Author response to referee comments for manuscript ESD-2018-84

TITLE: *Climate feedbacks in the Earth system and prospects for their evaluation*

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RESPONSE TO REVIEWER #2

!! ALL PAGE/LINE NUMBERS REFER TO THE DISCUSSION PAPER AS PUBLISHED ON THE ESD DISCUSSIONS WEBSITE !!

REVIEWER General comment:
This is a very well written and useful overview of the most important climate feedback processes that govern the Earth system response to an external forcing. The concept of feedbacks and its analysis via the electric circuit analogue is well explained, and all feedbacks discussed are presented in a similar schematic, which makes the discussion about the feedback mechanism good to follow. Some generic discussions were eye opening to me (such as the notion that the choice of a reference is not straightforward at ESM timescales, where the entire system is always in transition). In some occasions I had the impression that forcings and feedbacks work in another direction than was suggested by the authors, and have indicated so in the list of minor comments below.
The paper is quite long, but it is very comprehensive and therefore reads as elementary textbook material for every beginning or mature ESM developer or climate system analyst. Therefore, apart from a number of minor comments, I do support publication of this manuscript in ESD.

OUR RESPONSE:
We would like to thank reviewer#2 for the constructive comments.

REVIEWER Minor comment:
p3, l23: "prognostic": it is rarely the purpose of an ESM to make a prognosis (in the sense, an expected evolution of the climate system). There is always a lot of conditionality involved, which makes the term "projection" more appropriate

OUR RESPONSE:
We changed the sentence:
"Such complex model simulations reveal prevailing deficiencies in our prognostic capability of the full Earth system that need to be overcome."
To:
"Such complex model simulations reveal prevailing deficiencies in our capability to project the evolution of the full Earth system. These deficiencies need to be overcome."

REVIEWER Minor comment:
fig 1: we do miss some elements discussed later in this paper (e.g. the vegetation feedbacks on CO_2 levels)

OUR RESPONSE:
We will add vegetation feedbacks to increasing CO_2 levels, the fire feedback, and the soil moisture evapotranspiration feedback to Figure 1.

REVIEWER Minor comment:
p8, l5: "...are not included in the concept of ECS." Is this for principal or for practical reasons?

OUR RESPONSE:
This is for principal reasons. A world with perpetual constant twofold atmospheric CO_2 concentration as compared to the pre-industrial situation cannot be realised when including processes that alter the atmospheric CO_2 concentration themselves.
We will change:
"…and slow feedback-like changes in vegetation types and ice sheets are not included in the concept of equilibrium climate sensitivity (Knutti and Hegerl, 2008; Knutti and Rugenstein, 2015), which was mainly developed for physical climate models…"
To:
"…and slow feedback-like changes in vegetation types and ice sheets are <u>deliberately</u> not included in the concept of equilibrium climate sensitivity (Knutti and Hegerl, 2008; Knutti and Rugenstein, 2015), which <u>was developed mainly to inter-compare the performance of physical climate models</u>…"

REVIEWER Minor comment:
Eq 10: it was a bit confusing to interpret E not to be a flux but a cumulative emission in mass units, maybe explain this explicitly

OUR RESPONSE:
We will add the text "(cumulated emissions of CO_2 since beginning of industrialisation)" in the description of E.

REVIEWER Minor comment:
p9, l10: not sure I understand what d is*

OUR RESPONSE:
The coefficient d* is explained in line 15 (page 9). We will add a "(see below)" after the first time d* gets mentioned in line 10. Line: 15: "includes" will be replaced by "represents". We will add the text "(d* is the combination of modules in ESMs that convert greenhouse gas concentration changes into surface air temperature changes)" at line 16.

REVIEWER Minor comment:
p9, l15: what do you mean with "respective"?

OUR RESPONSE:
We will delete the word "respective".

REVIEWER Minor comment:
Fig 3: unclear what the black dashed arrow on the left of the figure means, it is not explained in the caption

OUR RESPONSE:
We will change the black dashed arrow so that it goes from the lower right corner (*CO_2 emissions*) to the left upper corner (*Radiative forcing*). We will add the following text to the caption of Figure 3: "The dashed black arrow illustrates that the CO_2 emissions are initially the same for the chemical and the radiative forcing."

