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To cite this article: Julia Pongratz and Ken Caldeira 2012 Environ. Res. Lett. 7 034001

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Environ. Res. Lett. 7 (2012) 034001 (8pp)

Attribution of atmospheric CO₂ and temperature increases to regions: importance of preindustrial land use change

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Received 26 April 2012 Accepted for publication 1 June 2012 Published 3 July 2012 Online at stacks.iop.org/ERL/7/034001

Abstract

The historical contribution of each country to today's observed atmospheric CO₂ excess and higher temperatures has become a basis for discussions around burden-sharing of greenhouse gas reduction commitments in political negotiations. However, the accounting methods have considered greenhouse gas emissions only during the industrial era, neglecting the fact that land use changes (LUC) have caused emissions long before the Industrial Revolution. Here, we hypothesize that considering preindustrial LUC affects the attribution because the geographic pattern of preindustrial LUC emissions differs significantly from that of industrial-era emissions and because preindustrial emissions have legacy effects on today's atmospheric CO₂ concentrations and temperatures. We test this hypothesis by estimating CO_2 and temperature increases based on carbon cycle simulations of the last millennium. We find that accounting for preindustrial LUC emissions results in a shift of attribution of global temperature increase from the industrialized countries to less industrialized countries, in particular South Asia and China, by up to 2-3%, a level that may be relevant for political discussions. While further studies are needed to span the range of plausible quantifications, our study demonstrates the importance of including preindustrial emissions for the most scientifically defensible attribution.

Keywords: attribution, atmospheric CO₂ concentration, climate change, preindustrial emissions, land use change/land cover change

S Online supplementary data available from stacks.iop.org/ERL/7/034001/mmedia

1. Introduction

The historical contribution of each country to today's observed atmospheric CO₂ excess and higher temperatures

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has become a basis for discussions around burden-sharing of greenhouse gas reduction commitments in the UNFCCC negotiations (UNFCCC Secretariat 1997, den Elzen et al 2005). While early proposals considered fossil-fuel emissions as the sole attribution criterion, they have been extended to include CO_2 emissions from land use changes (LUC) (den Elzen and Schaeffer 2002). Today, LUC, i.e. changes in vegetation cover due to agriculture and forestry, and related land management activities are the largest source of anthropogenic CO₂ emissions after fossil-fuel burning.

However, accounting methods considered emissions only during the industrial era-globally about 350 Gt C fossil-fuel (Marland et al 2008) and 150 Gt C LUC emissions (Houghton 2010). But unlike fossil-fuel burning, LUC led to substantial emissions already prior to the Industrial Revolution-between 20% and 40% (45-114 Gt C) of today's cumulative LUC emissions occurred in the preindustrial era (before AD 1850) (DeFries et al 1999, Olofsson and Hickler 2008, Strassmann et al 2008, Pongratz et al 2009, Stocker et al 2011). These preindustrial emissions not only increased the preindustrial atmospheric CO₂ concentration to levels higher than explicable by natural variability (Pongratz et al 2009), but also influenced the atmospheric CO_2 concentration during the industrial era. First, LUC causes substantial delayed emissions. When unmanaged land is transformed to agriculture only a part of the vegetation carbon is immediately released to the atmosphere, e.g. when burnt. The other part, such as roots and wood products, decays over years to centuries. Soil carbon pools adjust on a similar slow timescale. Second, the global carbon pools equilibrate slowly, so that anthropogenic CO₂ emissions cause an excess in atmospheric CO₂ over natural levels for a substantial time period: about half of the emissions are taken up by land and ocean carbon pools within 30 years, another 30% is removed from the atmosphere within a few centuries, and the rest remains in the atmosphere for millennia (Denman et al 2007).

