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Earth System Dynamics Discussions

Interactive comment on "Estimates of climatic influence on the carbon cycle" *by* Ian Enting and Nathan Clisby

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Line-by-line comments.
This includes responses to all line-by-line comments from reviewer 2, and some additional changes to address issues raised in the review.

Additional change: Line 3 We feel that inserting a summary of the technique at this point in the abstract can clarify issues noted in the next few review comments, and also insert the sentence into the summary of the paper in section 1. However we suggest that this sentence be part of a largely restructured abstract as proposed below.
Proposed change. Insert: We propose a parameterised relation between temperature and CO_2 changes and use regression analysis to estimate the strength of the climate-

to-carbon influence by matching calculated CO_2 levels to measured concentrations obtained from ice core data.

Line 6 *Proposed change* See proposed revision of whole abstract.

Line 8 Constraint is not being able to have citations in abstract. *Proposed change* None

Line 9 See our comments for line 37. We think the issue is addressed by our proposed insertion at line 3. *Proposed change* (see above).

Line 21 See author comment number 2. *Proposed change* Move citation of Oeschger et al. to after equation (5).

Additional change: After line 26 To emphasise the points that we make in author comment 3. *Proposed change. Insert:* Following Rubino et al. (2016) we note that equation (1) generalises to a timescale-dependent form and that, as shown by equation (5), the relation is particularly clear when using Laplace transforms. Since we are analysing pre-industrial variation, we cannot talk about unique pre-industrial values of either CO_2 or temperature. Rather, we have to consider $Q(t)$ and $W(t)$ as perturbations about arbitrary reference levels with a requirement for consistency at a notional equilibrium state that may never have actually occurred.

Additional change: Line 30 *Proposed change, insert sentence* We use a parameterised relation between temperature and CO_2 changes and apply regression analysis to estimate the strength of the climate-to-carbon influence by matching calculated CO_2 levels to measured concentrations obtained from ice core data.

Line 37 We think that the proposed change at line 30 should dispel any implication that the paleo-temperature reconstructions are determined by CO_2 *Proposed change* as above

Eqn 2 $Q(t)$ has already been defined in connection with equation (1). However, to deal with the broader issue (which we had deferred until later): *Proposed change* Enting (2010) analysed the carbon-climate feedback loop in terms of CO_2 variations, $Q(t)$, and temperature variations, $W(t)$, (with Laplace transforms $q(p)$ and $w(p)$ respectively) as

$$w(p) = u(p)[\alpha' \, q(p) + f_{\text{other}}(p)] \qquad \text{(Enting and Clisby(2))}$$

where $U(t)$ (with transform $u(p)$) gives the temperature response to radiative forcing. Given the variations, we cannot specify unique pre-industrial values of either CO_2 or temperature. Rather they are defined relative to reference levels, subject to a consistency constraint that depends on the strength of the climate-to-carbon coupling and which becomes part of our estimation.

Additional change: Eqn (3) and following As foreshadowed in author comment 1. Introduce $\alpha' u(p) = \alpha(p)$ for greater consistency with other studies. *Proposed change*

$$w(p) = \alpha(p)q(p) + w_{\text{other}} \qquad \text{(Enting and Clisby(3))}$$

where we define $\alpha(p) = \alpha' \, u(p)$ so that $\alpha(p)$ becomes a timescale-dependent generalisation of the term α used in other studies such as Friedlingstein et al. (2006: eqn 6) and subsequent analysis.

Eqn 4 *Proposed change* As indicated in connection with eqn (2).

Line 59 Since the Laplace transform expression $p\,r(p)$ is giving the airborne fraction for emissions that grow as $\exp(pt)$, cumulative and current airborne fractions are equal. *Proposed change* As noted by Oeschger et al. (1980) the partition factors depend on the timescale of growth and need to be written as $\beta_O(p)$ and $\beta_L(p)$. This can be related to response functions (Enting, 1990) so that for exponential growth at rate p (when cumulative and instantaneous airborne fractions are equal), the airborne fraction is $\psi(p) = 1/(1 + \beta_l(p) + \beta_O(p)) = p\,r(p)$. Defining $\gamma(p) = -h(p)/p$ and noting that $s(p)/p$ is the transform of integrated emissions, relation (4) becomes

Line 64 Of course all the connection is an example of normal feedback analysis and the specific case is given by Enting (2010) and Gregory et al (2009). But since Gregory doesn't do the timescale dependence and Enting (2010) may be difficult to access, we propose. (Note that, as foreshadowed in author comment 1, we have replaced α by α' and defined $\alpha(p) = \alpha'\,u(p)$). *Proposed change: replace line 63 with* Substituting (3) into (4) gives

$$q(p) = r(p)[s(p) + \alpha(p)h(p)q(p) + h(p)w_{other}(p)] \qquad (new)$$

whence

$$q(p)[1 - \alpha(p)r(p)h(p)] = r(p)[s(p) + h(p)w_{other}(p)] \qquad (new)$$

so that the feedback loop has a gain

Additional change: Equations 6, 7, 8 *Proposed change* Renumber these (and all subsequent equations) and replace $\alpha\,u(p)$ by $\alpha(p)$.

