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Developed and Developing World Contributions to Climate System Change Based on Carbon Dioxide, Methane and Nitrous Oxide Emissions

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ABSTRACT

One of the key issues in international climate negotiations is the formulation of targets for emissions reduction for all countries based on the principle of "common but differentiated responsibilities". This formulation depends primarily on the quantitative attribution of the responsibilities of developed and developing countries for historical climate change. Using the Commuity Earth System Model (CESM), we estimate the responsibilities of developed countries and developing countries for climatic change from 1850 to 2005 using their carbon dioxide, methane and nitrous oxide emissions. The results indicate that developed countries contribute approximately 53%–61%, and developing countries approximately 39%–47%, to the increase in global air temperature, upper oceanic warming, sea-ice reduction in the NH, and permafrost degradation. In addition, the spatial heterogeneity of these changes from 1850 to 2005 is primarily attributed to the emissions of greenhouse gases (GHGs) in developed countries. Although uncertainties remain in the climate model and the external forcings used, GHG emissions in developed countries are the major contributor to the observed climate system changes in the 20th century.

Key words: greenhouse gases, earth system model, climate change, climate modeling

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1. Introduction

Humans have changed the composition of Earth's atmosphere, leading to significant climate change over recent centuries (IPCC, 2013). To avoid the serious environmental threat posed by the exponential growth of greenhouse gas emissions, the international community has for 20 years attempted to reduce global carbon emissions through climate negotiations. One of the critical issue for climate negotiations is to differentiate the contributions of different countries to historical climate change, which potentially affects the formulation of emissions reduction programs (UNFCCC, 1997).

Previous studies have estimated a country's contribution to historical climate change as its share of global greenhouse gas (GHG) emissions over a certain period (Rosa et al., 2004; Allen et al., 2009; Ding et al., 2009; He et al., 2009; den Elzen et al., 2013). Using World Resources Institute and U.S. Energy Information Administration data, Zhang et al. (2008) showed that the G8 countries (the U.S., Canada, Japan, Britain, Germany, France, Italy and Russia) accounted for 61% of the cumulative GHG emissions from 1850 to 2004, and five large developing countries (China, Brazil, India, South Africa and Mexico) accounted for 13%. As indicated by den Elzen et al. (2013), developed countries and developing countries contributed 51.9% and 48.1% to the global GHG emissions from 1850 to 2010, respectively. Note that the GHG concentration remaining in the atmosphere is directly related to the climate change (Frank et al., 2010; Jones et al., 2013). The atmospheric GHG concentration depends not only on anthropogenic emissions but also on the response of natural sinks/uptake to the changes in the atmospheric composition and climate (Fung et al., 2005; Le Quéré et al., 2009). Therefore, attributing the contributions of countries to global warming based on GHG emissions is insufficient because the emissions lack direct links to climate change (Wei et al., 2014).

To consider the uptake/sink of GHGs along with their relationship with temperature, simple models have been developed to measure national contributions to the global tem-

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perature rise due to their GHG emissions (UNFCCC, 2002; Andronova and Schlesinger, 2004; Trudinger and Enting, 2005; Matthews et al., 2009). Based on the original Brazilian model, den Elzen et al. (1999) showed that developed countries and developing countries should bear responsibility for 54% and 46%, respectively, of the historical contribution to global warming from 1890 to 2000. By considering GHG concentrations and their effects on radiative forcings and changes in global temperature, Höhne and Blok (2005) indicated that 60% (40%) of the contribution to climate change from 1750 to 2000 was from developed countries (developing countries). Using MAGICC (Model for the Assessment of Greenhouse Gas Induced Climate Change), Prather et al. (2009) controlled the errors along with the causal chain of climate change and showed that the GHG emissions from 1990 to 2002 in developed countries led to an increase in the global mean temperature by $0.11^{\circ}\mathrm{C} \pm 0.03^{\circ}\mathrm{C}$ in 2003. Ward and Mahowald (2014) used the radiative forcing of anthropogenic emissions of long-lived greenhouse gases, ozone precursors, aerosols, and from albedo changes from land cover change, together with a simple climate model, to evaluate country contributions to climate change. Generally, simple models track the causal chain of climate change from human activities to GHG emissions, to radiative forcing and, finally, to global warming. The causal chain includes the basic processes through which anthropogenic GHGs affect climate but lacks a description of the spatial and temporal details of the entire climate system. Therefore, a comprehensive evaluation of the historical contribution to climate change cannot be achieved with simple models.

Current state-of-the-art earth system models, which contain longwave radiative processes of GHGs and complex interactions among different components of the climate system, can overcome certain shortcomings of statistical methods and simple model approaches in attributing national responsibilities for climate change. Matthews et al. (2014) used an intermediate-complexity global climate model UVic ESCM to simulate the change in temperature resulting from observed historical increases in the forcing for each of methane (CH_4), nitrous oxide (N_2O), and sulfate aerosols, from 1970 to 2005. Wei et al. (2012) designed numerical experiments with two earth system models and demonstrated that developed countries (developing countries) contributed approximately 60%–80% (20%–40%) to the global temperature rise, upper oceanic warming, and sea-ice reduction, by 2005. However, Wei et al. (2012) only considered the industrial carbon emissions from different countries and ignored other important GHGs, such as CH_4 and N_2O. Note that CH_4 and N_2O account for 14% and 8% of all anthropogenic GHGs emissions, respectively, and their global warming potential (GWP) is 21 times and 310 times the GWP of carbon dioxide (CO_2), respectively (IPCC, 1996). Excluding CO_2, other GHGs significantly change the relative share of global emissions for many countries (UNFCCC, 2002; den Elzen et al., 2005; den Elzen et al., 2013). Therefore, it is more accurate and more meaningful to estimate the historical responsibilities of countries based on the variations of all of these important GHGs.