REVIEWER Minor comment:
p12, l8: "The lower the compatible emissions, the stronger the underlying positive carbon cycle climate feedback." This is not straightforward to me. Can you explain?

OUR RESPONSE:
We will add the following text:
"This is illustrated by the following definition of compatible emissions in a model projection framework using prescribed atmospheric CO_2 (see also Box 6.4 in Cias et al., 2013):

$$Emissions_{compatible} = \left(\frac{dCO_2}{dt}\right)_{atmosphere}^{prescribed} + (carbon\ uptake)_{land} + (carbon\ uptake)_{ocean}$$

For a projection with increasing carbon uptake by land and ocean under rising atmospheric CO_2 concentrations, high compatible emissions would result. In contrast, for a projection with decreasing carbon uptake by land and ocean under rising atmospheric CO_2 concentrations, the compatible emissions would be smaller."

REVIEWER Minor comment:
Fig 4: I suggest to make a distinction between arrows that represent a flux and arrows that point at elements in the figure

OUR RESPONSE:
We will change the (now) black arrows in Figure 4 in order to make the distinction between fluxes and description of elements.

REVIEWER Minor comment:
p13, l12: "upper": do you mean the long or the short time scale here?

OUR RESPONSE:
We will change the following text:
"… where the upper end of the timescale spectrum …"
To:
"… where the upper end of the timescale (few years) …"

REVIEWER Minor comment:
p13, l19: "the feedbacks considered" in this physical subsection, is what you mean. Other feedbacks later in the manuscript do not fall in one of these categories

OUR RESPONSE:
We will change the following text:
"The feedbacks considered (regardless of whether they are fast or slow) can be grouped into four basic types:…"
To:
"The physical feedbacks considered (regardless of whether they are fast or slow) can be grouped into four basic types: …"

REVIEWER Minor comment:
p16, l25: "As the moist adiabatic lapse rate decreases with increasing surface temperature": this is also no straightforward to me. Why is this?

OUR RESPONSE:
We will add the following text on page 16, line 29, in order to clarify this point:
"Especially in tropical regions, a stronger warming of the troposphere as compared to the surface occurs under increased greenhouse gas concentrations in the atmosphere. This effect results in a negative feedback to climate due to an increase in thermal emission to space (Boucher et al., 2013; Bony et al., 2006)."

REVIEWER Minor comment:
p19, l2-3: I always understood that the positive feedback only occurs when cloud top is moved to a cooler layer reducing outgoing LW. When upward motion does not lead to reaching a cooler temperatures (due to warming the entire system), this positive feedback vanishes I would say. Why is it still present?

OUR RESPONSE:
We will change on page 19, lines 2-3 the text “positive longwave radiative feedback” to “positive cloud longwave feedback”.
We will add the following text on page 19, line 3: “The clouds are not warming synchronously with the surface temperature. Therefore, the warming Tropics become less efficient at radiating away heat. As a consequence, the clouds induce a positive feedback to climate (Zelinka and Hartmann, 2011).”
(The reference is already included in the discussion paper.)

REVIEWER Minor comment:
p19, l25: "with weaker shortwave radiation": I’m missing the essential step in this sentence, which involves reducing the ability to reflect sunlight on a bright surface

OUR RESPONSE:
We will change the phrase (page 19, line 25): “These shifts of clouds to higher latitudes with weaker shortwave radiation induce a positive feedback of an uncertain amount…”
To:
“These shifts of optically thick storm clouds to higher latitudes with weaker incoming solar radiation makes them less efficient radiation reflectors and thus induces a positive feedback of an uncertain amount…”.
Further we will change the section heading “3.2.3 Mid-latitude cloud amount feedback” to “3.2.3 Mid-latitude cloud amount feedback” to “3.2.3 Mid-latitude cloud reflectance feedback”. This change will also be made in Figure 6. In Figure 6, we will in addition change “polar cloud amount” to “mid-latitude cloud reflectance”.

REVIEWER Minor comment:
p19, l31: "increase" is not a proper, term. Probably you mean elevation, or an increase in the thickness of the layer exceeding 0°C

OUR RESPONSE:
We will change “increase in” to “elevation of”.

REVIEWER Minor comment:
p19,l34: why do we have a negative feedback here?

