Altes Material
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https://geosci.uchicago.edu/~archer/warming_papers/cox.2000.biota.pdf

Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model

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Abstract
The continued increase in the atmospheric concentration of carbon dioxide due to anthropogenic emissions is predicted to lead to significant changes in climate [1] .
- About half of the current emissions are being absorbed by the ocean and by land ecosystems [2] ,
- but this absorption is sensitive to climate [3,4] as well as to atmospheric carbon dioxide concentrations [5] , creating a feedback loop.

General circulation models have generally excluded the feedback between climate and the biosphere, using static vegetation distributions and CO2 concentrations from simple carbon-cycle models that do not include climate change [6] . Here we present results from a fully coupled, three-dimensional carbon- climate model, indicating that carbon-cycle feedbacks could significantly accelerate climate change over the twenty-first century.

We find that under a `business as usual' scenario,
- the terrestrial biosphere acts as an overall carbon sink until about 2050, but
- the terrestrial biosphere turns into a source thereafter.
- By 2100, the ocean uptake rate of 5 Gt C yr-1 is balanced by the terrestrial carbon source, and
- atmospheric CO2 concentrations are 250 p.p.m.v. higher in our fully coupled simulation than in uncoupled carbon models [2],
- resulting in a global-mean warming of 5.5 K, as compared to 4 K without the carbon-cycle feedback.

The coupled climate/carbon-cycle model was brought to equilibrium with a `pre-industrial' atmospheric CO2 concentration of 290 p.p.m.v., starting from an observed landcover data set [9]. The resulting state was stable, with negligible net land ±o atmosphere and ocean to atmosphere carbon fluxes in the long-term mean, and no discernible drift in atmospheric CO2 concentration.

This simulation produces the locations of the main land biomes, and estimates of
- ocean carbon (38,100 Gt C),
- vegetation carbon (493 Gt C),
- soil carbon (1,180 Gt C) and
- terrestrial net primary productivity (60 Gt C yr-1)

that are within the range of other estimates [2,10,11,12] . Ocean primary productivity is also compatible with results derived from remote sensing 13,14 , producing a global-mean total of 53 Gt C yr-1 , and realistic seasonal and latitudinal variations [15] . Transient simulations were carried out for 1860 - 2100, using CO2 emissions as given by the IS92a scenario [18] . Other greenhouse gases were also prescribed from IS92a, but the radiative effects of sulphate aerosols were omitted. Three separate runs were completed to isolate the effect of climate/carbon-cycle feedbacks;
- an experiment with prescribed IS92a CO2 and fixxed vegetation (that is, a `standard' General Circulation Model (GCM) climate change simulation),
- an experiment with interactive CO2 and dynamic vegetation but no direct effects of CO2 on climate (akin to `offline' carbon-cycle projections that neglect climate change [6]), and
- a fully coupled climate/carbon-cycle simulation.

An increase in the concentration of atmospheric CO2 alone tends to increase the rate of photosynthesis and thus terrestrial carbon storage, provided that other resources are not limiting [4] . However, plant maintenance and soil respiration rates both increase with temperature. As a consequence, climate warming (the indirect effect of a CO2 increase) tends to reduce terrestrial carbon storage [11] , especially in the warmer regions where an increase in temperature is beneficial for photosynthesis.
- At low CO2 concentrations the direct effect of CO2 dominates, and both vegetation and soil carbon increase with atmospheric CO2 .
- But as CO2 increases further, terrestrial carbon begins to decrease, because
  - the direct effect of CO2 on photosynthesis saturates but
  - the specfic soil respiration rate continues to increase with temperature.

The transition between these two regimes occurs abruptly at around 2050 in this experiment (Fig. 4b). The carbon stored on land decreases by about 170 Gt C from 2000 to 2100, accelerating the rate of atmospheric CO2 increase over this period.

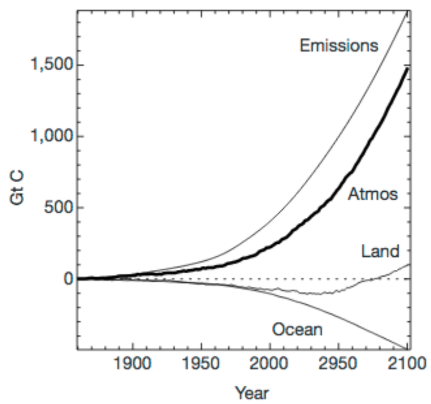

Fig. 2
Budgets of carbon during the fully coupled simulation. The thick line (Atmos) shows the simulated change in atmospheric CO2 . The thinner lines show the integrated impact of the emissions, and of land and ocean fluxes, on the atmospheric CO2 increase, with negative values implying net uptake of CO2 . We note that the terrestrial biosphere takes up CO2 at a decreasing rate from about 2010 onwards, becoming a net source at around 2050. By 2100 this source from the land almost balances the oceanic sink, so that atmospheric carbon content is increasing at about the same rate as the integrated emissions (that is, the airborne fraction is approx. 1).

