the base

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CO<sub>2</sub> concentration and the enhanced concentration are equal and radiation does not favour any kind. Note also that the perturbation lifetime of the tagged temperatures is significantly larger (90 yr) compared to the perturbation lifetime of the climate system of around 30 yr.

5 The increase of atmospheric longwave absorption leads to an increase in the atmospheric temperature. This increase is not caused by the category “sw” and hence the ratio  $T_a^{sw} / T_a$  decreases, meaning that the contribution of the shortwave component to the atmospheric temperature decreases. Hence the longwave downward flux associated with the “sw” component decreases, leading to a lower surface temperature associated to the category “sw”. (This mechanism is identical to the longwave contribution in the decrease of  $T_s^{sw}$  from a “no atmosphere” to a “full atmosphere” scenario. See previous section.)

10 The increase in the surface temperature also leads to an enhanced upward longwave surface flux, which in turn increases the absorption of the non-CO<sub>2</sub> greenhouse gases leading to an increase of the temperature  $T_s^{nC}$ .

15 Hence, this tagging methodology nicely allows a separation of non-linear effects. A doubling of the CO<sub>2</sub> concentration in this climate box model leads to an increase in the CO<sub>2</sub> related temperature of around 1.9 K, enhancing the overall greenhouse effect and hence also the contribution of non-CO<sub>2</sub> greenhouse gases by around 0.6 K, whereas the temperature associated with shortwave solar input is decreased by roughly 1.3 K. (Note that these numbers refer to steady state, i.e. after 500 yr.) Therefore, a temperature increase of 2.5 K from the greenhouse effect is reduced by 1.3 K due to the decreased importance of the shortwave components (“sw”), leading to an overall increase in temperatures of around 1.2 K.

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#### 4 Towards a temperature tagging in a comprehensive climate model – some remarks on the method and applications

The method of temperature tagging presented here, is applied to a very simple box climate model. It shows the feasibility of tagging temperature (or any other quantity). In comprehensive climate models the temperature equation includes advection, adiabatic heating, diffusion, and diabatic heating, e.g. radiation and latent heat release. A detailed description of a temperature tagging in such a model is beyond the scope of this paper. However, I like to give some ideas on possible implementations. A generalized tagging approach is presented in a companion paper.

The easiest part of the temperature equation is advection, since advection is a linear operator. Hence applying the advection scheme to the individual tagged temperature fields gives in the sum, if the advection scheme is mass conserving, the same result as the advection of the sum, i.e. the temperature. Also straight forward is the handling of the adiabatic heating term in the tagging equation. This is a process which affects all tagged temperature fields equally and hence the adiabatic heating term of the temperature equation can be linearly decomposed according to the contribution of the individual tagged temperatures to the total temperature.

The more complex part of the temperature tagging equation are the diabatic terms, as already in this application. It might be worth considering individual tagging categories for these terms, like temperature from latent heat, and (as in this application) from individual radiation components. For the latter, the heating rates caused by individual components have to be determined.

An implementation of a temperature tagging would provide a method to answer questions like “How much of the Russian heat wave is caused by man made CO<sub>2</sub> emissions?” (see also Introduction). This question must not be confused with another frequently asked question, whether this event would have happened in a world without climate change, which cannot be answered by the tagging method.

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Other applications might be the quantification of feedback processes, like the temperature change caused by ozone depletion. How large is the contribution to tropospheric temperatures? The large advantage of this method is its diagnostic nature. There are hardly any aspects of statistical noise.

## 5 Conclusions

In this study a new methodology is introduced, which attributes the influence of individual processes on temperature. This method, called temperature tagging, follows the idea of a fully tagged chemical system (Grewe et al., 2012). Fundamental to this tagging approach is the idea that two quantities are equally important when they are both controlling a process. This allows a decomposition of non-linear forcing terms into individual forcing terms for tagged quantities. The tagged quantities have to be seen as contributions to the total quantity. A cooling process may lead to a negative contribution to surface temperature, leading to a negative tagged temperature, which cannot be regarded as a physical temperature per se, but only as a portion of the total temperature.