OUR RESPONSE:
We will add the following text to explain this better: “Due to the larger reflectivity of liquid water clouds over ice clouds (cloud cover and water mass unchanged) a change from ice to liquid clouds must induce a negative (shortwave) cloud radiative feedback (Tan et al., 2016).”
We will add the reference:
Tan, I., Storelvmo, T., Zelinka, M. D. : Observational constraints on mixed phase clouds imply higher climate sensitivity, Science 352, 224-227, doi:10.1126/science.aad5300, 2016.

REVIEWER Minor comment:
fig 7/section 3.3: I would expect to also see physical feedback of evaporation increase due to higher temperature (modulated by soil moisture availability)

OUR RESPONSE:
We will include the positive soil moisture evapotranspiration feedback. Respective additions will be made to Figure 1, Figure 7, and Table 1.
The text on page 21, lines 1-5, will be changed to: “The most important fast land surface feedbacks are that of snow albedo, the positive soil moisture evapotranspiration feedback and the positive CO_2–stomata–water feedback (see feedback diagrams in Figure 7).”
The headline section 3.3.2 will be changed to: “Soil moisture evapotranspiration feedback and CO_2-stomata-water feedback”.

Before the sentence on page 21, line 19, the following text will be inserted: “Warming leads to an increase of evaporation from soils. This negative soil moisture anomaly leads to a positive surface temperature anomaly through the reduction in latent heat flux (Senerivatne et al., 2010). The result is a positive feedback. Next to this physical feedback a chemically forced feedback exists.”
We will add the following reference:
Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., and Teuling, A. J.: Investigating soil moisture-climate interactions in a changing climate: A review, Earth-Sci Rev, 99, 125-161, 10.1016/j.earscirev.2010.02.004, 2010.

REVIEWER Minor comment:
p21, l13: use K or °C throughout the paper

OUR RESPONSE:
We will convert in all unit descriptions $°C^{-1}$ instead of K^{-1}. For general descriptions of temperatures we will use °C, but for temperature differences K. A respective homogenisation of the manuscript will be carried out.

REVIEWER Minor comment:
p25, l2: how does thinner sea ice and its reduced insulation lead to a negative feedback?

OUR RESPONSE:
This is due to the increased heat loss of ocean water (which can lead to buoyancy driven convection and water column overturning), see also Notz and Marotzke (2012) (cited on page 24, line 19). We will add the following text on page 35, line 5: “The increased open water fracture in the thinning ice promotes new ice growth during the winter season which increases the ice covered area insulating the ocean below, and thus acting as a negative feedback. The negative feedback may be counteracted, however, by the effect of brine release. The ice brine released during the ice formation destabilizes the strongly stratified Arctic ocean water column below and induces convection which then may entrain warmer waters from below contradicting the new ice production. Please see and add a new reference (Goosse et al., 2018).”
We will add the reference:
Goosse, H., Kay, J. E., Armour, K. C., Bodas-Salcedo, A., Chepfer, H., Docquier, D., Jonko, A., Kushner, P. J., Lecomte, O., Massonnet, F., Park, H. S., Pithan, F., Svensson, G., and Vancoppenolle, M.: Quantifying climate feedbacks in polar regions, Nat Commun, 9, ARTN 1919, 10.1038/s41467-018-04173-0, 2018.

REVIEWER Minor comment:
p25, l25: the statement on effects of roughness on turbulent fluxes could deserve a reference, as this conclusion is not without controversy

OUR RESPONSE:
We will add the following reference on page 25, line 26:
Gustafsson, D., Lewan, E., and Jansson, P. E.: Modeling water and heat balance of the boreal landscape - comparison of forest and arable land in Scandinavia, J Appl Meteorol, 43, 1750-1767, Doi 10.1175/Jam2163.1, 2004.

REVIEWER Minor comment:
p27, l1: "thermal effects of evaporation": Normally E increases with T, but a negative feedback via available soil water applies. Vegetation feedbacks may occur in cases of episodic droughts

OUR RESPONSE:
We will add on page 27, line 27, after “thermal effects induced by evapotranspiration”: “(changes in latent and sensible heat fluxes modulated by soil moisture availability and prevailing vegetation)”.

REVIEWER Minor comment:
p27, l29: "in" -> "on"

OUR RESPONSE:
This will be corrected.

