

Developed and developing world responsibilities for historical climate change and CO₂ mitigation

Ting Wei^a, Shili Yang^a, John C. Moore^{a,b,c}, Peijun Shi^a, Xuefeng Cui^a, Qingyun Duan^a, Bing Xu^{a,d}, Yongjiu Dai^a, Wenping Yuan^a, Xin Wei^a, Zhipeng Yang^a, Tijian Wen^a, Fei Teng^e, Yun Gao^f, Jieming Chou^a, Xiaodong Yan^a, Zhigang Wei^a, Yan Guo^a, Yundi Jiang^g, Xuejie Gao^g, Kaicun Wang^a, Xiaogu Zheng^a, Fumin Ren^g, Shihua Lv^h, Yongqiang Yuⁱ, Bin Liu^e, Yong Luo^j, Weijing Li^k, Duoying Ji^a, Jinming Feng^a, Qizhong Wu^a, Huaqiong Cheng^a, Jiankun He^e, Congbin Fuⁱ, Duzheng Yeⁱ, Guanhua Xu^a, and Wenjie Dong^{a,1}

^aState Key Laboratory of Earth Surface Processes and Resource Ecology, College of Global Change and Earth System Science, Beijing Normal University, Beijing 100875/Zhuohai 519087, China; ^bArctic Centre, University of Lapland, PL122, 96100 Rovaniemi, Finland; ^cDepartment of Earth Sciences, Uppsala University, Villavägen 16, Uppsala SE-75236, Sweden; ^dDepartment of Environmental Science and Engineering, Tsinghua University, Beijing 100084, China; ^eEnergy, Environment, and Economy (3E) Research Institute, Tsinghua University, Beijing 100084, China; ^fClimate Change Division, Department of Science and Technology, China Meteorological Administration, Beijing 100081, China; ^gNational Climate Center, China Meteorological Administration, Beijing 100081, China; ^hCold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China; ⁱInstitute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China; ^jCenter for Earth System Science, Tsinghua University, Beijing 100084, China; and ^kLaboratory for Climate Studies, China Meteorological Administration, Beijing 100081, China

Edited by Mark H. Thieme, University of California San Diego, La Jolla, CA, and approved June 18, 2012 (received for review March 4, 2012)

At the United Nations Framework Convention on Climate Change Conference in Cancun, in November 2010, the Heads of State reached an agreement on the aim of limiting the global temperature rise to 2°C relative to preindustrial levels. They recognized that long-term future warming is primarily constrained by cumulative anthropogenic greenhouse gas emissions, that deep cuts in global emissions are required, and that action based on equity must be taken to meet this objective. However, negotiations on emission reduction among countries are increasingly fraught with difficulty, partly because of arguments about the responsibility for the ongoing temperature rise. Simulations with two earth-system models (NCAR/CESM and BNU-ESM) demonstrate that developed countries had contributed about 60–80%, developing countries about 20–40%, to the global temperature rise, upper ocean warming, and sea-ice reduction by 2055. Enacting pledges made at Cancun with continuation to 2100 leads to a reduction in global temperature rise relative to business as usual with a 1/3–2/3 (CESM 33–67%, BNU-ESM 35–65%) contribution from developed and developing countries, respectively. To prevent a temperature rise by 2°C or more in 2100, it is necessary to fill the gap with more ambitious mitigation efforts.

climate modeling | Coupled Model Intercomparison Project phase 5 | Cancun pledge | climate ethics | geoengineering

The impact of human activities on climate change at global and regional scales, including surface temperature (1), sea-level pressure (2), tropopause height (3), precipitation (4), and ocean heat content (5), has been explored and assessed. Greenhouse gas emissions, mostly CO₂, are the most important anthropogenic forcing on climate (6). The contribution of greenhouse gas emissions varies widely among nations in both the past and the future. As a result, the United Nations Framework Convention on Climate Change (UNFCCC) reached an agreement that each nation should accept its “common but differentiated responsibilities.” This ethical construct demands attribution studies of the historical contribution of emissions to climate change (7). To date, research has tracked the causal chain of climate change from human activities to greenhouse gas emissions, to radiative forcing, and finally to climate change. However, this conventional methodological flow does not consider the reverse process or include feedbacks from climate change to greenhouse-gas concentrations via biogeochemistry or decision-making processes (8). More than 100 countries have adopted a global warming limit of 2°C or below (relative to preindustrial levels) as a guiding principle for mitigation efforts to reduce climate-change risks, impacts, and damage (9, 10). The relationship between the climate policy

making and the 2°C target by an appropriate emission pathway has been studied in simple climate models and probabilistic analysis (11, 12). However, climate projection experiments under many emission scenarios, even the latest representative concentration pathways (RCPs) (13), have not considered actual inter-governmental agreements.