A simple climate box model is applied to determine the contribution of atmospheric shortwave (“sw”) and longwave absorption to temperature. The longwave absorption is split into 3 parts, absorption due to non-CO<sub>2</sub> greenhouse gases (“nC”), base concentration of CO<sub>2</sub> (“bC”) and an enhanced CO<sub>2</sub> concentration (“eC”). For each of the four tagging categories the associated fluxes and the temperature evolution are calculated.

Two experiments were performed. In the first, changes in fluxes and temperatures were investigated starting from a situation without an atmosphere (zero absorption) and steadily increasing the absorption to a full atmosphere, which leads to a surface temperature increase from 255 K to 286 K. This increase in temperature is composed of individual contributions of opposite signs. A decreasing contribution (−14 K) of the shortwave flux to the surface temperature results from the increasing shortwave absorption of the atmosphere leading to a lower transmittance of radiation to the surface.

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In the situation of no atmosphere, the surface temperature is caused by the shortwave influx and hence attributed to 100 % to the category “sw”. The increase in atmospheric absorption leads to a decrease of the contribution of the solar influx to the surface temperature, since the greenhouse effect starts to contribute significantly. The fluxes, which determine the temperatures are the net shortwave flux of  $192 \text{ W m}^{-2}$  and the longwave downward flux of  $198 \text{ W m}^{-2}$ , leading to a total of  $381 \text{ W m}^{-2}$ , which equals 286 K surface temperature. The longwave downward flux of  $198 \text{ W m}^{-2}$  has a contribution from the emitted radiation from the surface attributed to solar heating (category “sw”) of  $98 \text{ W m}^{-2}$  and  $91 \text{ W m}^{-2}$  attributed to the absorption of greenhouse gases. Hence roughly 25 % ( $91 \text{ W m}^{-2}$  out of  $381 \text{ W m}^{-2}$ ) or 68 K are attributed to the greenhouse effect.

Therefore, the difference in surface temperature between a situation with and without atmosphere of 31 K is only a part of the total greenhouse effect of 68 K, if we take the surface temperature caused by longwave absorption as a quantification of the greenhouse effect.

In a second experiment, the  $\text{CO}_2$  concentration is doubled, which leads to an increase in surface temperature of 1.2 K, resulting from an temperature increase due to  $\text{CO}_2$  of 1.9 K, due to non- $\text{CO}_2$  greenhouse gases of 0.6 K and a cooling of 1.3 K due to a reduced importance of the solar heating for the surface and atmospheric temperatures.

To summarize, temperature tagging adds an important information to calculated temperature changes. It allows to attribute causes to temperature changes, e.g. temperature changes caused by changes in greenhouse gas emissions and hence enables a deeper interpretation of calculated total changes in temperatures. This study shows that tagging of temperature is possible, i.e. that it is possible to keep track of changes in temperatures during a climate simulation. Including a full temperature tagging into a comprehensive climate model still needs more considerations, but its potential is clearly shown in this study.

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**Table 1.** Overview on parameters for the climate box model; lw = longwave; sw = shortwave; var. means that this parameter is described by a function (see text). The surface heat capacity  $c_p^{\text{sfc}}$  is a combination of 2/3 water and 1/3 soil heat capacity.

Parameter	Description	Value	Unit
$S$	Solar input	342	$\text{W m}^{-2}$
$a_l$	lw Absorption	var. (0.77)	–
$a_s$	sw Absorption	0.2	–
$A$	Albedo	0.3	–
$\sigma$	Stefan-Boltzmann-constant	$5.67 \times 10^{-8}$	$\text{W m}^{-2} \text{K}^{-4}$
$e$	Emissivity	1	–
$c_p^{\text{air}}$	Specific heat capacity (air)	1004	$\text{J kg}^{-1} \text{K}^{-1}$
$c_p^{\text{sfc}}$	Specific heat capacity (sfc)	3025	$\text{J kg}^{-1} \text{K}^{-1}$
$\rho^{\text{air}}$	Mean atmospheric density	0.5	$\text{kg m}^{-3}$
$\rho^{\text{sfc}}$	Mean surface density	1000	$\text{kg m}^{-3}$
$Z^{\text{air}}$	Atmospheric height	$10^5$	m
$Z^{\text{sfc}}$	Surface layer depth	1000	m
$T_a$	Atmospheric temperature	var.	K
$T_s$	Surface temperature	var.	K
$F_{\text{toa}}^{\uparrow}$	Top of the atmosphere upward shortwave radiation (also for sfc.; downward; lw)	var.	$\text{W m}^{-2}$

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**Table 2.** Overview on tagging categories.