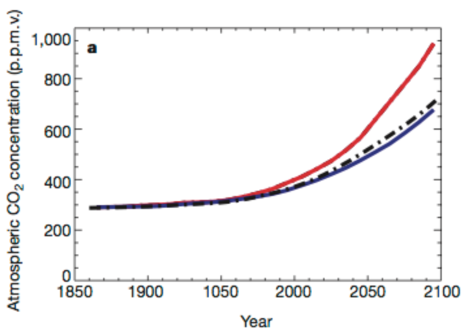

Figure 3
Effect of climate / carbon-cycle feedbacks on CO2 increase and global warming vs. year

3 simulations are shown;
1. the fully coupled simulation with interactive CO2 and dynamic vegetation (**red** lines),
2. a standard GCM climate change simulation with prescribed (IS92a) CO2 concentration and fixed vegetation (**dot-dashed** lines), and
3. the simulation which neglects direct CO2-induced climate change (**blue** lines).

The slight warming in the latter is due to CO2-induced changes in stomatal conductance and vegetation distribution.

Fig. 3a, Global-mean CO2 concentration.

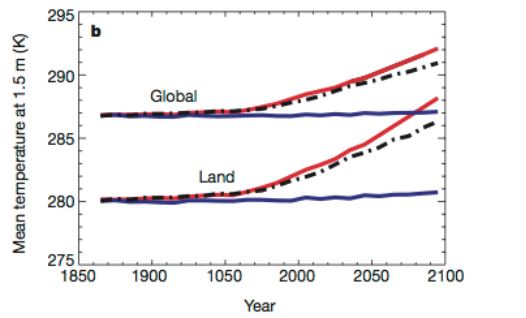

Figure 3
Effect of climate / carbon-cycle feedbacks on CO_2 increase and global warming vs. year

Fig. 3b, global-mean and land-mean temperature (K), versus year.

Ocean carbon-cycle model
The inorganic component of HadOCC has been extensively tested as part of the Ocean Carbon Cycle Intercomparison Project; it was found to reproduce tracer distributions to an accuracy consistent with other ocean GCMs [24] . The biological component treats four additional ocean Æelds: nutrient, phytoplankton, zooplankton and detritus [8] . The phyto- plankton population changes as a result of the balance between growth, which is controlled by light level and the local concentration of nutrient, and mortality, which is mostly as a result of grazing by zooplankton. Detritus, which is formed by zooplankton excretion and by phyto- and zooplankton mortality, sinks at a fixed rate and slowly remineralizes to reform nutrient and dissolved inorganic carbon. Thus both nutrient and carbon are absorbed by phytoplankton near the ocean surface, pass up the food chain to zooplankton, and are eventually remineralized from detritus in the deeper ocean. The model also includes the formation of calcium carbonate and its dissolution at depth (below the lysocline).

Terrestrial carbon-cycle model
TRIFFID (top-down representation of interactive foliage and Øora including dynamics) has been used ofØine in a comparison of dynamic global vegetation models [11] . Carbon fluxes for each vegetation type are calculated every 30 minutes as a function of climate and atmospheric CO_2 concentration, from a coupled photosynthesis/stomatal-conductance scheme [25,26], which utilizes existing models of leaf-level photosynthesis in C 3 and C 4 plants [27,28]. The accumulated Øuxes are used to update the vegetation and soil carbon every 10 days. The natural landcover evolves dynamically based on competition between the vegetation types, which is modelled using a Lotka±Volterra approach and a tree± shrub± grass dominance hierarchy. We also prescribe some agricultural regions, in which grass- lands are assumed to be dominant. Carbon lost from the vegetation as a result of local litterfall or large-scale disturbance is transferred into a soil carbon pool, where it is broken down by microorganisms that return $CO_2$2 to the atmosphere. The soil respiration rate is assumed to double for every 10 K of warming [29] , and is also dependent on the soil moisture content [30] . Changes in the biophysical properties of the land surface [5], as well as changes in terrestrial carbon, feed back onto the atmosphere.