Despite these legacy effects of preindustrial emissions, previous studies attributing the atmospheric CO₂ excess and consequent higher temperatures to different countries and regions have considered only industrial-era emissions of LUC and fossil fuels. Including preindustrial emissions can change the balance of attribution if their geographic pattern is very different from the pattern of industrial-era emissions. Industrial-era emissions are clearly dominated by fossil-fuel burning in the industrialized countries (Marland et al 2008). Some of these industrialized countries exhibited substantial LUC in the preindustrial era; e.g. in Eastern North America rates of deforestation rose steeply with progressing colonization (Ramankutty and Foley 1999), causing emissions in particular towards the end of the preindustrial era so that a substantial part of these emissions is still in the atmosphere today. In regions like North America, however, massive fossil-fuel burning leads to an only small ratio of preindustrial to industrial-era emissions. This picture is different in India and China. Here, the ratio of preindustrial to industrial-era emissions is high: when the world's population increased about five-fold between AD 800 and 1850 to over a billion, half of that population growth happened in India and China, leading to large-scale deforestation in the late-preindustrial era (McEvedy and Jones 1978). However, cumulative fossil-fuel emissions are low as these countries have started only relatively recently with substantial industrial activity. Due to such different geographic patterns of emissions over time, we hypothesize that consideration of preindustrial emissions will alter the balance of attribution of atmospheric CO₂ excess and higher temperatures between countries or regions.

To test our hypothesis we estimate the contribution to atmospheric CO_2 excess and higher temperatures based on recent studies that quantified LUC and associated CO₂ emissions for substantial parts of the preindustrial era. We then apply published approaches to estimate attribution of atmospheric CO₂ excess and higher temperatures to individual countries or regions (see section 2). Our analysis allows us to assess the importance of including preindustrial emissions. Uncertainties associated with LUC and the carbon cycle response are known to be substantial (Houghton et al 2012, den Elzen and Schaeffer 2002). We explore some of these uncertainties here by applying alternative emission datasets and carbon cycle models, but further studies considering preindustrial emissions would be needed to span the full range of uncertainties and develop quantitative estimates that are reliable enough to be used as a basis for international negotiations. We restrict our analysis to the effects of anthropogenic CO₂ emissions, the largest driver of current global warming, because estimates of preindustrial emissions of other substances are lacking, but our analysis can be extended as such estimates become available.

It has been acknowledged that the scientifically most accurate attribution of past climate change has to account for history, or would otherwise ignore the physical laws that atmospheric CO_2 excess results from emissions over a long time span (Neumayer 2000). While political decisions should be informed by the best available scientific basis, they take account of many different factors that are outside the realm of science. Key questions currently debated around burden-sharing of past emissions include: should countries be held responsible for emissions at a time where their effect on climate was not understood; should present generations be held responsible for historical activity, in particular as national identities were subject to change; should emissions be attributed to countries based on where they occur, as done in this and previous attribution studies, or based on where end products are consumed? While our study focuses on the scientific basis for attribution, these issues have been discussed in previous publications (Neumayer 2000, Gardiner 2004).

2. Methods

We use results from transient simulations over the last millennium (AD 800-2006) with the comprehensive climate model MPI-ESM (consisting of ECHAM5-JSBACH/MPIOM-HAMOCC5) including the closed, interactive carbon cycle (Jungclaus et al 2010). The land surface component JSBACH simulates the exchange of water, carbon, energy, and momentum between the terrestrial biosphere and the atmosphere. LUC is prescribed from maps and leads to a change in the fraction of vegetation type and a subsequent relocation of carbon to the atmosphere and to soil and product pools, where carbon decomposes with different turnover rates (Pongratz et al 2009). The first simulation applies a detailed land cover reconstruction (Pongratz et al 2008) to isolate the effects of LUC on climate, while the second simulation additionally includes CO2 emissions from fossil-fuel burning (Marland et al 2008). Emissions from LUC are calculated by additional uncoupled simulations of the terrestrial carbon pools as detailed in Pongratz et al (2009). These emissions are net LUC emissions in that they comprise both carbon losses to the atmosphere, as caused e.g. by clearing of forest, and carbon uptake by recovering vegetation, as caused e.g. when agricultural land is abandoned and forest regrows. Note that our LUC emission estimates differ slightly from Pongratz *et al* (2009): first, they are larger because we include fossil-fuel burning. The increase in atmospheric CO2 from fossil-fuel burning leads to additional CO2 fertilization that increases carbon stocks and therefore LUC emissions. Second, we split emissions into preindustrial and industrial parts not based on the time of release, but based on the time of the underlying LUC, i.e. we consider legacy emissions occurring after 1850 due to LUC before 1850 to be emissions from preindustrial LUC. This makes our study comparable to previous attribution studies, which did not consider any preindustrial LUC. Our analysis is spatially explicit at about 4° resolution; aggregated data refers to the regions and Annex I definition in table S1 (Houghton 2003) and S2 (UNFCCC 1998) (available at stacks.iop.org/ERL/7/034001/mmedia).