Description	Category	Tagged temperature	absorption	
			sw	lw
shortwave contribution	“sw”	$T^{\text{sw}}$	$a_s$	0
non-CO <sub>2</sub> GHE	“nC”	$T^{\text{nC}}$	0	$a^{\text{nC}}$
base CO <sub>2</sub> GHE	“bC”	$T^{\text{bC}}$	0	$a^{\text{bC}}$
GHE due to enhanced CO <sub>2</sub>	“eC”	$T^{\text{eC}}$	0	$a^{\text{eC}}$

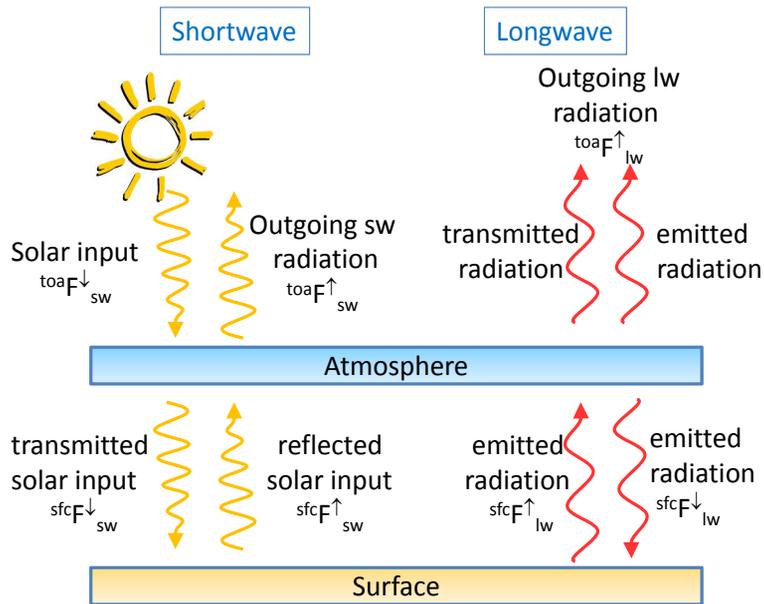


Fig. 1. Sketch of a simple climate box model.

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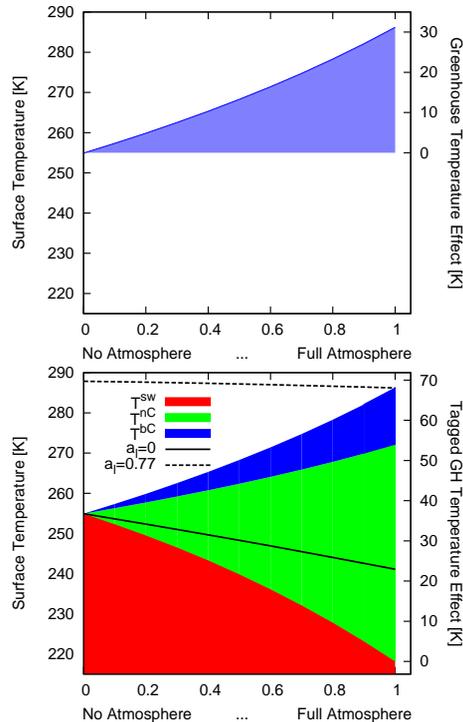
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**Fig. 2.** Top: steady-state surface temperature (K) for the situation of no atmosphere (= 0) to a full atmosphere (= 1). In between the shortwave and longwave absorption are scaled. Bottom: as top but with additional information of the contribution of the longwave absorption due to non-CO<sub>2</sub> greenhouse gases (“nC”, red) and CO<sub>2</sub> (“bC”, green). The temperature  $T_s^{SW}$  follows the lower edge of the red areas. Additionally two sensitivity experiments are included, where longwave absorption is excluded, which gives the effect of shortwave absorption on the surface temperature (solid line) and where longwave absorption is set to the “full atmosphere value” of  $a_1 = 0.77$  (dashed line).