In this study we quantify the responsibilities for CO₂ emissions of developed and developing countries and demonstrate the effect of emission cuts following the Cancun pledges on global temperature rise. Our study differs from earlier attempts in that we use two state-of-the-art, coupled earth-system models, NCAR/CESM (14) and BNU-ESM (15) (*Materials and Methods*), rather than a simple model to demonstrate the effect of CO₂ emission from different country groups on global historical temperature rise and future mitigation.

Results and Discussion

We divided nations by their UNFCCC Annex I status (Fig. S1). Three experiments were designed (Table S1): (i) ALL: global anthropogenic emissions [equivalent to the Coupled Model Intercomparison Project phase 5 (CMIP5) (16) 20th-century history experiment]; (ii) AX1: anthropogenic emissions only allowed from developed countries (i.e., Annex I countries); and (iii) NX1: anthropogenic emissions only allowed from developing countries (i.e., non-Annex I countries).

Fig. 1 shows the observed and simulated CO₂ concentration from the models. CO₂ concentration and its rising trend simulated by ALL are overestimated by the CESM model during the last 50 years, while the BNU-ESM model gives an underestimate during the late 19th and 20th centuries. However, this is not critical in the assessment of relative contributions. Since our separation into the two emission groups was only aimed at the anthropogenic CO₂ without consideration of other forcing, the increase of atmospheric CO₂ concentration simulated by ALL

Author contributions: W.D. designed research; T. Wei, S.Y., J.C.M., P.S., X.C., and W.D. performed research; X.W., Z.Y., T. Wen, F.T., Q.W., and J.H. contributed new reagents/analytic tools; T. Wei, S.Y., and Y. Guo analyzed data; and T. Wei, S.Y., J.C.M., P.S., X.C., Q.D., B.X., Y.D., W.Y., X.W., Z.Y., T. Wen, F.T., Y. Gao, J.C., X.Y., Z.W., Y. Guo, Y.J., X.G., K.W., X.Z., F.R., S.L., Y.Y., B.L., Y.L., W.L., D.J., J.F., Q.W., H.C., J.H., C.F., D.Y., G.X., and W.D. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Freely available online through the PNAS open access option.

¹To whom correspondence should be addressed. E-mail: dongwj@bnu.edu.cn.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1203282109/-DCSupplemental.