We approximate the response of the ocean and terrestrial biosphere to changes in atmospheric CO₂ by finding the multi-exponential response function that yields the best fit for the simulated atmospheric CO₂ concentration when convoluted with anthropogenic emissions (detailed in Pongratz *et al* (2011)). Convolution of the emission time series of each grid-cell with this response function quantifies the effect of the grid-cell emissions on global atmospheric CO₂ for each year. Because emissions are taken up over time by the ocean and terrestrial biosphere, earlier emissions have a smaller contribution to the atmospheric CO₂ concentration of any given year than recent emissions. This effect is commonly accounted for in attribution studies, and has been referred to as 'backward discounting of emissions' (UNFCCC Secretariat 2002, den Elzen et al 2005); it is illustrated in figure S1 (available at stacks.iop.org/ERL/7/034001/mmedia). We apply the response function of the first simulation throughout our analysis. Figure S2 (available at stacks.iop.org/ERL/7/ 034001/mmedia) shows that convolution with this response function closely approximates the simulated CO₂ evolution for both climate simulations. This analysis is repeated twice, first considering all emissions since AD 800, and second only emissions arising during the industrial era. The difference between the two results shows the relevance of including preindustrial emissions, which have been neglected by previous attribution studies.

We apply a common approximation (Trudinger and Enting 2005) to estimate changes in radiative forcing and temperature based on emissions from LUC and fossil-fuel burning. Figure S3 (available at stacks.iop.org/ERL/7/034001/mmedia) shows the global curves of LUC emissions, atmospheric CO₂ excess, radiative forcing, and temperature increase including and excluding preindustrial emissions.

We test the sensitivity of our results to uncertainties in LUC emissions and the carbon cycle response. The data and approach described above is referred to as our 'focal' analysis. This focal analysis has the advantage of providing estimates of LUC emissions and atmospheric CO₂ excess consistently from the same model and allows attribution of delayed emissions to preindustrial LUC activity. The focal analysis serves the primary aim of our study to show the importance of considering preindustrial emissions when attributing atmospheric CO₂ excess and higher temperatures to individual countries or regions. We assess uncertainties associated with LUC emission estimates and the carbon cycle response by applying alternative datasets to the ones used in the focal analysis: We repeat our analysis with an alternative response function (Maier-Reimer and Hasselmann 1987), which assumes a higher long-term airborne fraction of anthropogenic CO₂ emissions, and an alternative dataset of LUC emissions (Stocker et al 2011), applying the response function of Maier-Reimer and Hasselmann (1987). While the exact quantifications are subject to the choice of data and response function, the qualitative conclusions drawn in our study are robust.

Due to the paucity of preindustrial data on land management, neither LUC emission dataset (Pongratz et al 2009, Stocker et al 2011) includes activities such as wood harvest (Houghton 2010). However, including such effects would likely not alter our general conclusion. Emissions from land cover changes as they are considered in our analysis constitute the majority of CO2 emissions from LUC and land management (Houghton et al 2012). Further, both LUC and other land management practices are closely linked to population density in the preindustrial era (McEvedy and Jones 1978), so that emissions are expected to increase roughly proportionally to LUC emissions when other land management processes are included. Therefore, shifts in attribution between regions are not sensitive towards inclusion or exclusion of certain land use processes. By ignoring other land management, our estimate of the overall relevance of preindustrial LUC is expected to be on the conservative side by underestimating preindustrial emissions.

3. Results

We first present results including both preindustrial and industrial-era LUC emissions; then we present results that isolate the legacy effect of preindustrial LUC on today's atmospheric CO₂ excess and higher temperatures. Figure 1 shows emissions of world regions in absolute values, while figure 2 shows the relative contribution of each region to the atmospheric burden of atmospheric CO₂ excess over time after accounting for the timing of emissions and the uptake by land and ocean sinks. A striking feature is the large variability in relative contributions in the preindustrial era, which is caused by historic events such as wars and epidemics. Because population decreases during such historic events, agricultural land is abandoned, allowing forest to regrow and absorb CO₂ from the atmosphere. Wars and epidemics during the last millennium include the Black Death in Europe in the 14th century; the Mongol invasion in China in the 13th and 14th century and the fall of the Ming Dynasty in the 17th century; and the conquest of the Americas in the 16th and 17th century. While emissions from the Americas play