Line 73 *Proposed change* In the absence of any ability to partition the temperature changes represented by $w(p)$ into changes caused by CO_2 and changes from other causes, relation (9) . . .

Line 93 (reviewer has this as line 90) Ambiguity referred to past studies where the (now unambiguous) distinction had not been made. *Proposed change* A new part of our analysis is recognising the uncertainties in using responses that may explicitly represent R_{FB} explicitly vs responses presented as $R(t)$ but which may implicitly include climate-carbon feedback effects and estimating a scale factor to account for these uncertainties.

Eqn 11,12 We are not using the limits to fix the behaviour. We are merely saying what the limits are, in order to facilitate comparisons with other studies. The word 'interpolates' is a description of what the function does, not how we constructed it. Our re-wording also addresses issues relevant to the choice of τ. *Proposed change* Parameterisation (11) has simple limits of constant h and constant γ at large and small values of p respectively. However neither of these limits will be of great importance for our analysis, given the ice core data span less than 2000 years, and the nature of the bubble trapping smooths out rapid variations in concentration.

Additional change: After Line 114 Reviewer 2 notes the need to discuss the choice of τ, without specifying a particular place to do so. *Proposed change* As in the studies by Rubino et al. (2016) we have used $\tau = 100$ years, guided by the behaviour of various carbon cycle models, and by the recognition that, as noted above, the behaviour of $h(p)$ on timescales that are much longer or much shorter will not greatly influence our analysis.

Eqn 16 *Proposed change* As suggested, move equation to next section, and modify lines 119–120 as described in next point.

Additional change: Replacing Lines 119–120
Proposed change Our analysis uses regression based on equation (10), generalising the work of Rubino et al. (2016) who only used the second term. We use the generic

notation R_{ref} to cover various estimates and estimate a scale factor θ_s. Similarly, we define a reference function H_{ref} by

$$H(t) = \gamma' H_{\text{ref}}(t) \quad (16)$$

leaving another scale factor, γ', to be estimated.

Eqn 17 We think the issues are addressed by the change above. *Proposed change* As above.

Line 124 *Proposed change* As suggested, move sentence about hat notation to immediately after equation (18).

Eqn 18 The discussion continues in terms of Laplace transforms, firstly for compactness and readability (as we note in lines 134), but mainly as a path to discussion θ_s. Laplace transform relations are multiplicative and so we can factor out the terms $r_{\text{FB}}(p)$ and $r(p)$ to suggest $1/\theta_s$ is an estimate of $r_{\text{FB}}(p)/r(p)$ (while also making it explicit that a single number is serving as a proxy for a relation that depends on timescale). Without the ability to factor out terms, working in the time domain would mean that the relations would have to be expressed as integrals involving $W(t)$ and $H(t)$. (see author comment 3). *Proposed change* None/

Additional change after eqn 18
Proposed change insert after eqn 18 as used by Rubino et al. (2016).

Line 139 If we had a reliable estimate of $R(t)$, then we could dispense with θ_γ and just use γ'. This assumption was made in the analysis by Rubino et al. (2016). Similarly we could make θ_s exactly equal to 1 rather than a quantity to be estimated (thus leading to estimation based on equation (19)). However, as argued (with specific examples) by Enting (2011), empirical estimates of the CO_2 response are going to be closer to R_{FB} rather than $R(t)$. This interpretation is confirmed by our finding of estimates of θ_s that are less than one. Of course, as noted in the previous point, encapsulating the difference between $R(t)$ and $R_{FB}(t)$ through a single scaling factor is only an approximation. *Proposed change* None at this point. We think that the changes made at Line 93 address this issue.

Line 208 Expanding a little, to be more explicit.
Proposed change This suggests that the Moberg data are sampling regions that do not always represent hemispheric averages but which have a larger than average sensitivity of terrestrial carbon to northern hemisphere temperature.

