Comment on a too simple model of the anthropogenic carbon cycle

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In the discussion paper of Weber et al. (2015) a simple model of the anthropogenic carbon cycle is presented. The authors describe a simple linear model, consisting of one ordinary differential equation which describes the changes in CO_2 content of the atmosphere over time. The two free parameters of the equation are derived by fitting the results of the model (carbon content of the atmosphere) to the observations or reconstructions covering the last 150 years. The model is then applied to calculate the response of the global carbon cycle to future anthropogenic emissions and some conclusions on the fate of the anthropogenic carbon emissions until the year 2150 are then drawn. The findings show a rather fast reduction in atmospheric CO_2 and the conclusions are in contrast to the results of virtually all other global carbon cycle models, (e.g. Meinshausen et al., 2011; Stocker et al., 2013; Friedlingstein et al., 2014), which — in contrast to the simple model presented here — include the current state of understanding of the processes involved in the global carbon cycle.

We challenge the overall conclusions of the paper for the following reasons: The simple model (although not perfect) performs well for the anthropogenic period up to today, since the values of the two free parameters in the ordinary differential equation are based on observations (or to be more correct on model-based interpretation of observations). The agreement of the model to the historic atmospheric CO_2 record is therefore hardly surprising. Besides the balance of some carbon fluxes in and out of the atmosphere no further theoretical (process-based) understanding is implemented in the simple model. This is a valid approach for simulating the most recent (anthropogenic driven) past, but does not prove that the model contains prognostic value, which justifies its application on future emissions. The model can only be applied to future anthropogenic perturbations on the surmise that the

carbon cycle is not fundamentally altered. However, this is clearly not the case for nearly all future emission scenarios, most importantly because the carbon uptake capacity of the ocean depends on the carbonate chemistry (Revelle factor), which is changing at unprecedented speed.

In the following we briefly expand and justify our arguments:

Complexity of the model: As reviewed in detail recently by Friedlingstein (2015) the anthropogenic driven changes in carbon content of the ocean (ΔC_O) and the land (ΔC_L) depend on both (1) global temperature change ΔT_{g}, and (2) the change in atmospheric CO_2 mixing ratio (ΔC_A). This leads to the following two equations with four parameters:

$$\Delta C_L = \beta_L \cdot \Delta C_A + \gamma_L \cdot \Delta T_g \quad (1)$$

$$\Delta C_O = \beta_O \cdot \Delta C_A + \gamma_O \cdot \Delta T_g \quad (2)$$

with $\beta_L = 2 \pm 0.9$ GtC/ppmv, $\gamma_L = -28$ GtC/K, $\beta_O = 1.55 \pm 0.3$ GtC/ppmv, $\gamma_O = -8 \pm 3$ GtC/K.

The simple model of Weber et al. (2015) contains no temperature-dependent land carbon change (corresponding to $\gamma_L = 0$). So one of the largest fluxes in Friedlingstein (2015) is zero. The different temperature-dependent ocean carbon change γ_O is with -15.9 GtC/K by a factor of 2 larger than in the review of Friedlingstein (2015), probably because its value was estimated from only one study (Frank et al., 2010). The two fluxes CO_2-dependent land and ocean carbon uptake were derived from a different set of equations in Weber et al. (2015) than in Friedlingstein (2015) and are not directly comparable with β_L and β_O.

Underlying data sets: Weber et al. (2015) uses the data set of the global carbon budget 2014 (Le Quéré et al., 2015) to determine the values of the free parameters. Here, the global emissions from fossil fuel combustion, cement production and land-use change (anthropogenic drivers) are balanced by a rise in the carbon budgets of the (a) atmosphere, (b) ocean, and (c) land. From these sinks of the anthropogenic emissions only the atmospheric rise in CO_2 is purely based on data from either instrumental observations since 1959 or historical reconstructions from ice cores (since 1750). The oceanic sink was estimated with a combination of global biogeochemical models, in which the full marine carbonate chemistry is embedded (Le Quéré et al., 2015), the land sink is typically determined as residual of the other budget terms. This implies, that the suggestion of Weber et al. (2015), that the values of two free parameters are estimated from data, is not correct. Furthermore, one major suggestion put forward in the conclusions of Weber et al. (2015), that any differences of the simple model to other, more complex models might be caused by the Revelle factor, is in its present form difficult to justify. By fixing atmosphere-ocean-CO_2 exchange rates to historical observations any further changes in the oceanic carbon uptake capacity that are related to the carbonate chemistry and which can be expressed by the Revelle factor, are ignored in Weber et al. (2015).