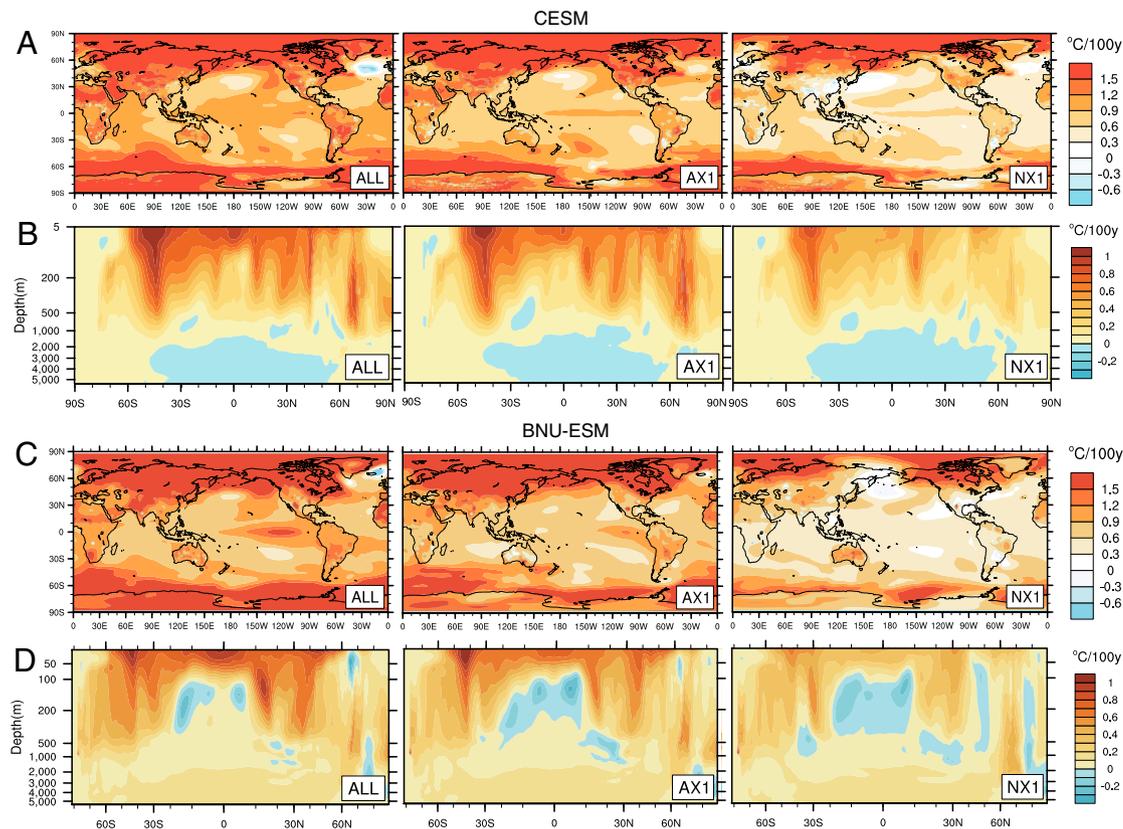


Fig. 2. Modeled centennial linear-trend patterns of air temperature (panels A and C, units: °C/100 y) and ocean temperature (panels B and D, units: °C/100 y) from 1906 to 2005 by the CESM and BNU-ESM model. Experiments used are labeled ALL (historical emissions), AX1 (developed world emissions only), and NX1 (developing world emissions only).

Fig. 3 shows the RCPs (13) and the four experiments we use in terms of concentration, illustrating that our scenarios are bracketed within the RCP range. Additionally, our future scenarios ABNC and ACNB produce similar atmospheric CO₂ concentrations to those of the RCP4.5 and RCP6.0, respectively (*Materials and Methods*). The simulated global mean air temperature during 2081–2100 in the ABNB, ABNC, ACNB, and ACNC scenarios are 3.2 °C, 2.4 °C, 2.8 °C, and 2.0 °C (BNU-ESM: 4.4 °C, 3.4 °C, 3.9 °C, 2.9 °C) higher than preindustrial levels. Using the normalized proportional approach, if developed and developing countries follow the Cancun pledges, their contributions to the slowing down of global warming by 2081–2100 are 1/3 and 2/3 (CESM 33%–67%, BNU-ESM 35–65%), respectively, compared with ignoring their pledges and pursuing business as usual (ABNB scenario).

Throughout the second half of the 20th century, developed economies have effectively exported their CO₂ emissions through their imports of manufactured products from developing countries (22). For example, international trade has cumulatively relocated 16 Gigatonne (Gt) CO₂ from developed countries to developing countries from 1990 to 2008 (23). In 2004, 23% of global CO₂ emissions, or 6.2 Gt CO₂, were traded internationally, primarily as exports from China and other emerging markets to consumers in developed countries (24). The results of this study show that the emissions-reduction commitments by developed countries in the Cancun pledges cannot effectively curb climate change, nor does it reflect their historical ethical responsibility, which still accounts for greater than half of the total climate change impacts by 2005, despite the rapid growth in emissions from the developing world. Thus stronger mitigation efforts by developed countries are needed to keep temperature rise below the 2 °C objective on the basis of equity in the future.