In this study, using a state-of-the-art coupled earth system model, we estimate the responsibilities of developed and developing countries for the changes in each component of the climate system from 1850 to 2005. We attempt to provide results by considering the effect of CO_2, CH_4 and N_2O emissions. In addition, we hope that our results provide information to partially resolve the controversial climate negotiations on emissions reduction. The remainder of the paper is organized as follows: Section 2 briefly describes the CESM, the construction of the GHG data, and the experimental setup. Section 3 evaluates the influences of the GHG emissions from different groups of countries on climate system change, obtained by modeling. Finally, section 4 concludes and discusses the likely effect of recent emissions and transferred emissions on the attribution.

2. Methods

2.1. *Model description*

CESM version 1.0.2 is a fully coupled, global climate model developed at NCAR. It is composed of an atmospheric model (CAM4/CAM5), an ocean model (POP2), a land surface model (CLM4), a sea-ice model (CICE4), and a central coupler component (CPL7). The principal GHGs with longwave radiative effects included in CAM5 are water vapor, CO_2, ozone (O_3), CH_4, N_2O, CFC11, and CFC12. CO_2 is assumed to be well mixed. The latter four (CH_4, N_2O, CFC11, and CFC12) are specified at globally uniform surface concentrations. In this study, the horizontal resolution of CAM5 is $1.9^{\circ}\ (lat) times 2.5^{\circ}$ (lon), with 26 levels in the vertical direction. The horizontal resolution of the ocean component is g16, corresponding to a nominal grid size of 1°, and there are 60 isopycnic vertical layers. Additional information concerning CESM can be found in Neale et al. (2010) and Gent et al. (2011). CESM has been proven to be able to capture the majority of characteristics of present-day climate (e.g., Feng et al., 2014; Yan et al., 2014). Specifically, CESM performs well in reproducing the trends of sea-ice extent and ocean heat content changes in recent decades and in capturing the relationship between the decrease in permafrost area and the warming air temperature over the present-day NH permafrost region (Flato et al., 2013; Slater and Lawrence, 2013; Shu et al., 2015).

2.2. *Data*

We first collected and constructed the CO_2, CH_4 and N_2O emissions datasets from developed and developing countries. Next, we converted the emissions data (units: Tg) to GHG concentrations (units: ppmv), which served as the external forcings of CESM.

2.2.1. *Carbon dioxide*

Based on gridded industrial carbon emissions (Andres et al., 2013), Wei et al. (2012) simulated the evolution of the CO_2 concentration from 1850 to 2005 under the scenarios of

all countries emitting (ALLGHGs), only developed countries emitting (AX1GHGs), and only developing countries emitting (NX1GHGs), using CESM. The simulated CO_2 variations, which included the interaction between the varying climate and carbon sinks, matched well with observations, with a correlation coefficient of 0.99. Although simulation biases existed over the last 50 years because of the high climate sensitivity of CESM, they were not critical in the evaluation of the relative contributions (Wei et al., 2012). Therefore, we employ the simulated CO_2 concentrations in the three scenarios as the external forcings in this study (Fig. 1a).

2.2.2. *Methane*

Höhne et al. (2011) compiled historical (1890–2005) CH_4 and N_2O emission datasets with the results from 192 countries or regions for energy, industry and agriculture/waste sec-