This Revelle (or buffer) factor R is an emerging property of the marine carbonate system and is implicitly considered in marine carbon cycle models. When CO_2 enters the ocean it reacts with seawater leading to the formation of carbonic acid (H_2CO_3) which subsequently dissociates into hydrogen ions (H^+) and bicarbonate ions (HCO_3^-). The carbonate chemistry in seawater describing these processes in detail is well known (compare, for example Dickson et al., 2007; Zeebe and Wolf-Gladrow, 2001). The Revelle factor is defined as the ratio of the relative change of dissolved CO_2 to the relative change of DIC (DIC = sum of dissolved CO_2, HCO_3^-, CO_3^{2-}), and can be readily calculated:

$$R = \frac{\Delta CO_2/CO_2}{\Delta DIC/DIC} \tag{3}$$

From open ocean data it is known that R varies between 8 and 15 (Sabine et al., 2004). A rise in atmospheric and oceanic carbon content goes along with an increase in the Revelle factor, a phenomenon which is already measurable (e.g. Hauck et al., 2010). This implies that DIC in the ocean will rise slower relative to the change in atmospheric CO_2 mixing ratio in a future with increasing anthropogenic CO_2 emissions than today, as already seen in all CMIP5 model simulations (Jones et al., 2013). Evidence for the existence of the Revelle effect are questioned and said to be *hypothetical* (Weber et al., 2015). This argument is based on one citation (Gloor et al., 2010), in which these authors apply another simple model (without carbonate chemistry) and make some analysis on the anthropogenic carbon cycle. We cannot follow the argument that the study of Gloor et al. (2010) suggests that the Revelle effect is hypothetical. Furthermore, the scientific literature describing the marine carbonate chemistry, which, if fully embedded, automatically includes the Revelle effect, is based on decades of lab experiments, field observations and theoretical understanding of the underlying chemical processes and is very well established. The books of Dickson et al. (2007); Zeebe and Wolf-Gladrow (2001) are only two examples of the state of knowledge in this field.

A Revelle factor of 8, for example, would imply an increase in DIC by 12.5% for a doubling of dissolved CO_2. However, increased CO_2 concentrations lead to a decrease of ocean pH (Stocker et al., 2013, and references therein) and an increase of the Revelle factor. Thus at higher CO_2 a doubling of CO_2 leads to a lower relative increase of DIC. See, for example, Fig 3 in Hauck and Völker (2015) for proposed change in the Revelle factor in the Southern Ocean, or Egleston et al. (2010).

Evaluating the Simple Model: At best Weber et al. (2015) should have compared the output from their future emission scenario with other models, in which the most important processes relevant on the time-scale of interest are implemented. It is our understanding that a carbon cycle model should include at least the complete marine carbonate chemistry, otherwise the oceanic carbon uptake rate might be biased once the carbonate equilibria shift to a largely different state due to anthropogenic emissions.

The comparison of the airborne fraction of the simple model with those of the model intercomparison of Joos et al. (2013) is the only comparsion they perform, and a first step, but the perturbation in the carbon cycle in this experiment was rather small (100 GtC). However, this comparison is already very useful, even when the anthropogenic CO_2 emissions in future scenarios over the next 150 years are assumed to be an order of magnitude larger.

For further evaluation we rerun the simple model of Weber et al. (2015) and compare it with simulation results of the simple carbon cycle box model BICYCLE (Köhler et al., 2005), in which the marine carbonate chemistry is implemented, and which also contains a simple land carbon scheme, in which land carbon uptake is a function of temperature change and CO_2 concentration. In BICYCLE we are able to switch on and off various functionalities, e.g. the terrestrial biosphere or the land carbon uptake (on: TB+, off: TB-) or the temperature-dependent oceanic carbon uptake (on: SST+, off: SST-).

We implement the simple model calculating changes in atmospheric CO_2 (N_A (in GtC) over time t as follows, corresponding to Eq 7 of Weber et al. (2015):

$$\frac{\delta N_A}{\delta t} = \frac{\left(E - \frac{1}{\tau}(N_A + S_A - N_{A,0})\right)}{1+b}, \tag{4}$$

with emissions E (GtC/yr) from reconstructions or scenarios, $\tau = 81.7$ years, $S_A = 15.9 \cdot \Delta T_g$, b= 0.668, $N_{A,0} = 278$ ppmv ($\times 2.12$ GtC/ppmv) to meet the CO_2 data in the reconstructions in year 1766 (Meinshausen et al., 2011). The equation is solved most simplistically by annually adding the calculated difference $\frac{\delta N_A}{\delta t}$ to N_A.