In addition to energy-saving and emissions-reduction measures, other controversial alternatives are being explored to cope with climate change and to keep temperature rise within a “safe”

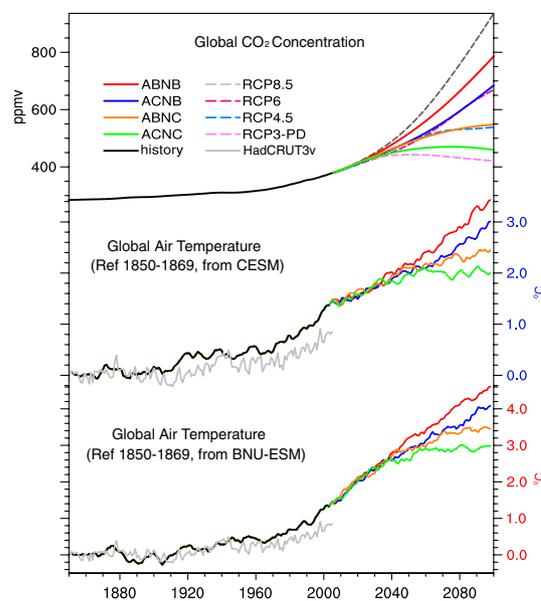


Fig. 3. CO₂ concentration and simulated air temperature in four future experiments simulated by two earth-system models. *Top:* Observed and predicted atmospheric CO₂ concentrations. The black line is the observed CO₂ concentration, which is supplied by CMIP5. The other real lines indicate four future scenarios. They are labeled ABNB (all countries follow business as usual), ACNB (developed countries follow Cancun pledges while developing world pursues business as usual), ABNC (developing countries follow Cancun pledges while developed world does not), and ACNC (all countries follow their Cancun pledges). The broken lines come from the latest representative concentration pathways (RCPs) (13). *Middle:* Air temperature anomalies (relative to 1850–1869, five-year running averaged field) simulated by CESM combining historical simulation and four future scenarios. The observed (gray line) is from HadCRUT3v (31). *Bottom:* same as middle, but based on simulations by BNU-ESM.

(2°C) limit (25). Should mitigation and adaptation measures prove to be difficult, states may be tempted to turn to geoengineering without sufficient research into consequences including its political implementation (26). The governance issues raised, however, as with other challenging social questions, cannot be addressed by simple measurement or models but must be reasoned out and are beyond the scope of this paper, except for emphasizing the urgency of addressing these issues.

Materials and Methods

Model Description. The two models we use here have participated in the CMIP5 and will be used as assessment tools in the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (16). The Community Earth System Model (CESM1_0_2) (14) is a fully coupled earth-system model. It is composed of four separate models simultaneously simulating the earth's atmosphere (CAM4), ocean (POP2), land surface (CLM4), and sea-ice (CICE4), and it includes one central coupler component (CPL7). It has an interactive carbon cycle model in the land component and an ecosystem-biogeochemical module in the ocean component. The first version of Beijing Normal University—Earth System Model (BNU-ESM) (15) is a fully coupled earth-system model. In addition to one central coupler component (improved NCAR-CPL6), it contains four separate models simultaneously simulating the earth's atmosphere (NCAR-CAM3.5), ocean (GFDL-MOM4p1), land surface (BNU-CoLM3), and sea ice (LANL-CICE4.1). It has an interactive carbon cycle model in the land component (BNU-DGVM based on LPJ) and an ecosystem-biogeochemical module in the ocean component (IBGC). In the two models, simulated atmospheric CO₂ concentrations are fully coupled to land and ocean CO₂ fluxes and are thus used directly to compute radiative forcing. Methane release due to permafrost melting is a potentially huge impact on warming. But CESM and BNU-ESM have only very simple carbon permafrost models presently and no marine methane release is included.

