Developed and developing world responsibilities for historical climate change and CO_2 mitigation

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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 2005. 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 CO_2, 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 intergovernmental agreements.

In this study we quantify the responsibilities for CO_2 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 CO_2 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 CO_2 concentration from the models. CO_2 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 CO_2 without consideration of other forcing, the increase of atmospheric CO_2 concentration simulated by ALL

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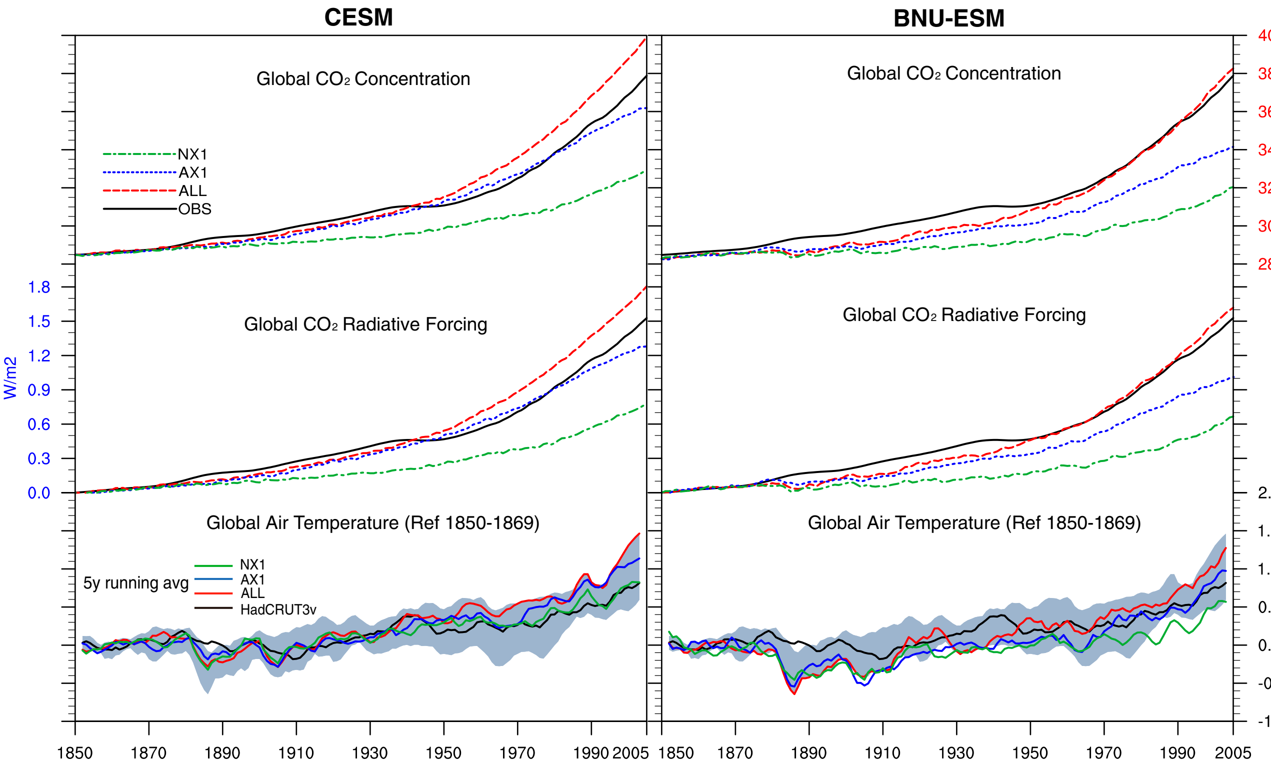

Fig. 1. CO_2 concentration and air temperature in three historical experiments simulated by two earth-system models (*Left*: CESM; *Right*: BNU-ESM). *Top*: Observed (black, supplied by CMIP5) and modeled time series of annual CO_2 concentration from ALL (red, historical emission), AX1 (blue, developed world emissions only), and NX1 (green, developing world emissions only). *Middle*: Annual radiative forcing for the three experiments. *Bottom*: Five-year running averaged global mean air temperature anomaly relative to 1850–1869 with shading showing the range of values from 10 models' CMIP5 14 esm-historical experiments. The models are BCC-ESM, BNU-ESM, CanESM2, CESM1_0_2, inmcm4, GFDL-ESM-2M, GFDL-ESM-2G, HadGEM2-ES, MIROC-ESM, and MPI-ESM-LR. The black line is the observed air temperature from HadCRUT3v (31).

is nonlinearly dependent on the sum of that by AX1 and NX1. We overcome this by using the "normalized proportional" method to get the relative contributions from developed and developing countries (*Materials and Methods*). Results show that the contribution to the increased CO_2 concentration from 1850 to 2005 estimated by CESM is 61% from the developed countries and 39% from the developing countries (for BNU-ESM the split is 63%–37%). A simple carbon-cycle model (17) simulated the contributions as 70% and 30% for developed and developing countries, respectively (Fig. S2).