The marine carbon uptake dynamic in BICYCLE compares very well with the more sophisticated models in Joos et al. (2013) and has an airborne fraction of 0.45 on a 100-years time scale (going down to 0.2 on a 1000-years time scale) when land carbon uptake is ignored (Figure 1, replotted from Fig. S6d in SI of (Köhler et al., 2014)) for a 100 GtC pulse emission (same experiment as in Joos et al. (2013)). The airborne fraction of this scenario (100 GtC pulse added to a modern carbon cycle background characterised by an atmospheric pCO_2 of 389 ppmv similar to Joos et al. (2013)) was also reproduced with the simple model (Figure 1). We show results for two model versions, one without carbon uptake by the terrestrial biosphere (TB-; $b = 0$), but oceanic uptake being a function of ΔT (SST+; $S_A \neq 0$) (to be comparable with the results from the BICYCLE model), and one with the opposite (TB+, SST-), which was most likely the realisation chosen in Weber et al. (2015). Note, that our results differ for yet unknown reasons from what is shown in Figure 5 in Weber et al. (2015). Both our versions of the simple model differ in two aspects: In the version with and due to the active terrestrial carbon uptake (SST- TB+) the airborne fraction in the year 2000 of the 100 GtC pulse never exceeds 0.6, while it is 1.0 in year 2000 in the other version. On the long run (longer than a century) the airborne fraction of this version (SST- TB+) is slightly larger than that of the other version (SST+ TB-). Independent of the model version we found on a 100-yr time scale the airborne fraction in the simple model is already below 0.3, falling after more than 200-250 years below 0.1. The simple

model therefore contains on 100- to 1000-years time scale an oceanic carbon uptake that is clearly larger (leading to smaller atmospheric CO_2 and airborne fraction) than the range found in common carbon cycle models.

In using BICYLE, we are able to run a model which includes the marine carbonate chemistry and similar land- and ocean carbon uptake processes as the simple model of Weber et al. (2015). We are therefore able to estimate, how important the marine carbonate chemistry might be when analysing future emissions scenarios. Here, we have chosen to use the RCP scenarios (Moss et al., 2010; Meinshausen et al., 2011), which are in the underlying data sets extended to the year 2500 (with stable or decreasing emissions after the year 2100). We also use the data compilation of the instrumental or historical periods as contained in Meinshausen et al. (2011), which differs in details only slightly from the compilation of Le Quéré et al. (2015).

The evaluation of the historical period for both the simple model and the BICYCLE model (here applied in the identical setup as used in Köhler et al. (2010)) shows that both approaches are able to simulate the rise in atmospheric CO_2 comparable to the observations (Fig. 2). It also illustrates that for the historical period in both approaches the influence of land carbon uptake on atmospheric CO_2 is similar and more important than the temperature-dependency of oceanic carbon uptake.

When considering future emission scenarios the simple approach of Weber et al. (2015) needs to make some assumptions on global temperature change. Probably due to the lack of future ΔT_g data, Weber et al. (2015) have chosen to neglect this process. Our previous evaluation has already shown that the temperature-dependent oceanic carbon uptake is of minor importance at least for the historical period, so $\gamma_O = 0$ (as assumed in the simple model) might be a valid assumption. Alternatively one might (and we do) calculate ΔT_g out of atmospheric CO_2 using the transient climate sensitivity of on average 2 K warming per CO_2 doubling (see Thematic Focus Element (TFE) 6 in the Technical Summary of the IPCC AR5 (Stocker et al., 2013), page 84).

When applying the different model versions of the simple model and of BICYCLE to the RCP future emission scenarios (Fig. 3) we also compare them with the mean CO_2 obtained from the RCP emissions scenarios (Meinshausen et al., 2011), that should be taken as greenhouse gas forcing in climate models within CMIP5, the most recent climate model intercomparison that is also analysed within the framework of the IPCC AR5 (Stocker et al., 2013). It turns out that the BICYCLE simulation results spread up to two branches, depending on whether land carbon uptake is considered (TB+) or not (TB-). The simulations without land uptake are very close to the RCP output, while an active terrestrial carbon cycle reduces atmospheric CO_2 too much. In detail, the CO_2 fertilisation effect for high CO_2 concentrations is probably too strong in BICYCLE. This might also be the case for more complex land carbon models that do not consider the nitrogen cycle. Land carbon models which consider nitrogen sequester a lot less carbon on land and are more in line with the atmospheric CO_2 projections of CMIP5 (Friedlingstein and Prentice, 2010; Friedlingstein et al., 2014; Friedlingstein, 2015).