Historical Simulations. Time series of industrial CO₂ emissions (i.e., fossil-fuel burning, cement manufacturing, and gas flaring in oil fields) are available at 1° × 1° spatial resolution from 1751 to 1949 at annual resolution and from 1950 to 2007 at monthly resolution (27). Deforestation is an important factor contributing to total carbon emissions (28). A significant number of forests in developing countries were cut during the 1960s to 1980s, mostly to supply the demands from the developed countries that had already depleted their own forest resources (29). Therefore, we do not consider deforestation as an attributing factor by nation (Fig. S2). We used the CESM version 1_0_2 at 0.9° × 1.25° resolution and the BNU-ESM version 1.0 at T42 resolution (approximately 2.8° × 2.8°). The model was integrated over the historical period (1850–2005) by prescribing the three kinds of CO₂ emissions (i.e., ALL, AX1, NX1). Other forcings varying over the historical period include non-CO₂ greenhouse gases (CH₄, N₂O, halocarbons), aerosols, solar irradiance, and volcanoes (Table S1).

Future Simulations. For future simulations we conducted four experiments (i.e., ABNB, ABNC, ACNB, and ACNC) covering the period from 2006 to 2100. We calculated global carbon emission projections to CO₂ concentration in the atmosphere using the MAGICC5.3 model (30). We then applied the CESM at 1.9° × 2.5° resolution and the BNU-ESM at T42 resolution, employing the global CO₂ concentrations as the forcing data instead of the interactive carbon cycle used in the historical scenarios. Other forcing was based on the historical and RCP4.5 (Table S2).

Normalized Proportional Approach. If we define V_{AX1} as the outcome of the CO₂ emissions from developed countries between some start and ending dates, those from developing countries as V_{NX1} , and V_{ALL} as the whole world's emissions, then we note that $V_{AX1}/V_{ALL} + V_{NX1}/V_{ALL} \neq 1$ due to non-linearity. Therefore we need to normalize the contributions as $V_{AX1}/(V_{AX1} + V_{NX1})$ for the developed countries and $V_{NX1}/(V_{AX1} + V_{NX1})$ for the developing countries. We can use the same approach for changes in any field of interest such as CO₂ concentration, surface temperature, or sea ice. In partitioning the developed and developing countries' services to slow down global warming relative to business as usual, $V_0 = V_{ACNC} - V_{ABNB}$ is considered to be the total effect by all countries following the Cancun pledges and further reductions. $V_1 = V_{ACNB} - V_{ABNB}$ denotes the effect caused by emission reductions from developed countries and $V_2 = V_{ABNC} - V_{ABNB}$ denotes the effect caused by emission reductions from developing countries. When using the normalized proportion approach, the value of V is the difference between 1850 and 2005 for CO₂ concentration and its radiative forcing since they are smoothly varying variables, while the value of V is the difference between 20-year averages 1986–2005 (2081–2100) and 1850–1869 for the other fields (temperature, sea ice, and oceanic heat content) to smooth their annual fluctuations.

The Representative Concentration Pathways (RCPs). RCPs are descriptions of potential future discharges to the atmosphere of substances that affect the Earth's radiation balance, such as greenhouse gases and aerosols. They are meant to serve as input for climate and atmospheric chemistry modeling. RCP4.5 is the emission pathway for stabilization at 4.5 W/m² radiative forcing in 2100; it results in an atmosphere concentration of 650 ppm equivalent CO₂ in 2100. Similarly, RCP6.0 is the emission pathway to stabilization at radiative forcing of 6.0 W/m² in 2100, which results in an atmospheric concentration of 850 ppm equivalent CO₂ (13). The ABNC and ACNB emission paths produce similar atmospheric CO₂ concentrations to those produced by RCP4.5 and RCP6.0, respectively.

ACKNOWLEDGMENTS. We thank Marion Ferrat for comments on the manuscript. The work is funded by the National Key Program for Global Change Research of China Grant 2010CB950500.