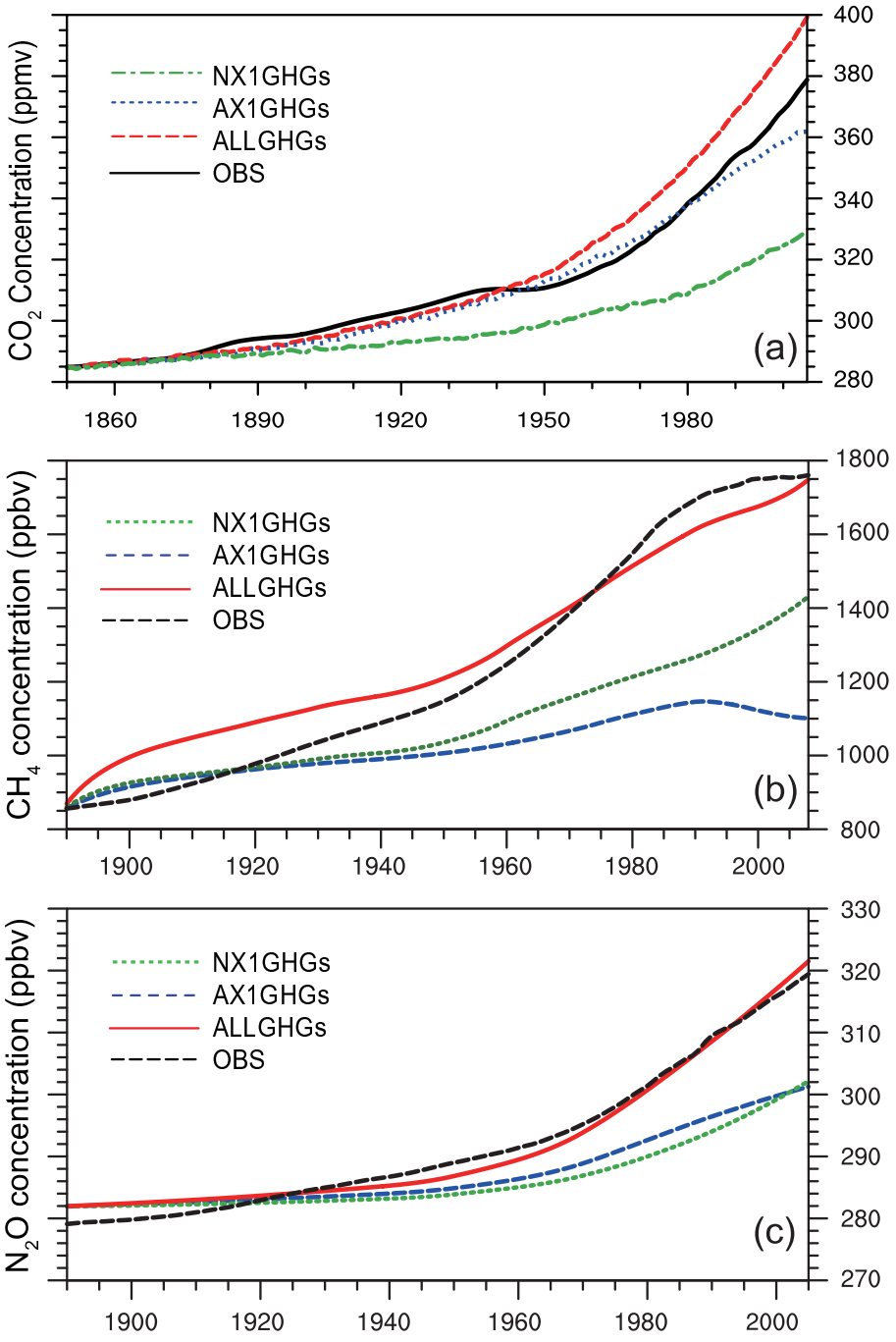

Fig. 1. Observed (black; supplied by CMIP5) and modeled time series of the annual (a) CO_2, (b) CH_4 and (c) N_2O concentration under the ALLGHGs (red; historical emissions), AX1GHGs (blue; developed world emissions only), and NX1GHGs (green; developing world emissions only) scenarios.

tors. We divided the national CH_4 emissions into developed and developing country groups and found that CH_4 from developing countries, which are consistently higher than those from developed countries from 1890 to 2005, markedly increased with the economic reconstruction occurring since the 1950s. Over the past 15 years, CH_4 emissions from developed countries have been greatly reduced, while the rising trend from developing countries has been maintained (figure not shown).

In the original and revised Brazilian proposal (UNFCCC, 1997; den Elzen et al., 1999), the concentration of CH_4 is a function of its emissions and is calculated using an exponential decay function with a constant atmospheric lifetime [Eq. (1)]. In a more general formulation, as used in IMAGE (Integrated Model to Assess the Greenhouse Effect) and MAGICC, the concentration of a non-CO_2 greenhouse gas follows a mass balance equation. These functions are referred to as the Brazilian model:

$$\rho_g(t) = C_g \int_{-\infty}^{t} \varepsilon_g(t') e^{-(t-t')/\tau_g} dt' \,, \qquad (1)$$

where subscript g is a specie of gas, $\rho_g(t)$ is the atmospheric concentration at time t (ppbv); t' is the variable for time integral; C_g is a mass-to-concentration conversion factor and is set equal to 3.8 (ppbv Tg^{-1}), as in Meta-IMAGE/IMAGE; ε_g is the annual rate of anthropogenic emissions (Tg yr^{-1}); and τ_g is the atmospheric exponential decay time or lifetime (yr), which considers the soil carbon sequestration $\tau_g = \tau_{atm,g} + \tau_{soil,g}$ in which $\tau_{atm,g}$ is atmospheric sink, $\tau_{atm,g} = 9.08$ yr in 1990 and $\tau_{soil,g}$ is soil sink, $\tau_{soil,g} = 150$ yr (Harvey et al., 1997). The constant lifetime ignores the indirect effect of methane on atmospheric chemistry (such as hydroxyls and tropospheric O_3) and the chemical interaction of CH_4 with oxidants in the atmosphere, which could lead to a change in the CH_4 lifetime by 10%–20% over a historical period (IPCC, 1996). Therefore, we use the historical concentration data to validate the modeling approach and to obtain the value of 7.5 yr for $\tau_{atm,g}$.

Figure 1b shows the observed and calculated CH_4 concentration from Eq. (1). The CH_4 concentration and its rising trend are overestimated prior to 1970. This result is attributed to the uncertainties in the model parameters, which are suitable for the prediction after 1990 and in the application for the constant lifetime, which neglects the chemical interaction between CH_4 and the atmosphere. However, the bias is not critical in the evaluation of the relative contributions. In addition, the CH_4 concentration due to the emissions of developing countries is higher than that caused by the emissions of developed countries, and the difference is substantially larger after the 1950s, simultaneous with the post-war reconstruction period.