https://geosci.uchicago.edu/~archer/warming_papers/allen.2009.trillionth_ton.pdf
Warming caused by cumulative carbon emissions towards the trillionth tonne (1000 GtC)
Myles R. Allen[1], David J. Frame[1,2], Chris Huntingford[3], Chris D. Jones[4], Jason A. Lowe[5], Malte Meinshausen[6] & Nicolai Meinshausen[7]
Vol 458 | 30 April 2009 | doi:10.1038/nature08019 1163 Macmillan Publishers Limited. All rights reserved ©2009

Figure 1: **Idealized carbon dioxide emission scenarios** *and* **response to benchmark scenario**

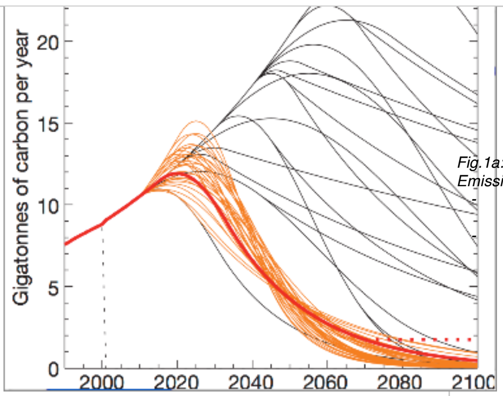

Fig.1a:
Emissions, including zero emissions after 2000 (dotted black line).
- *Solid red and orange lines show scenarios with cumulative emissions 1750–2500 within 1% of 1 Tt C.*
- **Solid red line shows benchmark case** *and* **dotted red line shows the '490 p.p.m. stabilization' scenario.**

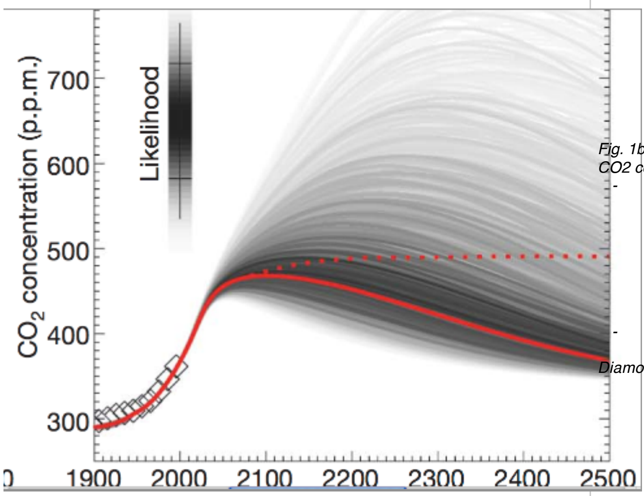

Fig. 1b:
CO_2 concentration response to
- *benchmark scenario*
  - *with* **best-fit combination of simple climate model parameters (solid red line***) and*
  - *with* **random parameter combinations shaded by likelihood** *(***grey plume***).*
  - *The vertical scale bar shows the corresponding likelihood profile for a normally distributed quantity, with black line showing 5–95% (horizontal tickmarks: 17–83%) confidence interval.*
- stabilization scenario
  - **dotted red line** shows **best-fit response**.

Diamonds show **observed** *CO_2 concentrations (relative to 1900–1920).*

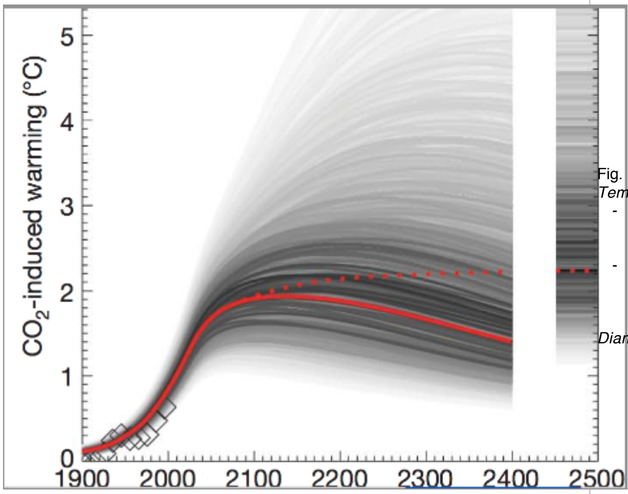

Fig. 1c:
Temperature response:
- *to benchmark scenario from simple model*
  - **best fit in red** *and*
  - **likelihood profile in grey**.
- *to '490 p.p.m. stabilization' emissions scenario:*
  - **Bar** *on right shows* **likelihood profile for peak warming response**
  - *in cases where temperatures are still rising in 2500, equilibrium warming response to 2500 CO2 concentration is plotted.*