REVIEWER Minor comment:
p28, l6: This is the first time that bias is mentioned. Should other feedback considerations be assessed using knowledge about the impact of bias?

OUR RESPONSE:
We think, that the implications for other feedbacks due to this bias cannot as yet be assessed due to lacking knowledge. We will introduce a “potentially” before “complex implications” on page 28, line 7.

REVIEWER Minor comment:
p29, l23: how do wetlands modulate the amount of precipitation received?

OUR RESPONSE:
It was not our intention to state that wetlands modulate precipitation. In order to avoid such a misunderstanding, we will change the sentence on page 29, lines 22-24, from:
“Further, in a warmer world, permafrost areas may shrink and more wetlands may appear due to this process or develop in already humid regions, which may receive additional precipitation.”
To:
“Further, areas that experience additional precipitation in response to warming, permafrost areas may shrink and more wetlands may appear due to this process or develop in already humid regions. This additional precipitation in response to warming is projected for many regions (Collins et al., 2013).”
The reference is already included in the discussion paper.

REVIEWER Minor comment:
fig 12+13: this is quite a busy picture. I suggest to group all boxes saying "CO_2 (or CH_4) warming" and reroute the feedbacks loops via that single box

OUR RESPONSE:
We prefer to have each single feedback be represented separately (also due to sometimes different sign) and think that the simplification with such a single box would make the figures more difficult to understand.

REVIEWER Minor comment:
fig 12: increased biomass leading to more forest fires is a negative feedback on enhanced plant growth; I don’t understand this one very well

OUR RESPONSE:
We do not understand the comment. In Figure 12, the biomass limited fire feedback is leading to more CO_2 release and hence provides a positive feedback to the atmospheric CO_2 concentration.

REVIEWER Minor comment:
p31, l9: "radioactively"?

OUR RESPONSE:
We will change “radioactively” to “radiatively”.

REVIEWER Minor comment:

p34, l8: "physical downward transport of surface waters": do you refer to freshwater suppression of convection? A bit unclear

OUR RESPONSE:
We will change the text passage:
"This negative feedback (Figure 13) is expected to be considerably smaller than the feedback due to reduced physical downward transport of surface waters with high anthropogenic carbon loadings (Broecker, 1991; Maier-Reimer et al., 1996; Plattner et al., 2001). The stronger partial retention of waters with high anthropogenic CO_2 burdens at the sea surface will thus dominate over the more efficient biogenic downward particle flux in a more slowly overturning ocean."
To:
"This negative feedback (Figure 13) is expected to be considerably smaller than the feedback due to reduced physical downward transport of surface waters with high anthropogenic carbon loadings (Broecker, 1991; Maier-Reimer et al., 1996; Plattner et al., 2001)."

REVIEWER Minor comment:
p37, l14: "as a consequence": does dust production depend on global temperature? That is not stated explicitly

OUR RESPONSE:
We will delete: "As a consequence".

REVIEWER Minor comment:
p42, l32: the negative RF of stratospheric ozone is a surprise to me: I always thought ozone is an absorber in the UV spectrum and so heats up the climate system

OUR RESPONSE:
The referee is right that the radiative impact of ozone is a local heating. The text, however, is addressing stratospheric ozone depletion, i.e., the radiative impact *change* of an ozone decrease. This induces a cooling, both locally in the stratosphere, but also to the troposphere surface system below (for the latter effect both shortwave and longwave effects have to be considered).
We will add the following text on page 42, line 33:
"The stratospheric ozone depletion induces a cooling, both locally in the stratosphere, but also to the troposphere surface system below. For the latter, a negative radiative forcing at the tropopause originates from the longwave radiative effect induced by a lower stratosphere ozone decrease (Hansen et al., 1997)."
(The reference is already included in the discussion paper.)

REVIEWER Minor comment:
p45, l20: insert "and" before "which"

OUR RESPONSE:
We will carry out this change.

REVIEWER Minor comment:
p47, l3: larger what?

OUR RESPONSE:
We will correct this ("larger <u>range</u>").

REVIEWER Minor comment:
p47, l34: "which happens after 120 years": please make explicit that this time you include the carbon uptake processes

OUR RESPONSE:
We think that this should be clear already (because we write “including interactive carbon cycle”).