2.2.3. *Nitrous Oxide*

The anthropogenic N_2O emission data covering 192 countries or regions were also derived from Höhne et al. (2011). These data, spanning from 1890 to 2005, are the longest time series of N_2O emissions currently available. From 1890 to 1990, the N_2O emitted by developed countries was slightly higher than that emitted by developing countries. N_2O emitted by developing countries shows an obvious linear increasing trend from 1990 to 2005, while this amount is substantially reduced for developed countries (figure not shown).

The Brazilian model can also be used to calculate the concentration of N_2O but with different model parameters. However, the gap between the modeled N_2O concentration and the historical observation is large and increases with time. In addition, the lifetime of N_2O, which is relatively different from the lifetime of CO_2 and CH_4, is quasi-steady and relatively long (120 years; den Elzen et al., 1999), allowing us to use the curve fitting method to calculate the atmospheric N_2O concentration during the historical period. Because the concentration of greenhouse gases in the atmosphere is determined by their long-term emissions, we calculate the atmospheric N_2O concentrations with a cubic function [Eq. (2)] and the cumulative emissions of anthropogenic N_2O since 1890:

$$\rho_g(t) = a + b1 \times E_g(t) + b2 \times E_g^2(t) + b3 \times E_g^2(t) \,, \qquad (2)$$

where $\rho_g(t)$ is the atmospheric concentration at time t (ppbv); $E_g(t)$ is the cumulative anthropogenic emissions from 1890 to time t (Tg N_2O); and a, $b1$, $b2$ and $b3$ are fitting coefficients with values of 279.888, 0.165, 0.0, and 4.32×10^{-7}, respectively.

The correlation coefficient between the calculated N_2O concentration in the ALLGHGs scenario and the observation is 0.995, at the 99% significance level (Fig 1c). The fitting result is especially close to the observation since the 1920s. In addition, the change in the N_2O concentration caused by developed countries is close to that caused by developing countries.

2.3. *Experimental design*

To examine the historical responsibilities of developed and developing countries, we designed four experiments using CESM under four different emissions scenarios (Table 1). In each experiment, the model used the results of a 351-year preindustrial control run as its initial field and was then integrated over the historical period from 1850 to 2005. The four emissions scenarios we designed are summarized as follows: (1) A00GHGs: anthropogenic GHG (CO_2, CH_4 and N_2O) emissions from all countries were set to zero (considered as the reference scenario)—thus, the concentrations of CO_2, CH_4 and N_2O were maintained at pre-industrial (i.e., 1850) levels; (2) ALLGHGs: global anthropogenic GHG emissions the same as in the 20th century historical experiment in CMIP5 (Taylor et al., 2012); (3) AX1GHGs: anthropogenic GHG emissions were only allowed from developed countries (i.e., Annex I countries); (4) NX1GHGs: anthropogenic GHG emissions were only allowed from developing countries (i.e., non-Annex I countries). The annual concentrations of CO_2, CH_4 and N_2O under these emissions scenarios are shown in Fig. 1. The other forcings, including aerosols, CFC gases, volcanoes and solar irradiance, were maintained the same in each of the experiments.

Table 1. Experimental design. The simulation period is from 1850 to 2005.

Experiment	Forcing			
	CO_2	CH_4	N_2O	Other forcings
A00GHGs	284.7 ppm	791.0 ppb	275.4 ppb	same as in CMIP5 historical experiment
ALLGHGs	concentrations from all countries' emissions			same as in CMIP5 historical experiment
AX1GHGs	concentrations only allowed from developed countries' emissions			same as in CMIP5 historical experiment
NX1GHGs	concentrations only allowed from developing countries' emissions			same as in CMIP5 historical experiment

3. Accounting the contribution to climate system change

3.1. *Atmospheric warming*

Air temperature is an important indicator reflecting the overall features of the climate system. Figure 2a shows the global mean air temperature anomalies under different emissions scenarios relative to the A00GHGs scenario, revealing that human-induced GHG emissions have led to significant global warming since 1850. However, the magnitudes of warming caused by the emissions from different country groups show substantial differences. The warming trend under the AX1GHGs scenario is similar to that under the ALLGHGs scenario but substantially larger than that under the NX1GHGs scenario since the 1900s. Over the last 20 years of the study period (1986–2005), the gap in the warming trends between the AX1GHGs and NX1GHGs scenarios reduced due to the rapid industrialization of developing countries. Compared with the A00GHGs reference scenario, the global annual mean temperature averaged over 1986–2005 increased by 0.93°C, 0.71°C and 0.56°C under the ALLGHGs, AX1GHGs and NX1GHGs scenarios, respectively. We use the "normalized proportional" method (Höhne et al., 2011; Wei et al., 2012) to obtain the relative contributions from developed and developing countries. The results show that 56% of the contribution to the rising air temperature is from the emissions of developed countries, and 44% is from the emissions of developing countries. The gap in the contribution rates between the two country groups is smaller than the result from Wei et al. (2012), in which only CO_2 emissions were considered. Therefore, considering the influence of other important GHGs (i.e., CH_4 and N_2O) could increase (decrease) the contribution of developing (developed) countries. And this result is similar with those of some previous studies (Höhne et al., 2011; den Elzen et al., 2013; Matthews et al., 2014; Ward and Mahowald, 2014).