Robust evidence (1, 6, 18) shows significant changes in the atmosphere, ocean, and cryosphere in response to climate change that may be attributed to radiative forcing. Radiative forcing is proportional to the logarithm of CO_2 concentration and is divided 53–47% by CESM (BNU-ESM 62–38%) for the developed and the developing countries from 1850 to 2005 using the normalized proportional approach. Additionally, the same approach results in splits of 60% versus 40% (BNU-ESM 64–36%) for global mean air temperature rise (Fig. 1), 61% versus 39% (BNU-ESM 87–13%) for northern hemisphere sea ice reduction, and 58% versus 42% (BNU-ESM 71–29%) for global upper oceanic (0–700 m) heat-content increase between developed and developing countries, respectively (Fig. S3).

The differences between impacts and radiative forcing attribution reflects the earlier CO_2 emissions from the developed countries in comparison to the developing countries and the long response times associated with cryospheric and oceanic processes (5). The relatively greater contributions from the developed world estimated by the BNU-ESM compared with the CESM are due to the relatively smaller increase in radiative forcing after 1950 in the BNU-ESM.

Fig. 2 shows the linear-trend patterns of temperature change during the 20th century (1906–2005) simulated by CESM and BNU-ESM. It is clear that the CESM gives somewhat larger warming than the BNU-ESM as expected given the higher CO_2 concentrations and radiative forcing of the CESM (Fig. 1). The spatial distribution from both models of the rising trends in scenario AX1 share great similarity to that in scenario ALL, while that in scenario NX1 differs significantly. At high northern latitudes, where warming is most significant, temperature increases in NX1 are 1.5 °C/100 y less than that modeled by ALL. During the latter part of the 20th century, world ocean heat content (0–3000 m) increased significantly (19, 20). This oceanic warming trend also can be seen in the ALL run, especially in the upper 700 m. Under the AX1 scenario, this trend diminished slightly in most waters except for those north of 60 °N. The warming trend modeled by NX1, however, is smaller in all waters. The increased oceanic and Arctic air temperatures under the AX1 scenario lead to a decreasing trend in sea-ice fraction in the Northern Hemisphere. In contrast, the NX1 case shows much less Arctic warming and greater sea-ice distribution over the Northern Hemisphere (Fig. S4).

To analyze the impact of the Cancun pledge (10), we developed CO_2 emission pathways for the 21st century depending on whether Annex I and non-Annex I nations follow a business-as-usual path or adopt a CO_2 mitigation policy (21). These emission scenarios are: (*i*) ABNB: Annex I and non-Annex I countries ignore their pledges and pursue business as usual; (*ii*) ABNC: Annex I countries follow business as usual, non-Annex I countries follow the Cancun pledges and then make a 50% deviation from business as usual by 2050 and zero emissions by 2100; (*iii*) ACNB: Annex I countries follow the Cancun pledges and then make 80% reductions by 2050 and zero emissions by 2100, non-Annex I countries follow business as usual; and (*iv*) ACNC: both groups of countries follow the Cancun pledges and further reductions outlined above.