Figure 1. Emissions from land use change (LUC). (a) Global emissions. The left panel shows the preindustrial era, the right panel the industrial era with an expanded vertical range. A running mean of 10 years is applied. (b) Emissions for world regions. Running means are 50 years for the preindustrial and 30 years for the industrial era. Note that for Pacific Developed negative LUC emissions are simulated as explained in the supplemental discussion (available at stacks.iop.org/ERL/7/034001/mmedia).

a minor role in the global carbon budget due to the high fraction of non-agriculturally active people, the other events lead to a significant regional carbon sink (as in the case of the strong, long-lasting event of the Mongol invasion) or at least substantially reduce emission rates in the affected regions (Pongratz *et al* 2011). Atmospheric CO_2 excess attributed to these regions therefore stagnates or even decreases during the events. These events result in decreases in relative contributions (shown in figure 2) as other regions continue to emit at increasing rates. A more continuous sink behavior is simulated for North Africa/Middle East. This region was affected by various invasions, the bubonic plague, and the Mediterranean economic recession between the 11th and 17th century. These events caused permanent agricultural area to be abandoned and allowed natural vegetation to regrow, leading to a simulated uptake of CO_2 and a negative contribution to the global CO₂ increase. The simulated carbon uptake in Australia (Pacific Developed) is likely an artifact owing to the lack of representation of grazing on natural lands in our model, but does not considerably affect attribution of atmospheric CO₂ excess and higher temperatures to regions, in particular outside Australia (see supplemental material available at stacks.iop.org/ERL/7/034001/mmedia).

Overall, tropical regions contribute most to today's (defined as 2006) atmospheric CO_2 excess caused by LUC, while South Asia (predominantly India) and China account

for almost half of the atmospheric CO_2 excess that had occurred by the beginning of the industrial era (figures 2(a) and 3(a)). As none of these regions has caused substantial fossil-fuel burning when compared with the industrialized countries (figures 2(d) and 3(b)), including LUC in addition to fossil-fuel emissions shifts attribution of atmospheric CO_2 excess towards the tropical regions at the end of the industrial era (den Elzen *et al* 1999), and towards South Asia and China earlier in the industrial era (figures 2(e) and 3(c)).

We isolate the legacy effect of preindustrial LUC emissions on today's atmospheric CO₂ excess by comparing attribution results including and excluding preindustrial LUC, shown in figures 2(e)-(f) and 3(d). Although globally, preindustrial emissions have contributed only about 5% to today's atmospheric CO₂ excess (table S3 available at stacks.iop.org/ERL/7/034001/mmedia), this fraction amounts to 10–40% in regions of low industrial-era emissions such as in South Asia and China (figure 3(e)). Thus, considering preindustrial emissions leads to a shift in attribution of atmospheric CO₂ excess from the industrialized countries to South Asia and China not just early in the industrial era, but still today (figure 3(f)).

Various climate model studies suggest that LUC emissions have increased global mean temperature by 0.16-0.30 K in the 20th century (Brovkin *et al* 2004, Matthews *et al* 2004 and Pongratz *et al* 2010). Preindustrial emissions have a larger proportional effect on today's temperature than on today's atmospheric CO₂. The atmospheric CO₂ excess is taken up by land and ocean over time, but temperature increases from these earlier periods of CO₂ excess persist due primarily to ocean thermal inertia. In our focal analysis, preindustrial LUC is responsible for 9% of the 0.74 K increase in today's global mean temperature (table S4 available at stacks.iop. org/ERL/7/034001/mmedia). Consideration of preindustrial LUC emissions alters the relative contribution to higher global temperatures of the world regions, and between Annex I and non-Annex I countries, by up to 2% (table 1).