Due to the spatial heterogeneity of climate change, we further investigate the spatial patterns of temperature changes relative to the A00GHGs scenario. Figure 2b shows that the largest warming due to the increased GHGs is primarily located in the Arctic regions, with little change in the temperature over the oceans at midlatitudes. The spatial distribution of the temperature trends under the AX1GHGs scenario is very similar to that under the ALLGHGs scenario but differs with that under the NX1GHGs scenario (Figs. 2c and d). At northern high latitudes, the warming magnitude under the NX1GHGs scenario is 1°C smaller compared with that under the ALLGHGs scenario. In addition, the temperature changes over Oceania are more sensitive to the emissions scenarios. Generally, GHGs emitted by developed countries contributed 52%–61% of the warming in each continent (Table 2).

3.2. *Oceanic warming*

Ocean warming dominates the increase in the energy stored in the climate system, accounting for more than 90% of the energy accumulated from 1971 to 2010, and more than 60% of the net energy increase in the climate system is stored in the upper ocean (0–700 m) (IPCC, 2013). Figure 3a shows the simulated heat content in the global upper ocean under different scenarios relative to the A00GHGs scenario. The time series shows an increasing trend of heat content in the global ocean in response to GHG emissions. It appears that the differences in the ocean content among the different scenarios are more noticeable than the differences in the air temperature. The warming trend under the NX1GHGs scenario is substantially smaller than that under the AX1GHGs sce-

Table 2. Differences in air temperature (°C) during 1986–2005 over each continent between the sensitivity experiments (ALLGHG, AX1GHG and NX1GHG) and control experiment (A00GHG). Data in the brackets are the contributions to the change of temperature from developed/developing countries.

Scenario	Region							
	Global ocean	Global land	North America	South America	Europe	Africa	Asia	Oceania
ALLGHGs minus A00GHGs	0.82	1.20	1.35	1.02	0.92	1.19	1.19	0.94
AX1GHGs minus A00GHGs (Developed countreis' contribution)	0.62 (54%)	0.93 (58%)	1.23 (56%)	0.80 (56%)	0.65 (52%)	0.94 (59%)	0.88 (60%)	0.79 (61%)
NX1GHGs minus A00GHGs (Developing countreis' contribution)	0.52 (46%)	0.67 (42%)	0.95 (44%)	0.63 (44%)	0.60 (48%)	0.64 (41%)	0.58 (40%)	0.51 (39%)

Note: The regions are defined according to Giorgi and Francisco (2000).