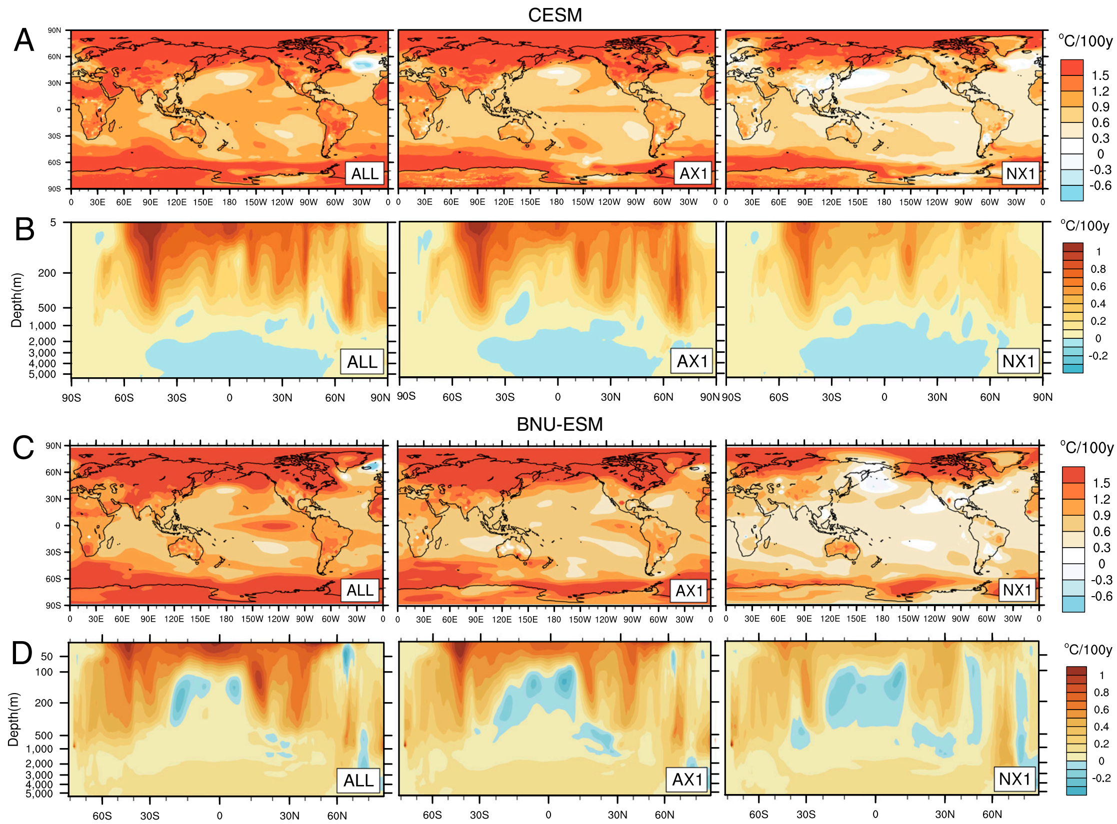

Fig. 2. Modeled centennial linear-trend patterns of air temperature (panels *A* and *C*, units: °C/100 y) and ocean temperature (panels *B* and *D*, units: °C/100 y) from 1906 to 2005 by the CESM and BNU-ESM model. Experiments used are labeled ALL (historical emissions), AX1 (developed world emissions 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 CO_2 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 CO_2 emissions through their imports of manufactured products from developing countries (22). For example, international trade has cumulatively relocated 16 Gigatonne (Gt) CO_2 from developed countries to developing countries from 1990 to 2008 (23). In 2004, 23% of global CO_2 emissions, or 6.2 Gt CO_2, 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"

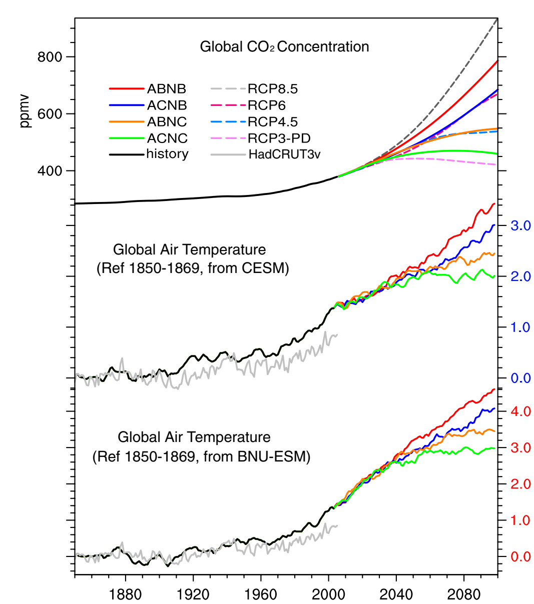

Fig. 3. CO_2 concentration and simulated air temperature in four future experiments simulated by two earth-system models. *Top*: Observed and predicted atmospheric CO_2 concentrations. The black line is the observed CO_2 concentration, which is supplied by CMIP5. The other real lines indicate four future 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 CO_2 concentrations are fully coupled to land and ocean CO_2 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 CO_2 emissions (i.e., fossil-fuel burning, cement manufacturing, and gas flaring in oil fields) are available at $1° \times 1°$ 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 $0.9° \times 1.25°$ resolution and the BNU-ESM version 1.0 at T42 resolution (approximately $2.8° \times 2.8°$). The model was integrated over the historical period (1850–2005) by prescribing the three kinds of CO_2 emissions (i.e., ALL, AX1, NX1). Other forcings varying over the historical period include non-CO_2 greenhouse gases (CH_4, N_2O, 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 CO_2 concentration in the atmosphere using the MAGICC5.3 model (30). We then applied the CESM at $1.9° \times 2.5°$ resolution and the BNU-ESM at T42 resolution, employing the global CO_2 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 CO_2 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 nonlinearity. 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 CO_2 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 CO_2 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/m^2 radiative forcing in 2100; it results in an atmosphere concentration of 650 ppm equivalent CO_2 in 2100. Similarly, RCP6.0 is the emission pathway to stabilization at radiative forcing of 6.0 W/m^2 in 2100, which results in an atmospheric concentration of 850 ppm equivalent CO_2 (13). The ABNC and ACNB emission paths produce similar atmospheric CO_2 concentrations to those produced by RCP4.5 and RCP6.0, respectively.

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