The results of the simple model of Weber et al. (2015) are on the long term all dominated by the underlying CO_2-related oceanic carbon uptake (Fig. 3). Model results for the different model versions differ only slightly in the long run and all result in very low atmospheric CO_2 levels in the distant future. This is readily explained with the missing carbonate chemistry. The model simulates identical oceanic carbon uptake rates for a given atmospheric carbon anomaly independent of the anthropogenic history, while the process-based understanding tells us that the marine chemistry and here namely the Revelle or buffer effect will be the major bottle neck of the marine carbon uptake and will slow down future oceanic carbon uptake (Jones et al., 2013; Hauck et al., 2015).

In summary, the developed simple model of Weber et al. (2015) is an interesting application for present and historical anthropogenic carbon cycle changes. However, due to its simplicity it is not able to capture the most important changes in the anthropogenic carbon cycle for the coming centuries. It is simply too simple and the most important process relevant on this time scale (the reduced oceanic CO_2 uptake due to a change in the buffer capacity of the marine carbonate system in a high-CO_2 ocean, all very well understood) is missing.

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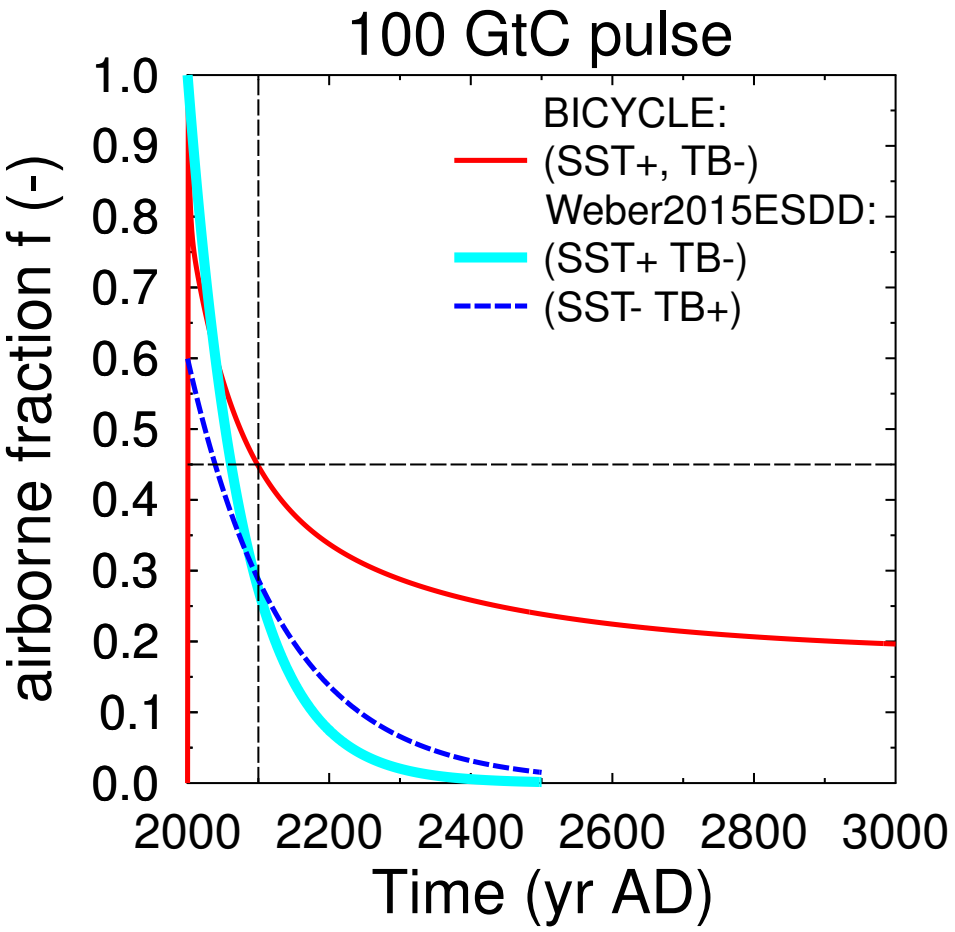

Figure 1: Comparing the airborne fraction of BICYCLE with the simple model of Weber et al. (2015) for a 100 GtC pulse as in Joos et al. (2013). The 100 GtC pulse is release in year 2000 on a modern background, implying that in BICYCLE atmospheric pCO_2 is 389 ppmv (no other emissions considered), while in the simple model the 100 GtC pulse is added in year 2000 to the background emissions of the RCP85 scenario. Results in the simple model are very similar if the pulse is released without background emissions. The model versions contain no land carbon uptake (TB-), but considers temperature-dependent oceanic carbon uptake (SST+). Additionally the simple model is run with the opposite, active land carbon uptake, but no temperature-dependent oceanic carbon uptake (SST- TB+).