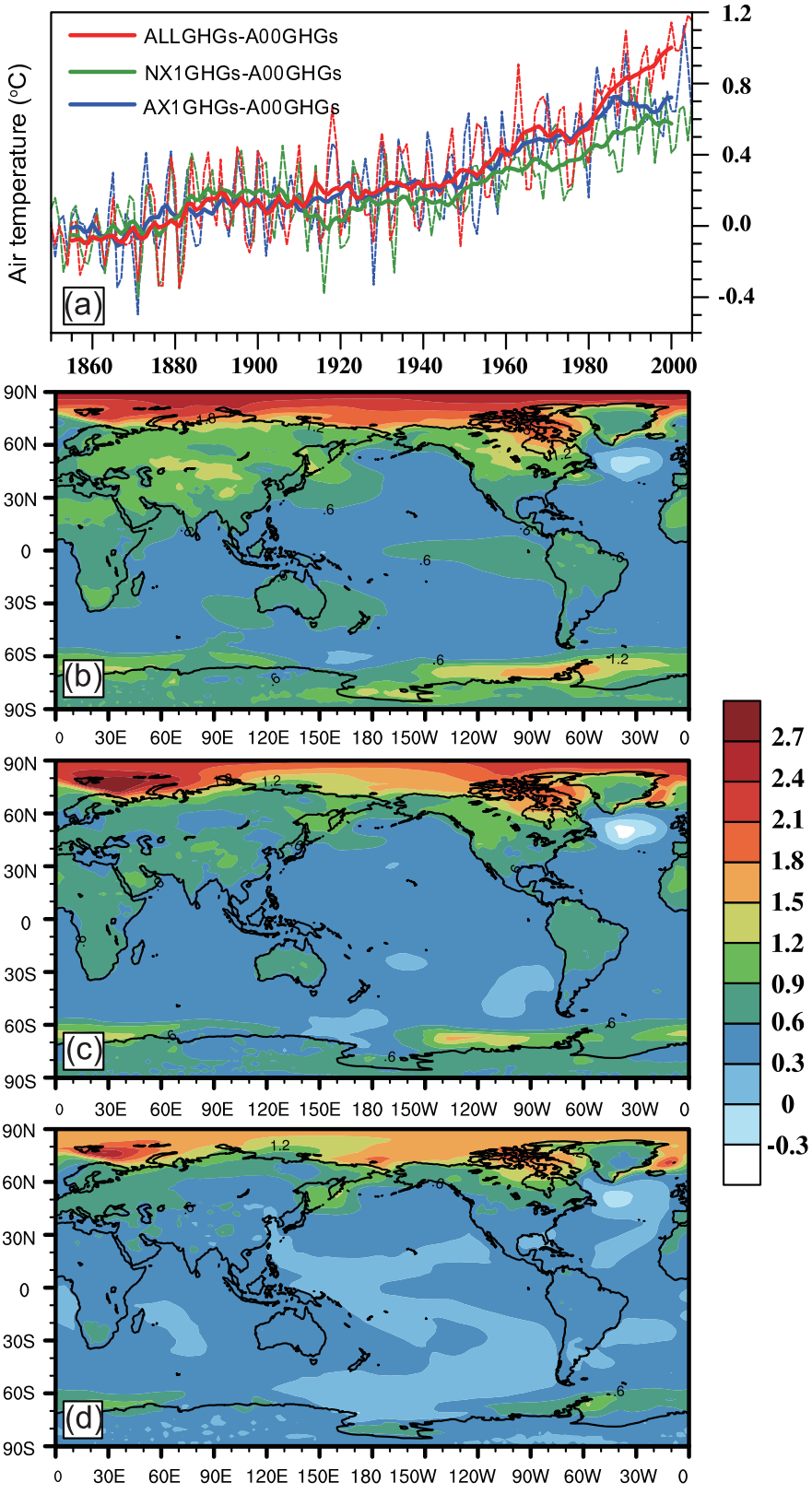

Fig. 2. Differences between the air temperature in the ALLGHGs, AX1GHGs and NX1GHGs scenarios and the A00GHGs reference scenario. (a) Time series of global mean air temperature. The thin dashed lines are the annual values, and the thick solid lines are the 11-year running values. Simulated patterns of air temperature under the (b) ALLGHGs, (c) AX1GHGs and (d) NX1GHGs scenarios relative to the A00GHGs scenario from 1956 to 2005. Units: °C.

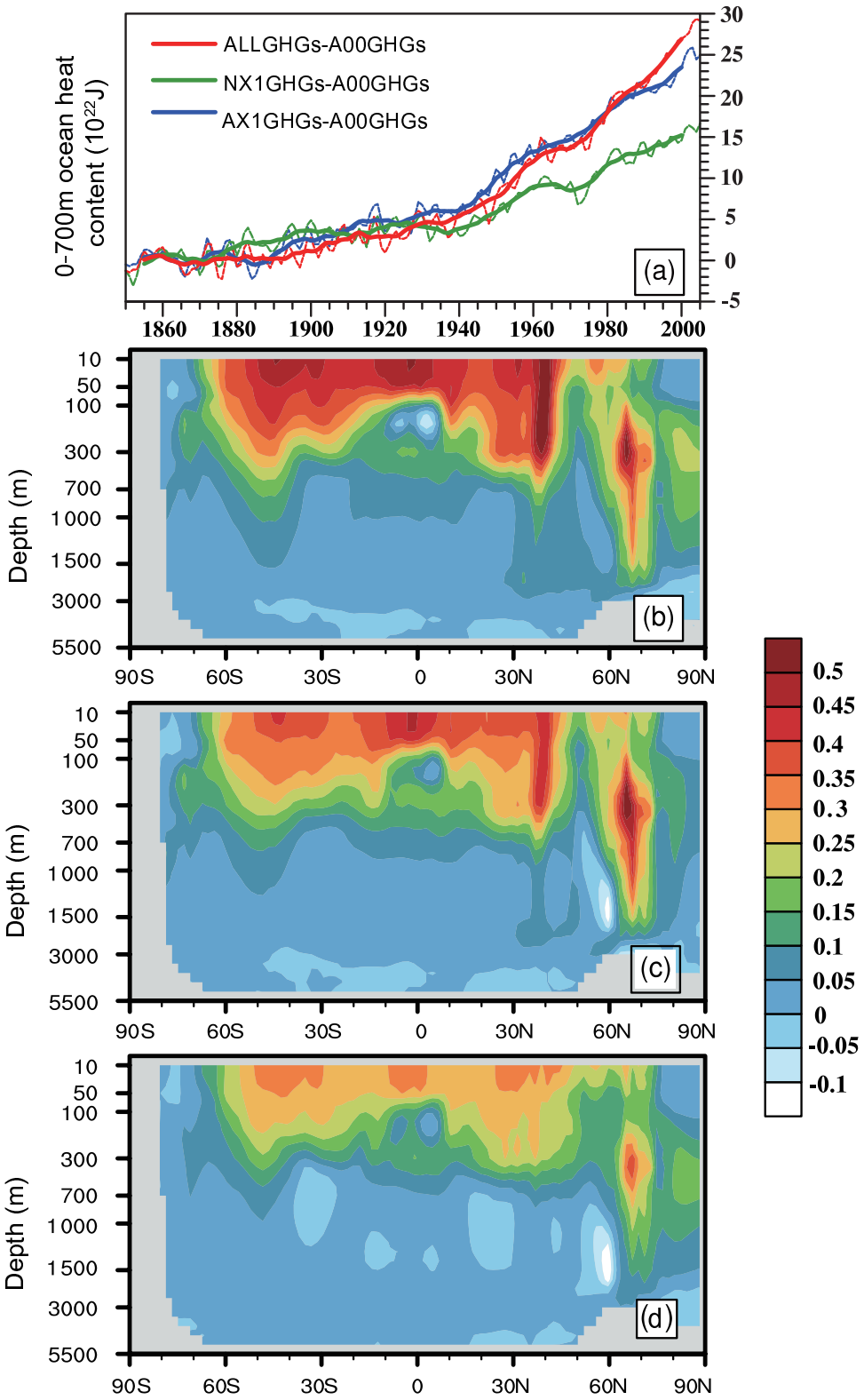

Fig. 3. Similar to Fig. 2 but for the time series of heat content in the global upper (0–700 m) ocean (units: $\times 10^{22}$ J) and latitude–depth section of the oceanic potential temperature (unit: °C).

nario that is consistent with that under the ALLGHGs scenario. From 1986 to 2005, the heat content in the upper ocean under the ALLGHGs, AX1GHGs and NX1GHGs scenarios relative to the A00GHGs scenario is 24.57×10^{22} J, 22.22×10^{22} J and 14.56×10^{22} J, respectively. Using the normalized proportional approach, 61% (39%) of the simulated upper ocean warming is attributed to developed countries (developing countries).