- Barnett T, et al. (2005) Detecting and attributing external influences on the climate system: A review of recent advances. *J Clim* 18:1291–1314.
- Gillett NP, Zwiers FW, Weaver AJ, Stott PA (2002) Detection of human influence on sea-level pressure. *Nature* 88:292–294.
- Santer BD (2003) Contributions of anthropogenic and natural forcing to recent tropopause height changes. *Science* 301:479–483.
- Zhang X, et al. (2007) Detection of human influence on twentieth-century precipitation trends. *Nature* 448:461–465.
- Barnett TP, et al. (2005) Penetration of human-induced warming into the world's oceans. *Science* 309:284–287.
- Hegerl GC, et al. (2007) *IPCC Climate Change 2007: The Physical Science Basis*, eds S Solomon et al. (Cambridge Univ Press, Cambridge, UK), pp 663–746.
- Den Elzen MGJ, Schaeffer M (2002) Responsibility for past and future global warming: Uncertainties in attributing anthropogenic climate change. *Clim Change* 54:29–73.
- Frank DC, et al. (2010) Ensemble reconstruction constraints on the global carbon cycle sensitivity to climate. *Nature* 463:527–530.
- Meinshausen M, et al. (2009) Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature* 458:1158–1162.
- United Nations Framework Convention on Climate Change Report of the conference of the parties on its sixteenth session, held in Cancun from 29 November to 10 December 2010 (2011). Available at <http://unfccc.int/resource/docs/2011/sb/eng/inf01r01.pdf>.
- Den Elzen MGJ, Hof AF, Roelfsema M (2011) The emissions gap between the Copenhagen pledges and the 2°C climate goal: Options for closing and risks that could widen the gap. *Global Environ Change* 21:733–743.
- Rogelj J, et al. (2011) Emission pathways consistent with a 2°C global temperature limit. *Nat Clim Change* 1:413–418.
- Moss RH, et al. (2010) The next generation of scenarios for climate change research and assessment. *Nature* 463:747–756.
- Gent PR, et al. (2011) The community climate system model version 4. *Bull Am Meteorol Soc* 24:4973–4991.
- College of Global Change and Earth System Science (2012) *Beijing Normal University—Earth System Model*, Available at http://esg.bnu.edu.cn/BNU_ESM_webs/htmls/index.html.
- Taylor KE, Stouffer RJ, Meehl GA (2012) An overview of CMIP5 and the experiment design. *Bull Am Meteorol Soc* 93:485–498.
- Den Elzen MGJ, et al. (1999) The Brazilian proposal and other options for international burden sharing: An evaluation of methodological and policy aspects using the FAIR model. *RIVM Report No.728001011*, Available at <http://unfccc.int/resource/brazil/documents/rap728001011.pdf>.
- Vinnikov KY, et al. (1999) Global warming and Northern Hemisphere sea ice extent. *Science* 286:1934–1937.
- AchutaRao KM, et al. (2007) Simulated and observed variability in ocean temperature and heat content. *Proc Natl Acad Sci USA* 104:10768–10773.
- Levitus S, Antonov JI, Boyer TP (2005) Warming of the world ocean, 1955–2003. *Geophys Res Lett* 10.1029/2004GL.
- He JK, Chen WY, Teng F, Liu B (2009) Long-term climate change mitigation target and carbon permit allocation. *Adv Clim Change Res* 5:78–85, Available at <http://www.climatechange.cn/CN/abstract/abstract8471.shtml>.
- Peters GP, Hertwich EG (2008) CO₂ embodied in international trade with implications for global climate policy. *Environ Sci Technol* 42:1401–1407.
- Peters GP, et al. (2011) Growth in emission transfers via international trade from 1990 to 2008. *Proc Natl Acad Sci USA* 108:8903–8908.
- Davis SJ, Caldeira K (2010) Consumption-based accounting of CO₂ emissions. *Proc Natl Acad Sci USA* 107:5687–5692.
- Royal Society (2009) *Geoengineering the climate: Science, governance and uncertainty*. *RS Policy Documents*, Available at <http://royalsociety.org/policy/publications/2009/geoengineering-climate/>.

26. Royal Society (2011) Solar radiation management: The governance of research. *RS Policy Documents*, Available at <http://royalsociety.org/policy/projects/solar-radiation-governance/report/>.
27. Andres R, Gregg JS, Losey L, Marland G, Boden T (2011) Monthly, global emissions of carbon dioxide from fossil fuel consumption. *Tellus Ser B* 63:309–327.
28. Bonan G (2008) Forest and climate change: Forcing, feedbacks, and climate benefits of forests. *Science* 320:1444–1449.
29. Kaplan J, Krumhardt K, Zimmermann N (2009) The prehistoric and preindustrial deforestation of Europe. *Quat Sci Rev* 28:3016–3034.
30. Wigley T (2008) MAGICC/SCENGEN 5.3: User manual (version 2), Available at <http://www.cgd.ucar.edu/cas/wigley/magicc/UserMan5.3.v2.pdf>.
31. Brohan P, et al. (2006) Uncertainty estimates in regional and global observed temperature changes: A new dataset from 1850. *J Geophys Res* 10.1029/2005JD.