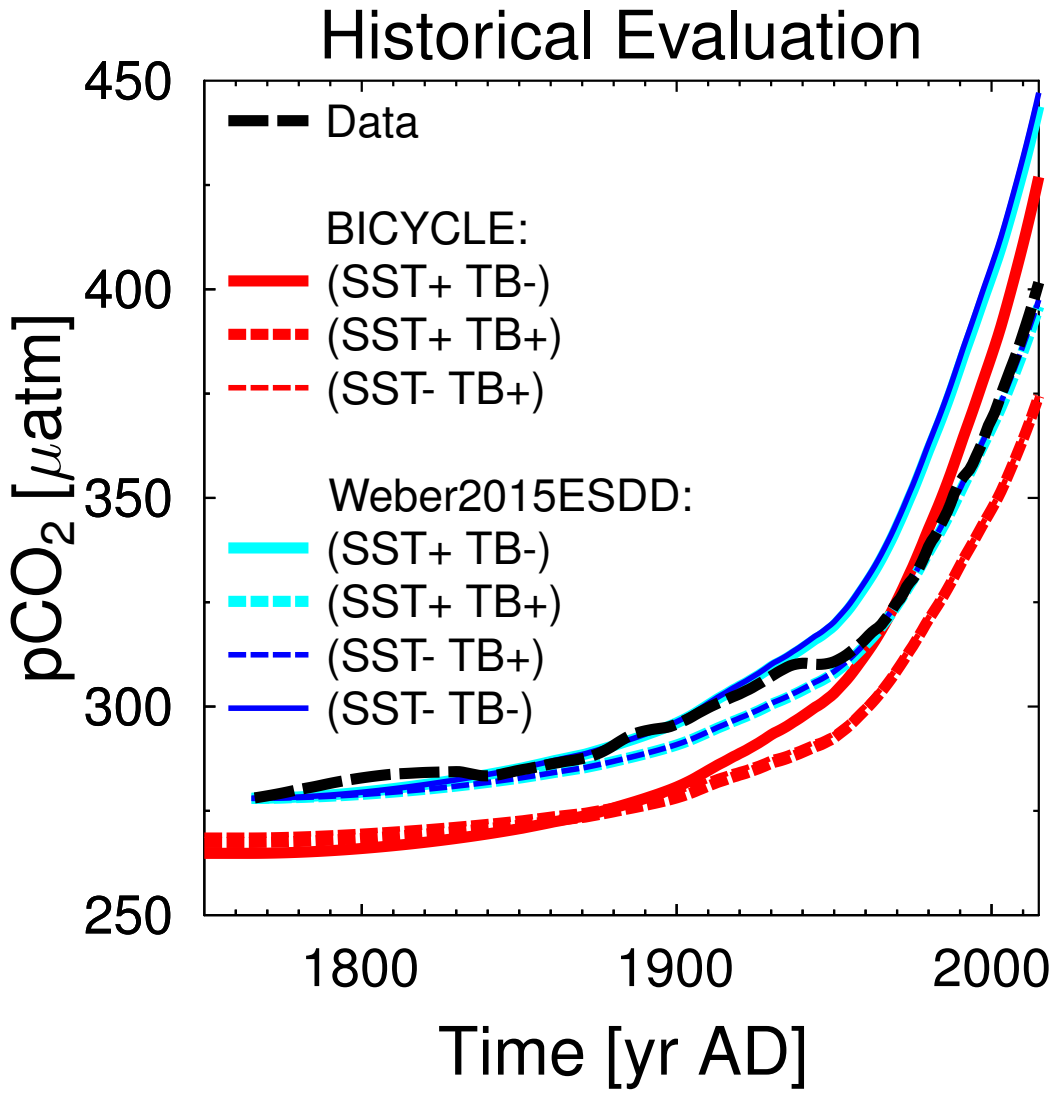

Figure 2: Comparing the simple model of Weber et al. (2015) with BICYCLE and data for historical times. Model versions neglect (-) or consider (+) land carbon uptake (TB), and temperature-dependent oceanic carbon uptake (SST).