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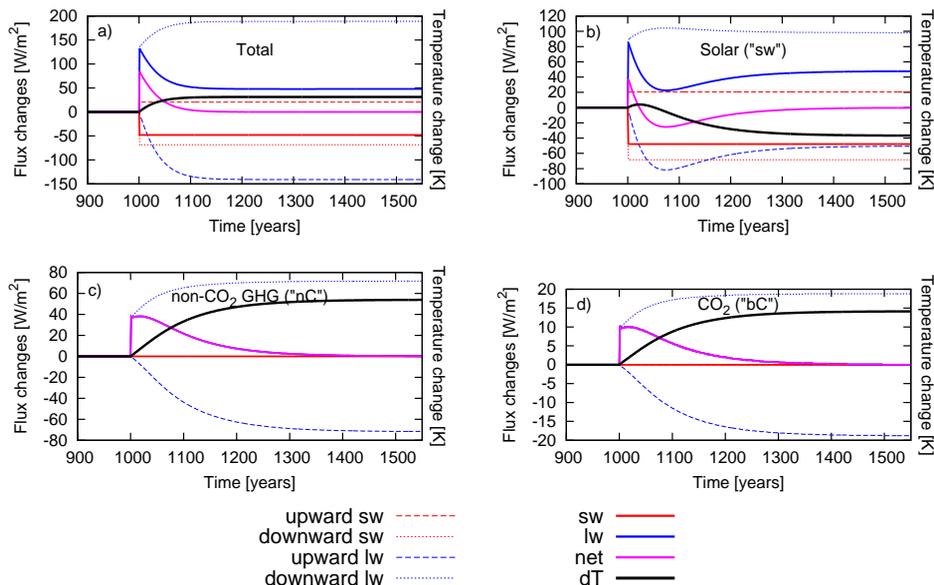
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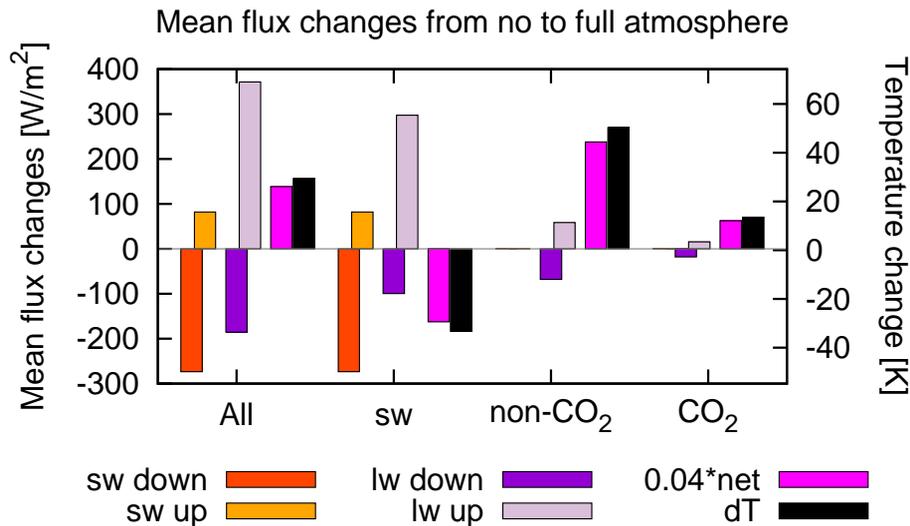
**Fig. 3.** Evolution of flux changes ( $\text{W m}^{-2}$ ) (coloured lines) and temperature changes (K) (black line) in the experiment, where the shortwave and longwave absorption is zero during the spin-up time (1000 yr) and then set to the “full atmosphere” values ( $a_s = 0.2$  and  $a_l = 0.77$ ). Shortwave fluxes are shown in red, longwave in blue. Upward (negative) and downward (positive) fluxes are dashed and dotted, respectively. The total net-flux changes are shown as a purple solid line. Changes are shown for the total flux and temperature changes **(a)** and the individual tagging categories: “sw” **(b)**, “nC” **(c)**, and “bC”.