4. Discussion

The model applied in our focal analysis, MPI-ESM, has been shown to deliver results within the range of observations and other biosphere-atmosphere models with respect to climate and carbon cycle variables (Friedlingstein et al 2006, Raddatz et al 2007). The emission estimates used in this study have been evaluated on the global scale and shown to be within the range of previous estimates for the preindustrial period (Pongratz et al 2009). They have been shown to be consistent with estimates from bookkeeping models, other process-based models, and inventory data for the industrial era (Houghton 2010). However, uncertainties associated with LUC emissions are large—globally on the order of $\pm 50\%$ —because of differences in processes included in individual analyses, rates of change in land use, carbon density, and fate of affected carbon stocks and land (Houghton et al 2012). Applying an alternative dataset of LUC emissions (Stocker et al 2011) (see section 2), the relative contributions of regions to the global temperature increase differ by a few per cent between



Figure 2. Contribution (in %) of world regions to atmospheric CO₂ excess in years AD 1000–2006. (a) Contribution based on emissions from land use change (LUC) (L), repeated in (b) for the time period since AD 1850. 'L' consists of L_{pre} based on only emission from preindustrial-era LUC shown in (a) before 1850, and L_{ind} based on only emissions from industrial-era (after 1850) LUC shown in (c). (d) Contribution based on emissions from fossil-fuel burning (F). (e) Contribution based on combined emissions from LUC since AD 800 (bold colors) and fossil-fuel burning (pale colors). (f) Contribution based on combined emissions from LUC since AD 1850 (bold colors) and fossil-fuel burning (pale colors). (f) Contribution based on combined emissions from LUC since AD 1850 (bold colors) and fossil-fuel burning (pale colors). The attribution of the atmospheric CO₂ excess for example in AD 1500 is a consequence of the emissions from AD 800 to 1500 in each region and global uptake of the ocean and the biosphere. The atmospheric CO₂ excess due to L and L + F is shown in figure S2 (available at stacks.iop.org/ERL/7/034001/mmedia). Figure S4 (available at stacks.iop.org/ERL/7/034001/mmedia) shows the data from (a) in absolute values (Gt C).

Table 1. Attribution of temperature increase in 2006 to regions (in % of global temperature increase): accounting for emissions from fossil-fuel burning and land use change only during the industrial era AD 1850–2006, as in previous studies, or accounting for emissions AD 800–2006. Table S5 (available at stacks.iop.org/ERL/7/034001/mmedia) shows corresponding data for the attribution of the atmospheric CO₂ excess.

	1850-2006	800-2006	Difference
Latin America	11.6	11.5	-0.1
Southeast Asia	6.7	7.1	0.4
Tropical Africa	5.9	5.8	-0.2
North America	23.7	22.5	-1.2
Former Soviet Union	11.4	11.5	0.0
Europe	19.8	19.1	-0.7
South Asia	5.1	7.0	1.9
China	8.2	8.7	0.5
Pacific Developed	4.7	4.3	-0.4
North Africa/Middle East	2.7	2.5	-0.2
Annex I	58.1	55.8	-2.2
Non-Annex I	41.9	44.2	2.2
Global	100.0	100.0	0.0

the focal and alternative analysis (table S6 available at stacks. iop.org/ERL/7/034001/mmedia). Such differences are in line with previous studies that assessed the uncertainty of LUC emission data in attribution studies (den Elzen *et al* 1999). However, for both emission datasets the shift in relative contribution caused by accounting for preindustrial LUC is generally of similar magnitude and pattern. In particular the shift from industrialized countries to South Asia and China, and from Annex I to non-Annex I countries, is robust. Differences in sign of the shift between emission datasets occur for 2 regions: in Tropical Africa, LUC emissions are known only with substantial uncertainties even today (Houghton and Hackler 2006); in Europe, the focal analysis assumes lower emissions in the late-preindustrial era than the alternative dataset, but the timing of occurrence of preindustrial LUC in Europe has recently been disputed with suggestion of even less LUC in the centuries preceding the Industrial Revolution (Gaillard *et al* 2010). For the other 8 of the 10 regions, the sign of the shift is unaffected by the choice of LUC emission dataset.

The choice of carbon cycle response function has similar importance for attribution results as the choice of LUC emission dataset. Again, the relative contributions of regions to the global temperature increase differ from the focal analysis by a few per cent when we apply the carbon cycle response function of Maier-Reimer and Hasselmann (1987). Under this alternative response function, the importance of accounting for preindustrial emissions is generally slightly larger; shifts in attribution e.g. from Annex I to non-Annex I countries are 2.8% as compared to 2.2% in the focal analysis. The sign of the shift in relative contributions caused by accounting for preindustrial LUC are in the same direction as in the focal analysis for all regions.