Supporting Information

Wei et al. 10.1073/pnas.1203282109

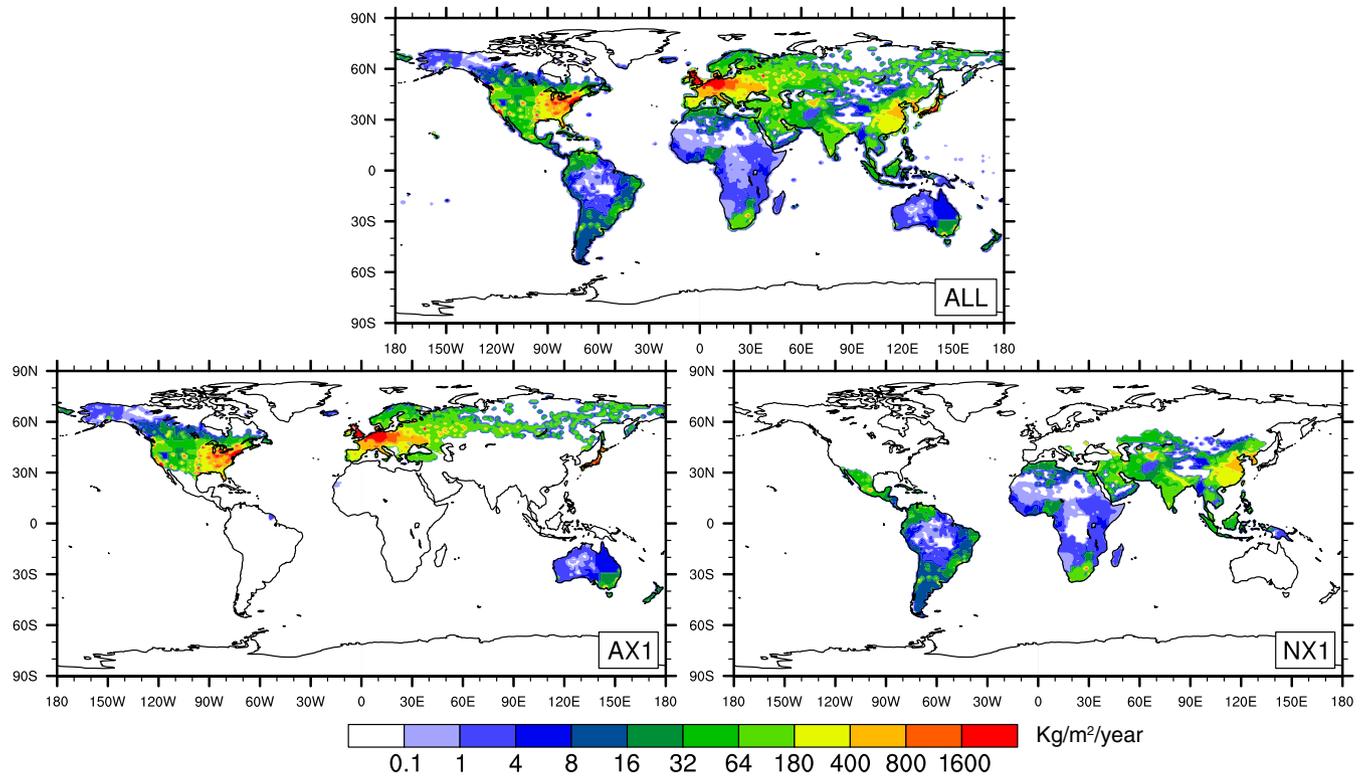


Fig. S1. Cumulative CO₂ emission flux from 1850 to 2005 for experiments ALL (historical emission), AX1 (developed world emissions only), and NX1 (developing world emissions only). The spatial resolution of $0.9^\circ \times 1.25^\circ$ is used to match that of CESM model and T42 to BNU-ESM model.