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**Fig. 4.** Summary of Fig. 3. Mean flux changes over the simulation period are shown for the total (“All”) and the regarded tagging categories. Shortwave and longwave fluxes are shown in red and blue, respectively. Downward fluxes are shown in darker colour than upward fluxes. The net flux (purple) is scaled for presentation reasons. temperature changes are in black.

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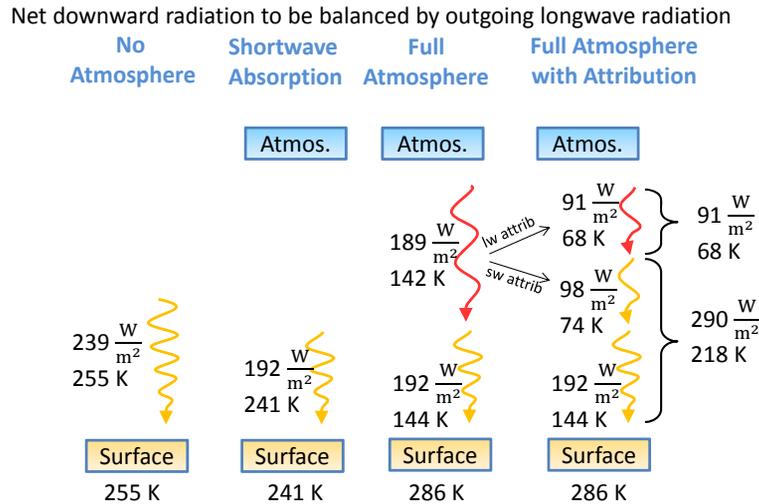
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**Fig. 5.** Shortwave (net) and longwave (downward) fluxes at the surface ( $Wm^{-2}$ ) and respective surface temperature contribution (K) for the case without an atmosphere (left) with an atmosphere only absorbing in the shortwave (second left), with a full atmosphere (second right) and additionally temperatures attributed to longwave and shortwave radiation. The surface temperature leads to a upward longwave radiation, which has to be balanced by the net shortwave and longwave fluxes.

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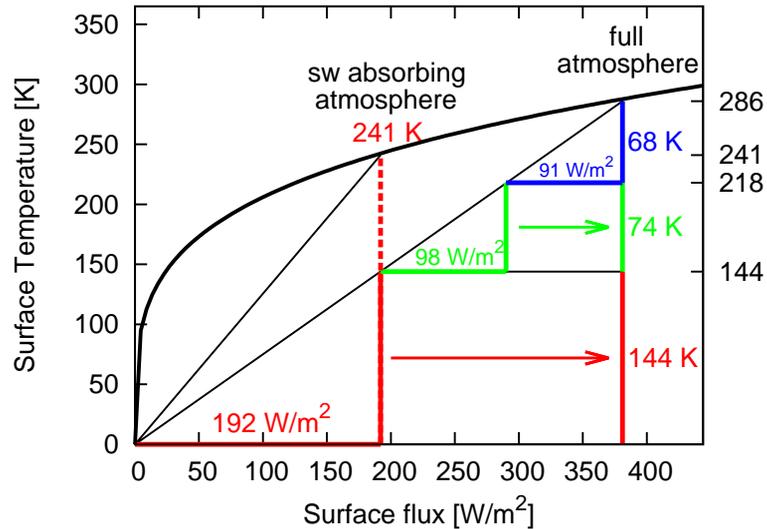
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**Fig. 6.** Surface temperature (K) as a function of the surface flux (sum of net sw and downward lw) ( $\text{Wm}^{-2}$ ) and attribution of temperature contributions to fluxes. See also Fig. 5.