Overall, across the tested LUC emission datasets and carbon cycle response functions, the importance of preindustrial emissions for attribution is on the order of 2-3% changes in relative contribution to global temperature



Figure 3. Contribution to today's (AD 2006) atmospheric CO₂ excess. (a) Contribution based on emissions from land use change (LUC) (L) since AD 800. (b) Contribution based on emissions from fossil-fuel burning (F). (c) Contribution based on emissions from combined LUC and fossil-fuel burning (L + F). Contributions in (a)–(c) are expressed relative to the mean contribution per unit area from both LUC and fossil-fuel burning (i.e., the mean value over land for panel (c) is 1.0; panel (c) is the sum of panel (a) and panel (b)). (d) Contribution to today's atmospheric CO₂ excess caused by emissions from preindustrial LUC only (also included in panel (a)). (e) Fraction (unit-less) of today's atmospheric CO₂ excess caused by LUC and fossil-fuel burning that is attributable to preindustrial LUC. (f) We recalculate panel (c) excluding the effect of preindustrial LUC and subtract the result from panel (c). It therefore shows the change in attribution of today's atmospheric CO₂ excess when preindustrial emissions are taken into account. Areas with the highest positive values in panel L_{pre}/(L + F), such as South Asia, China, Southeast Asia, and the Western parts of the Former Soviet Union, would be underestimated (red colors in panel Δ_{pre}) if preindustrial LUC emissions were not taken into account, and regions with the lowest values, such as Western Europe and Northeast USA, would be overestimated (blue colors in panel Δ_{pre}).

increase of individual regions and Annex I versus non-Annex I countries. Changes of 2-3% are of similar magnitude as the uncertainties associated with the choice of LUC emission dataset (den Elzen et al 1999) or the choice of approach to distribute effects of non-linearities in the climate system (Trudinger and Enting 2005). Such changes can be important politically if regional contributions are used as basis for sharing the burden of climate change mitigation (Trudinger and Enting 2005). While changes in contributions of individual regions to global temperature increase are small from a global perspective, these changes can be substantial at a regional level. For example, without considering preindustrial LUC, we estimate that in the focal analysis 5.1% of global temperature increase can be attributed to South Asia. With consideration of preindustrial LUC, attribution to South Asia increases to 7.0% (table 1). This represents a 37% increase in the share of temperature increase attributed to South Asia (27-47% spanning the range of tested LUC emission datasets and carbon cycle response functions (table S6 available at stacks.iop.org/ERL/7/034001/ mmedia)). For China, these changes are 6-14%. Increases of this magnitude may be quite important to affected countries.

Much discussion has been devoted to the starting date of the accounting period (den Elzen *et al* 2005). The Brazilian Proposal suggested 1840 to account for the history of emissions. Here we show that including emissions prior to 1840 would give a more scientifically defensible attribution. Of emissions occurring even earlier than the last millennium, less than 20% remain in the atmosphere (Maier-Reimer and Hasselmann 1987). Beyond the millennial time scale, carbonate compensation and silicate weathering draw the airborne fraction further down (Archer *et al* 2009). Thus, preindustrial emissions before the last millennium are of secondary importance compared to the late-preindustrial emissions considered in our study.

Irrespective of the choice of starting date, a clearly defined accounting requires a clear definition for what types of CO₂ emissions are to be considered as occurring within the accounting period. This is particularly relevant to LUC because it causes substantial delayed emissions. In our focal analysis, 10 of the 62 Gt C caused by preindustrial LUC are released after 1850, increasing today's atmospheric carbon content by 3 Gt C. Similarly, carbon sinks in the terrestrial biosphere, for example the regrowth of natural vegetation on abandoned agricultural land, affect net emission rates over decades to centuries-the timescale of soil carbon pools to recover and of trees to fully regrow. This effect has reduced the contribution to atmospheric CO₂ excess of the Middle East in our study. Similar carbon sinks created in Europe and the eastern USA due to cropland abandonment since the 1850s (Ramankutty and Foley 1999) have offset a significant portion of their LUC emissions. High spatial resolution and a sufficiently long history of LUC are required to capture such sink effects and their consequences for later time periods, which, unlike the event of abandonment, may be covered by the accounting period.