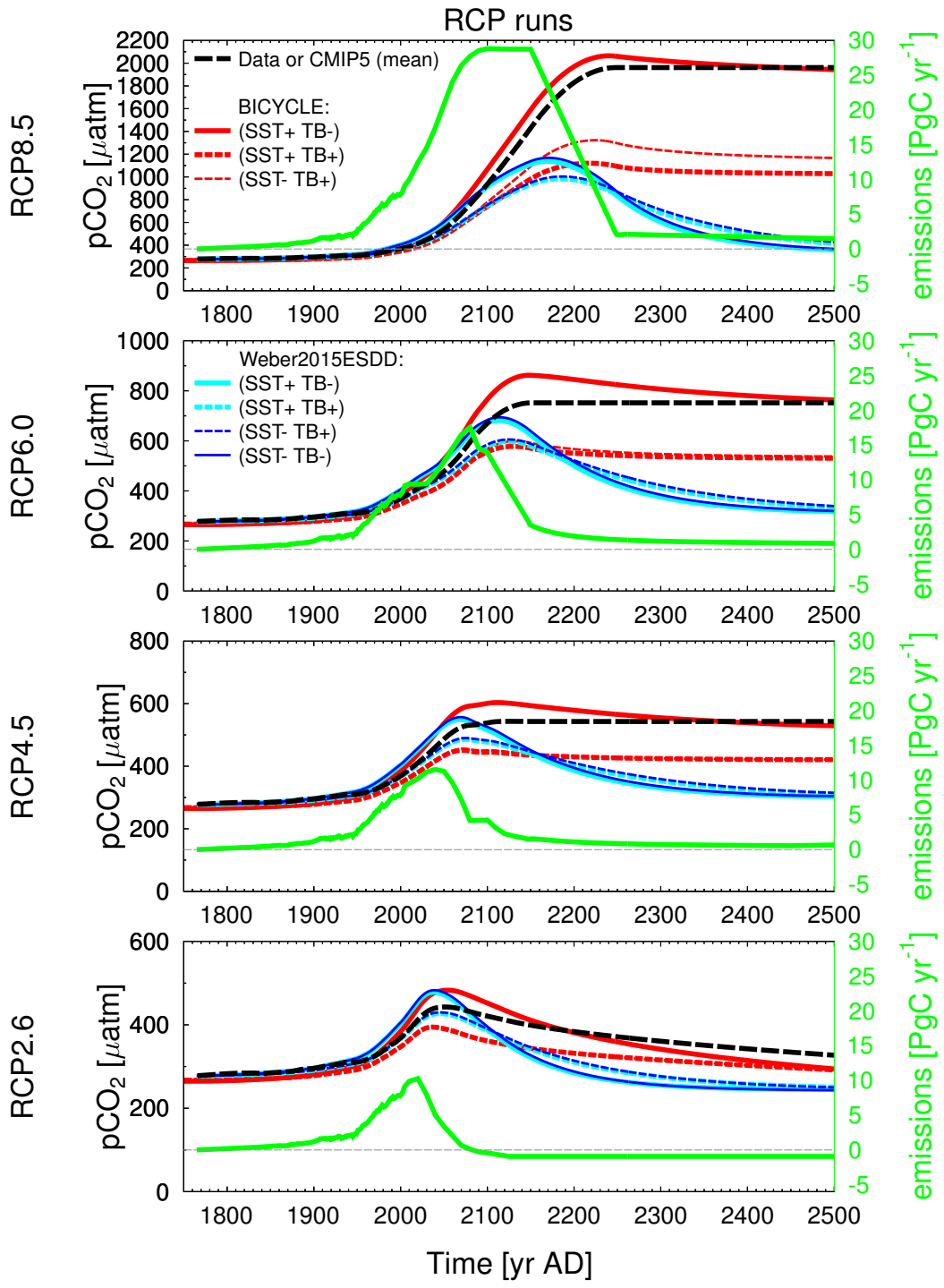

Figure 3: Comparing the simple model of Weber et al. (2015) with BICYCLE and CMIP5 projections for RCP emission scenarios for the next five centuries (until year 2500). Model versions neglect (-) or consider (+) land carbon uptake (TB), and temperature-dependent oceanic carbon uptake (SST).