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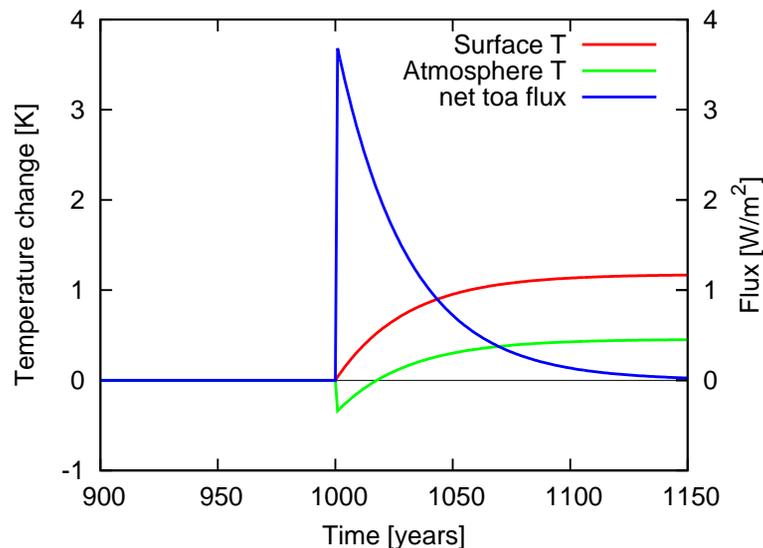
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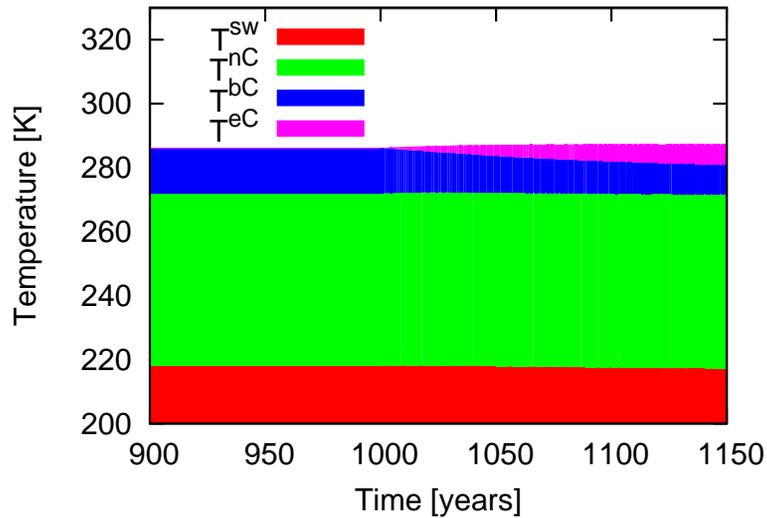
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**Fig. 7.** Temporal development of the top of the atmosphere flux ( $^{\text{toa}}F_{\text{net}}$ ) in ( $\text{W m}^{-2}$ ), surface and atmosphere temperature ( $T_s$  and  $T_a$ ) in an experiment, where after a 1000 yr spin-up  $\text{CO}_2$ -concentration is doubled.

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**Fig. 8.** Temporal development surface temperature and the individual tagged surface temperatures (K) in an experiment, where after a 1000 yr spin-up  $CO_2$ -concentration is doubled.

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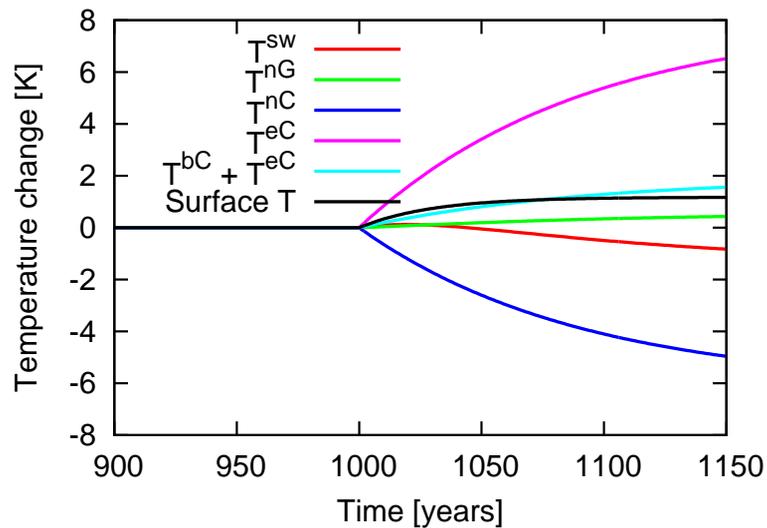
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**Fig. 9.** As Fig. 8, but for changes relative to the year 1000, i.e. before the CO<sub>2</sub> doubling.

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