Diamonds show **observed** *temperatures (relative to 1900–1920).*

uncertainties:
- climate system uncertainty: Equilibrium Climate Sensitivity (ECS): DT2x = 2.8 Celsius
  - assessment method: variation about 2.8 Celsius
- carbon cycle model uncertainties:
  - assessment method: random variation of key parameters

uncertainties cont.
- With most likely values of key parameters in this model (including an Equilibrium Climate Sensitivity, or ECS, of 2.8 degrees C for doubling atmospheric CO2) these emissions cause a warm- ing of 2.2 degrees C above pre-industrial by 2500,
- but much higher responses (shown by the shaded bar on the right of Fig. 1c) are also consistent with current uncertainties in ECS [1,2] and carbon cycle [9–11].
- The shading shows the range arising solely from known uncertainties in current feedbacks:
  - the true uncertainty is greater, particularly for long time- scales and higher responses, because feedbacks may change as the climate changes [3].
  - In practice, our descendants would be unlikely to adhere to this specific emissions scenario in the event that both CO2 and temperature overshoot the original targets, but
- this illustrates the 'stabilization dilemma':
  - either we specify a temperature or concentration target and accept substantial uncertainty in the emissions required to achieve it
  - or we specify emissions and accept even more uncertainty in the temperature response.

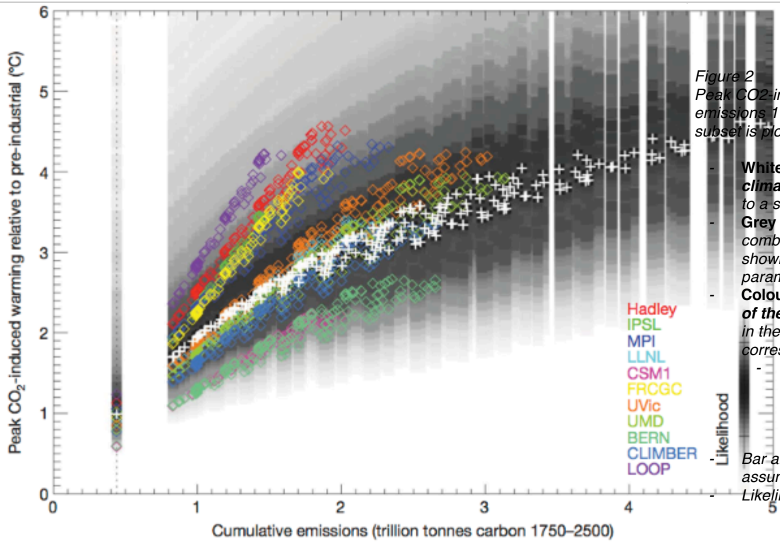

Figure 2
Peak CO2-induced warming as a function of total cumulative emissions 1750–2500 for 250 idealized emission scenarios. (A subset is plotted as black lines in Fig. 1a.)

- **White crosses** *correspond to best-fit values of* ***simple climate model*** *parameters, with each cross corresponding to a single scenario.*
- **Grey shading** *shows relative likelihood of other parameter combinations, plotted in order of increasing likelihood, showing the uncertainty in peak warming arising from parameter uncertainty in the simple model.*
- **Coloured diamonds** *show responses of* ***different versions of the HadSCCCM1 model*** *with parameters fitted to ESMs in the C4MIP experiment, with colours indicating the corresponding ESM.*
  - *Diamonds are plotted only where temperatures remain within 0.5 degrees C of the range of the tuning data set (the Special Report on Emission Scenarios (SRES) A2 scnario) to ensure a valid emulation.*
- *Bar and symbols at 0.44 TfC show peak warming assumung zero emissions after 2000.*
- *Likelihood scale bar as in Fig. 1b.*

Fig.2 plots peak carbon-dioxide-induced warming against the total carbon dioxide released over the entire period 1750 to 2500, expressed as Tt C, for **250 containment scenarios** (a subset of which are shown by the solid black lines in Fig. 1a).
- **most likely values of model parameters:**
  - *Each* white cross in Fig. 2 shows maximum warming under *one* scenario in the simple climate model with most likely values of model parameters.
- **uncertainty in modelled carbon cycle, atmosphere and ocean:**
  - The black–grey– white shading denotes the relative likelihood of different levels of warming for the same total carbon dioxide released, allowing for uncertainty in modelled carbon cycle, atmosphere and ocean.