5. Conclusions

Discussions around burden-sharing of greenhouse gas reduction commitments are commonly based on the historical contribution of each country to today's observed atmospheric CO₂ excess and higher temperatures. Previous attribution studies have considered emissions from fossil-fuel burning and land use change (LUC) only after 1840, despite substantial preindustrial LUC. Here we show that accounting for CO₂ emissions from preindustrial LUC shifts attribution from the industrialized to less industrialized countries. A higher attribution is simulated in particular for South Asia (predominantly India) and China, and a lower attribution to the Annex I countries. Changes in the relative contribution of regions to global temperature increase are on the order of 2-3%. The relevance of accounting for preindustrial emissions is therefore of the same order of magnitude as has been found in previous studies for the sensitivity of attribution results to the choice of emission datasets or the choice of approach to distribute effects of non-linearities in the climate system. It is thus relevant to political discussions. While a coordinated research program would be needed to generate reliable estimates that can be used quantitatively as the basis for international negotiations, our quantifications demonstrate the importance of considering preindustrial LUC for an accurate and scientifically defensible attribution of atmospheric CO₂ excess and higher temperatures. Furthermore, it is instructive to note that, just as the relatively small amounts of CO₂ emitted many centuries ago continue to have impacts on atmospheric CO₂ concentrations and climate today, the relatively large amounts of CO_2 we are emitting today will continue to have relatively large impacts on atmospheric CO₂ concentrations and climate many centuries into the future.

Acknowledgments

We thank Christian Reick, Thomas Raddatz and Martin Claussen for helpful discussions and their contribution to the land cover/climate modeling work on which this study is based. The climate–carbon cycle simulations for this study were carried out at the Max Planck Institute for Meteorology and the German Climate Computation Center (DKRZ), Hamburg, as part of the 'Community Simulations of the Last Millennium' (www.mpimet.mpg.de/en/science/internalprojects/millennium.html); we thank Johann Jungclaus and all participants.

References

- Archer D *et al* 2009 Atmospheric lifetime of fossil fuel carbon dioxide *Annu. Rev. Earth Planet. Sci.* **37** 117
- Brovkin V, Sitch S, von Bloh W, Claussen M, Bauer E and Cramer W 2004 Role of land cover changes for atmospheric CO₂ increase and climate change during the last 150 years *Glob. Change Biol.* **10** 1253–66
- DeFries R, Field C, Fung I, Collatz G and Bounoua L 1999 Combining satellite data and biogeochemical models to estimate global effects of human-induced land cover change on

carbon emissions and primary productivity *Glob. Biogeochem. Cycles* **13** 803–15