As shown in Figures 3b–d, the majority of the ocean regions experiences significant warming because of increasing

GHGs. The maximum warming appears in the global upper ocean, and the largest warming depth appears in the North Atlantic Ocean. Notably, the warming amplitude in each region under the AX1GHGs scenario is larger than that under the NX1GHGs scenario, especially at the surface of the global ocean and the North Atlantic Ocean. Thus, the spatial heterogeneity of the global ocean warming primarily responds to the GHG emissions of developed countries.

3.3. *Sea-ice reduction*

Observations have shown that one of the most significant features of global warming is the accelerated reduction of Arctic sea ice. From 1979 to 2012, the Arctic sea-ice extent decreased at a rate of 3.5% (10 yr)$^{-1}$–4.1% (10 yr)$^{-1}$

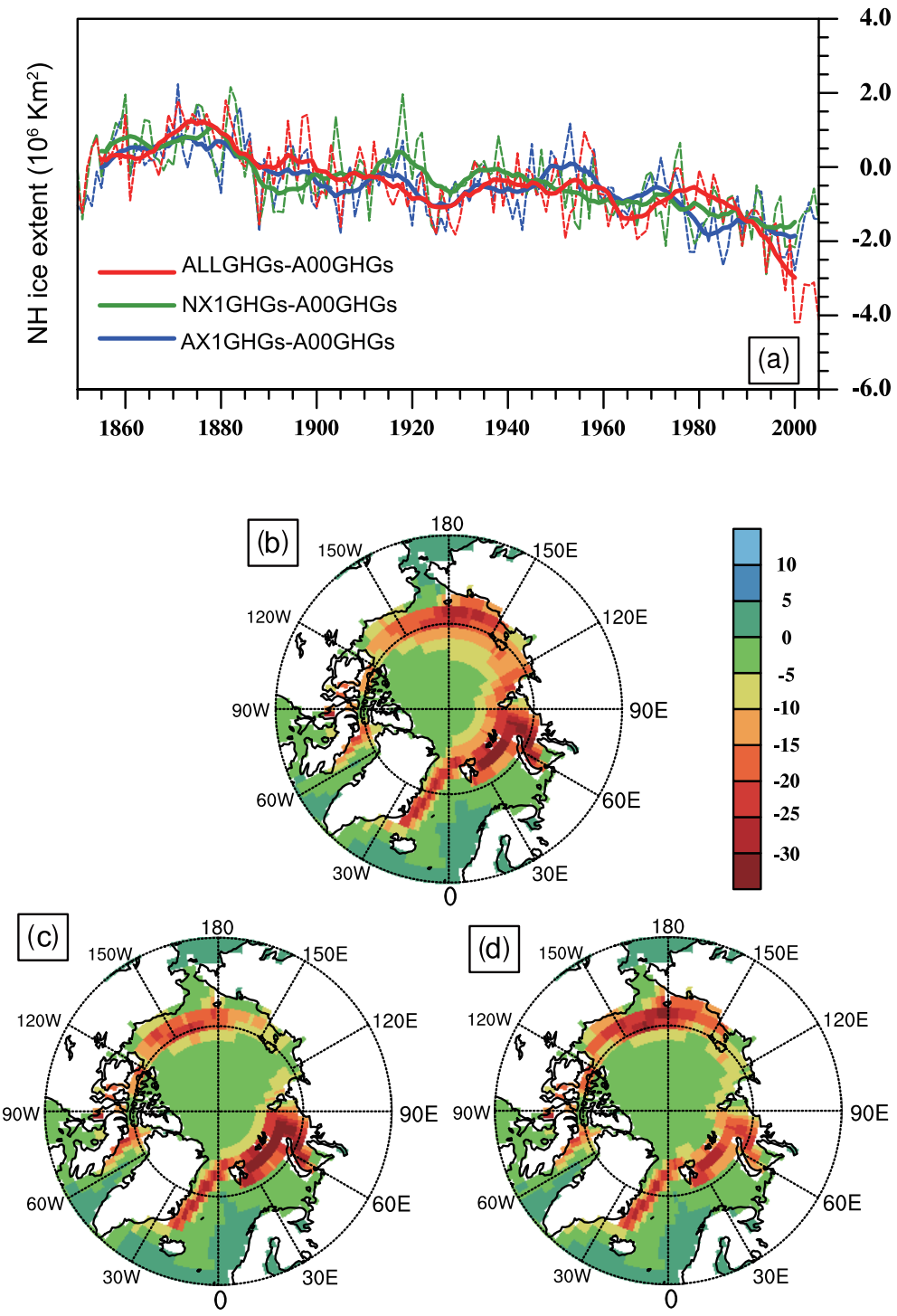

Fig. 4. Similar to Fig. 2 but for the time series of Arctic sea-ice extent (units: $\times 10^6$ km^2) and the patterns of Arctic sea-ice fraction (units: %) in September.