Line 209 *Proposed change, replace sentence on 208–9 by* This would explain why Bastos et al. (2016) were unable to explain the 1940s plateau and why Rafelski et al. (2009) were unable to explain the combination of the plateau and the anomalously great increase in CO_2 over the preceding decades.

Line 238 *Proposed change* Bauska et al. based their analyses on CO_2 fluxes obtained by model-based deconvolutions. Within the linear approximation, deconvolution can be represented as $1/r(p)$ (Enting 2007) and so their analysis corresponds to . . .

Line 240 *Proposed change, move as suggested. So at end of line 236:* The Laplace transform is $x_k(p) = \lambda_k/(p + \lambda_k)$.

Line 240 Rewording, following on from the change to line 238. *Proposed change* In terms of our parameterisation this corresponds to fitting $\gamma(p)\, w(p) \sim \beta_k\, x_k(p)\, w(p)$

l**Line 255** *Proposed change (as suggested)* having

Line 261 *Proposed change (remove dash as suggested) but emphasise that failure to include time-scale dependence is a form of over-parameterisation. Change to:* . . . over-parameterisation, especially through the failure . . .

Line 262 dangling word reflects our incorrect bracketing of reference. *Proposed change* .. notably Bauska et al. (2015).

Line 282–287 While desirable, an error analysis would require knowing the covariance structure of the paleodata. We see this as beyond the scope of this paper. *Proposed change* None.

Line 287–291 This could indeed be cut, but we think that our reasons for not including analysis of glacial-interglacial changes are things that should be considered by anyone who extends our analysis to consider pre-Holocene times. *Proposed change:* Defer to editor's view.

Line 300 The use of the hat as common statistical notation is introduced in line 124, immediately before the section where we start using it. Since it is part of the notation, we think it is worth flagging in the notation section, in the same way as other items in the notation are duplicating definitions that are given in the text. *Proposed change* None.

Additional change: Line 332 (As foreshadowed in AC1) *Proposed change* Keep this line as definition of α' and follow with line defining $\alpha(p) = \alpha' \, u(p)$

Table 1 *Proposed change. Reword first 2 sentences of caption as* Estimates, $\hat{\theta}_\gamma$, from fitting ice core CO_2 data over the time frame shown. All cases use response R_{init} and $\tau = 100$ years

Table 2 *Proposed change. Reword first 2 sentences of caption as* Estimates, $\hat{\theta}_\gamma$ (upper row), and $\hat{\theta}_s$ (lower row), from fitting ice core CO_2 data over the time frame shown. All cases use response R_{init} and $\tau = 100$ years

Figure 3 (with same change on figures 4 and 5) *Proposed change, add to caption* Triangles show CO_2 concentrations from Law Dome DSS ice core (see Rubino et al. (2016).

Additional change: Line 384 *Proposed to insert:* The authors gratefully acknowledge the thoughtful and detailed review comments.

Proposed re-write of abstract

The influence of climatic change on the carbon cycle is important as part of a CO_2-climate feedback loop. Quantitative analysis needs to go beyond characterising the climate-to-CO_2 influence by a single number γ relating CO_2 variation to temperature variation.

Several paleo-temperature reconstructions are analysed assuming that CO_2 is influenced by the history of temperature changes, thereby incorporating a time-scale dependence into the characterisation of the climate-to-carbon influence. The analysis is based on a parameterised relation between temperature and CO_2 changes and uses regression analysis to estimate the strength of the climate-to-carbon influence by matching calculated CO_2 levels to measured concentrations obtained from ice core data.

Expanding on such previous analyses of the pre-industrial period 1000–1750, shows that even when accounting for time-scale dependence, the coldest part of the Little Ice Age seems to reflect different behaviour to that in earlier or later centuries. Different temperature reconstructions appear to capture distinct aspects of pre-industrial climate fluctuations with varying consequences for implied CO_2 changes and differences in when and how closely these match the observed CO_2 changes. This disparate behaviour is consistent with recent analyses showing a lack of global coherence in pre-industrial climate variation.

The analysis is extended into the industrial period. both by extrapolating pre-industrial fits and, once taking anthropogenic emissions into account, fits that include the 20th century. Again the results show disparate behaviour from different paleo-data sets. Most paleo-temperature data fail to imply a plateau (or plateaus) in 20th century ice-core CO_2. One particular high-resolution reconstruction that does not closely reflect hemispheric temperature changes, does imply CO_2 changes that match observed plateaus in concentration. The implication is that the reconstruction possibly sampled a pattern of variation where the terrestrial carbon exchange is anomalously sensitive to regional climate variations. These various results suggest that this type of empirical study may have limited applicability to the 21st century.

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