- den Elzen M, Berk M, Schaeffer M, Olivier J, Hendriks C and Metz B 1999 The Brazilian Proposal and Other Options for International Burden Sharing: An Evaluation of Methodological and Policy Aspects Using the FAIR Model, RIVM Report 728001011/1999 (The Netherlands: RIVM)
- den Elzen M and Schaeffer M 2002 Responsibility for past and future global warming: uncertainties in attributing anthropogenic climate change *Clim. Change* **54** 29–73
- den Elzen M, Schaeffer M and Lucas P 2005 Differentiating future commitments on the basis of countries' relative historical responsibility for climate change: uncertainties in the 'Brazilian proposal' in the context of a policy implementation *Clim. Change* 71 277–301
- Denman K et al 2007 Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change ed S Solomon, D Qin, M Manning, Z Chen, M Marquis, K Averyt, M Tignor and H Miller (Cambridge: Cambridge University Press)
- Friedlingstein P *et al* 2006 Climate–carbon cycle feedback analysis: results from the C4MIP Model Intercomparison *J. Clim.* **19** 3337–53
- Gaillard M et al 2010 Holocene land-cover reconstructions for studies on land cover-climate feedbacks Clim. Past 6 483–99
- Gardiner S 2004 Ethics and global climate change *Ethics* **114** 555–600
- Houghton R 2003 Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use 1850–2000 *Tellus* B **55** 378–90
- Houghton R 2010 How well do we know the flux of CO₂ from land-use change? *Tellus* B **62** 337–51
- Houghton R and Hackler J 2006 Emissions of carbon from land use change in sub-saharan Africa J. Geophys. Res. 111 G02003
- Houghton R, van der Werf G, DeFries R, Hansen M, House J, Pongratz J and Ramankutty N 2012 Regional carbon cycle assessment and processes (RECCAP) synthesis chapter G2: carbon emissions from land use and land-cover change *Biogeosci. Discuss.* 9 835–78
- Jungclaus J *et al* 2010 Climate and carbon-cycle variability over the last millennium *Clim. Past* **6** 723–37
- Maier-Reimer E and Hasselmann K 1987 Transport and storage of CO₂ in the ocean—an inorganic ocean-circulation carbon cycle model *Clim. Dyn.* 2 63–90
- Marland G, Andres B and Boden T 2008 *Global CO*₂ *Emissions* from Fossil-Fuel Burning, Cement Manufacture, and Gas Flaring: 1751-2005 (Oak Ridge, TN: Carbon Dioxide Information Analysis Center)
- Matthews H, Weaver A, Meissner K, Gillett N and Eby M 2004 Natural and anthropogenic climate change: incorporating historical land cover change, vegetation dynamics and the global carbon cycle *Clim. Dyn.* 22 461–79
- McEvedy C and Jones R 1978 Atlas of World Population History (Harmondsworth: Penguin Books)
- Neumayer E 2000 In defence of historical accountability for greenhouse gas emissions *Ecol. Econ.* **33** 185–92
- Olofsson J and Hickler T 2008 Effects of human land-use on the global carbon cycle during the last 6000 years *Vegetat. Hist. Archeobot.* **17** 605–15
- Pongratz J, Caldeira K, Reick C and Claussen M 2011 Coupled climate–carbon simulations indicate minor global effects of wars and epidemics on atmospheric CO₂ between AD 800 and 1850 *Holocene* 21 843–51
- Pongratz J, Reick C, Raddatz T and Claussen M 2008 A reconstruction of global agricultural areas and land cover for the last millennium *Glob. Biogeochem. Cycles* 22 GB3018
- Pongratz J, Reick C, Raddatz T and Claussen M 2009 Effects of anthropogenic land cover change on the carbon cycle of the last millennium *Glob. Biogeochem. Cycles* 23 GB4001

 Pongratz J, Reick C, Raddatz T and Claussen M 2010
Biogeophysical versus biogeochemical climate response to historical anthropogenic land cover change *Geophys. Res. Lett.* 37 L08702

- Raddatz T, Reick C, Knorr W, Kattge J, Roeckner E, Schnur R, Schnitzler K G, Wetzel P and Jungclaus J 2007 Will the tropical land biosphere dominate the climate–carbon cycle feedback during the twenty-first century? *Clim. Dyn.* 29 565–74
- Ramankutty N and Foley J 1999 Estimating historical changes in global land cover: croplands from 1700 to 1992 *Glob. Biogeochem. Cycles* **13** 997–1027
- Stocker B, Strassmann K and Joos F 2011 Sensitivity of Holocene atmospheric CO₂ and the modern carbon budget to early human land use: analyses with a process-based model *Biogeosciences* 8 69–88
- Strassmann K, Joos F and Fischer G 2008 Simulating effects of land use changes on carbon fluxes: past contributions to

atmospheric CO_2 increases and future commitments due to losses of terrestrial sink capacity *Tellus* B **60** 583–603

- Trudinger C and Enting I 2005 Comparison of formalisms for attributing responsibility for climate change: non-linearities in the Brazilian proposal approach *Clim. Change* **68** 67–99
- UNFCCC (United Nations Framework Convention on Climate Change) 1998 Kyoto Protocol to the United Nations Framework Convention on Climate Change (www.unfccc.int/ resource/docs/convkp/kpeng.pdf)
- UNFCCC (United Nations Framework Convention on Climate Change) Secretariat 1997 Paper No. 1: Brazil; Proposed Elements of a Protocol to the United Nations Framework Convention on Climate Change, presented by Brazil in response to the Berlin Mandate. UNFCCC/AGBM/1997/ MISC.1/Add.3 GE.97- (Bonn: UNFCCC)
- UNFCCC (United Nations Framework Convention on Climate Change) Secretariat 2002 Methodological Issues. Scientific and Methodological Assessment of Contributions to Climate Change. FCCC/SBSTA/2002/INF.14 (New Delhi: UNFCCC)