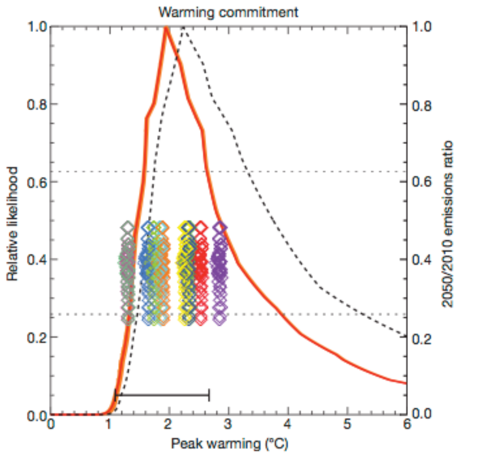

Figure 3 | Warming commitment for selected scenarios shown in Fig. 1a. Red and orange curves (superimposed) show likelihood profiles for cumulative warming commitment (CWC) under 49 scenarios with total emissions within 1% of 1 Tt C estimated with the simple climate-carbon- cycle model; dotted black curve shows likelihood profile for peak warming under '490 p.p.m. stabilization' scenario. Horizontal dotted lines show thresholds for the 17–83% and 5–95% confidence intervals19. The horizontal location of coloured symbols shows corresponding 1 Tt C CWCs predicted by HadSCCCM1 fitted to the ESMs in the C4MIP ensemble. The vertical location and right-hand axis shows fractional decrease in emissions 2010 to 2050 for each of the 49 emissions scenarios. Solid error bar shows 5–95% Bayesian posterior probability interval (1.1–2.7 uC) for 1 Tt C CWC based on an independent model and approach20.

Figure 3 shows an analysis of uncertainty in Cumulative Warming Committment (CWC) for the specific case of 1 Tt C total anthropogenic emission of CO2.

The 49 solid red and orange curves (superimposed and almost indistinguishable) show 'likelihood profiles' for peak warming response to the red and orange containment scenarios plotted in Fig. 1a, all of which represent cumulative emissions over 1750–2500 that fall within 1% of 1 Tt C.

- These show the relative likelihood of the most likely versions of the simple climate model out of the subset that gives the values of peak warming shown on the horizontal axis, where likelihoods are computed from the constraints detailed in Supplementary Figs S1 and S2.
- The overall best-fit (most likely) value of the 1 Tt C CWC is 2 C, and
- the 5–95% confidence interval (given by the range over which likelihoods exceed the corresponding threshold) is 1.3–3.9 C, again independent of which scenario is used to estimate it.
- The black dotted curve shows the likelihood profile for peak warming in response to the '490 p.p.m. stabilization scenario': the higher emissions in this scenario after 2070 have little impact on the most likely peak warming (they prolong the peak rather than raising it), but they double the likelihood of warming in the 3–6 C range because CO2 levels and temperatures continue to rise in more sensitive versions of the model.

Coloured symbols in Fig. 3 show CWC under these 49 1TtC containment scenarios predicted by HadSCCCM1 emulating the C4MIP ESMs.

- The horizontal spread of each set of coloured symbols is small, reiterating that CWC does not depend on the shape of the emission pathway.
- The variation in emission pathway is illustrated by the vertical position of coloured symbols, showing the fractional reduction in emissions from 2010 to 2050 (right axis) for each of the 49 scenarios.
- The large vertical spread shows that very different emission pathways with the same cumulative total give the same peak warming: reductions by 2050 only matter insofar as they affect the total CO2 released.

The black horizontal error bar in Fig. 3 shows a 5–95% Bayesian posterior probability interval for 1TtC CWC estimated from an additional independent model and approach detailed in ref. 20 using their representative distribution for climate system properties and our benchmark scenario. Corresponding intervals for the other 48 1 Tt C containment scenarios are almost identical, providing further evidence that the timing of emissions has no impact on CWC. The lower bound is consistent with the other two approaches detailed here. The upper bound is lower primarily because the posterior upper bound on past CO2-attributable warming implied by ref. 20, although consistent with typical inter-model ranges for Transient Climate Response1, is lower than the upper bound used to constrain the simple model, which is more consistent with observationally constrained confidence intervals for the transient response1,14,21

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