REVIEWER Minor comment:
p49, l11: the time of emergence of 30-60 yrs, does that apply to temperature?

OUR RESPONSE:
We will insert “for surface air temperature” after “30–60 years”.

REVIEWER Minor comment:
p49, l30: delete "among"

OUR RESPONSE:
We will correct this.

REVIEWER Minor comment:
section 5.2.4: not entire clear how these paleo runs can add insights on feedbacks

OUR RESPONSE:
We will revise section 5.2.4. We will include a remark on the general idea on how one can use past changes in forcing to assess the response of ESMs through comparison of model results with palaeo-climatic time series data. We will give a few more examples (next to the ones cited already in the discussion paper) to illustrate how palaoe-climatic model runs can help in quantifying feedbacks and climate sensitivity. We will change section 5.2.4 by rearranging existing text and adding text:
“Palaeoclimatic experiments with ESMs can be useful for assessing the models’ ability to account for slow feedbacks and for constraining sensitivity of models to forcings in general. The general concept is to expose ESMs to reconstructed anomalies in forcing, to diagnose the models’ response, and to compare the model results with palaeoclimatic observations. Model forcings for respective experiments are taken from orbital parameter variations of the Earth (eccentricity, axial tilt, precession; Berger and Loutre (1991)), solar activity indices, volcanic eruption records, and different ice sheet topographies. Typical test events for simulations with ESMs include the last glacial maximum (LGM, 21 kyr BP, important for quantifying the positive carbon cycle climate feedback) (Braconnot et al., 2007a; Braconnot et al., 2007b; Frank et al., 2010;Schmidt et al., 2014) and the last 1000 years including the Maunder minimum (300 yr BP, “little ice age” mechanisms) (Ottera et al., 2010; Zorita et al., 2005). Observational data used in comparison with ESM results are based on the marine and terrestrial palaeoclimate record (such as stable carbon and oxygen isotopes from sediment core analysis, pollen analysis, bore hole temperatures etc.; see, e.g. Bradley (1999)). Palaeo-climatic observations consist of proxies, i.e. preserved environmental characteristics that replace direct measurements of the instrumental record. These proxy records contain a climate signal, but embedded in a suite of other influences of non-climatic origin (Bradley, 1999). Specific links between proxy records and climate state variables rely on respective empirical transfer functions. Proxy data are therefore associated with a considerable uncertainty range. This deficiency is to some degree compensated for by the higher signal-to-noise ratio of the respective variations in climatic state variables during certain time intervals within the Quaternary. On the other hand, modified ice sheet states and sea-level positions for dates older than a few thousand years complicate ESM simulations. Cause–effect links for changes in specific feedback processes may thus be masked by other processes. We give now a few examples for useful palaeo-climatic studies to assess feedback strengths. Frank et al. (2010) employed climatic forcing data over the past millennium with observations from ice cores in order to constrain the carbon cycle feedback to temperature changes to the lower half of the range than inferred from projections by ESMs (Friedlingstein et al., 2006). A comparison of simulations with ESMs under forcing conditions for (a) the last glacial maximum and (b) the mid-holocene provided indications for the strength of the vegetation climate feedback (inducing changes in the evapotranspiration) and the albedo feedback due to changes in snow-cover and sea ice (Braconnot et al., 2007b). The various resulting feedback strengths can be weighted through a rigorous comparison of model results and observational palaoe-climatic data following a

maximum likelihood approach. ESMs can also be used for simulating the various palaeo-climatic time windows as given in (PALEOSENS Project Members, 2012) in order to calibrate their sensitivities."
We will add the reference:
PALEOSENS Project Members: Making sense of paleoclimatic sensitivity, Nature, 491, 683-691, 10.1038/nature11574, 2012.

REVIEWER Minor comment:
p53,l25: "similarities with the real world": this statement does deserve a citation

OUR RESPONSE:
We will add the following references: Flato (2011), and Flato et al. (2013) (both are already in the reference list of the discussion paper).

REVIEWER Minor comment:
p54, l14: "projection parameters (e.g. resolution matrices)": unclear to me

OUR RESPONSE:
We will remove the text passage "include projection parameters (e.g. resolution matrices) which". It is not relevant for the non-expert in this field.