[or 0.45–0.51 million km^2 (10 yr)$^{-1}$], with the most significant decrease occurring in summer (IPCC, 2013). From the relative changes in the Arctic sea-ice extent in Fig. 4a, we can see that the increasing GHGs have led to a reduction in Arctic sea ice since 1850, and the decreasing rate became faster after the 1970s. Compared with the A00GHGs scenario, the Arctic sea-ice extent from 1986 to 2005 under the ALLGHGs, AX1GHGs and NX1GHGs scenarios decreased by 2.29×10^6 km^2, 1.61×10^6 km^2 and 1.44×10^6 km^2, respectively. Using the normalized proportional approach, the contribution rate to the decrease in Arctic sea-ice extent is 53% and 47% in developed and developing countries, respectively. The gap in the contribution rate between the two country groups is smaller than the results for the air temperature and oceanic heat content. This result may be because, aside from anthropogenic GHGs, the change in the sea-ice extent is also affected by the natural variability of large-scale atmospheric circulation (e.g., Arctic Oscillation) (Rigor et al., 2002).

Figures 4b–d show the patterns of Arctic sea-ice extent in September from 1956 to 2005 simulated by CESM. Because of the increasing GHGs, the sea ice in most of the Arctic regions, especially in the East Siberian Sea and Chukchi Sea, decreased significantly. The magnitude of sea-ice reduction in the Chukchi Sea under the AX1GHGs scenario is similar to that under the ALLGHGs scenario but larger than that under the ALLGHGs scenario. In the East Siberian Sea, however, the change in the sea-ice extent in the NX1GHGs case is larger than that in the AX1GHGs case.

3.4. *Permafrost degradation*

In terms of area extent, frozen ground is the largest component of the cryosphere (IPCC, 2013). The permafrost temperature regime is a sensitive indicator of decadal to centennial climatic variability (Lachenbruch and Marshall, 1986; Osterkamp, 2005). Observations have shown that the permafrost has degenerated, and the thickness of the active layer over the permafrost has increased in most regions since 1975 (IPCC, 2013). Figure 5a shows that GHGs have led to a significant decrease in surface (0–4.7 m) permafrost since the industrial revolution, and the degeneration rate is especially high after the 1960s. Because the sensitivity of permafrost to anthropogenic GHGs is relatively high, the magnitudes of its degeneration caused by emissions from different country groups show large differences. The decreasing trend of the permafrost area under the AX1GHGs scenario is substantially larger than that under the NX1GHGs scenario since the 1900s. From 1986 to 2005, the surface permafrost area in the ALLGHGs, AX1GHGs and NX1GHGs scenarios decreased by 2.53×10^6 km^2, 2.05×10^6 km^2 and 1.61×10^6 km^2, respectively, compared with the A00GHGs scenario. Using the normalized proportional approach, developed and developing countries contribute 56% and 44% to global permafrost degeneration, respectively.

The thickness of the active layer over permafrost increases with the GHG emissions (Figs. 5b–d). In the Stanovoy Mountains and Alaska Mountains, the incrassation of the active layer is substantially more significant. The spatial distribution of the change in the active layer over the permafrost under the AX1GHGs scenario is very similar to that under the ALLGHGs scenario, while it differs to that under the NX1GHGs scenario. In the regions along 60°N, especially in the Stanovoy Mountains and central Canada areas, which are sensitive regions to human-induced GHGs, the difference in the permafrost degeneration between the AX1GHGs and NX1GHGs scenarios is even larger.

4. Conclusions and discussion

The key issue in international climate negotiations is the formulation of targets for emissions reduction for all countries based on the principle of "common but differentiated responsibilities" (UNFCCC, 1997). This formulation depends primarily on the quantitative attribution of the responsibilities of developed and developing countries for historical climate change. In this study, a state-of-the-art model, CESM, was used to attribute the responsibilities of developed/developing countries for climate change due to their GHG emissions (i.e., CO_2, CH_4 and N_2O). Simulations with CESM demonstrate the following:

(1) The contribution rate to the rising air temperature since pre-industrial times is 56% from the GHGs (i.e., CO_2, CH_4 and N_2O) emitted by developed countries and 44% from that emitted by developing countries. Different regions show various sensitivities to the emissions scenarios. GHGs emitted by developed countries are the major driver (52%–61%) for the warming in each continent and for the global warming patterns.

(2) CESM attributes 61% of the contribution to global ocean warming to developed countries and 39% to developing countries. In most of the regions, especially at the surface of the global ocean and the North Atlantic Ocean, which are the most sensitive regions to GHGs, the GHG emissions from developed countries exert a greater effect on warming.

(3) The contributions from developed and developing countries to the decrease in Arctic sea-ice extent are 53% and 47%, respectively. Because of the increasing GHGs, the sea ice in the East Siberian Sea and Chukchi Sea has decreased significantly. However, the sea-ice extent, which is also affected by the natural variability of large-scale atmospheric circulation, shows various sensitivities to GHG emissions scenarios.

(4) For the change in global permafrost degeneration, the contributions of developed and developing countries are 56% and 44%, respectively. Developed countries are the major contributor to the incrassation of the active layer over permafrost in the regions along 60°N, especially in the Stanovoy Mountains and central Canada areas.

The simulation results presented in this study show that the total relative contribution to climate change is 53%–61% from developed countries and 39%–47% from developing countries, from 1850 to 2005. Based on statistical cumula-

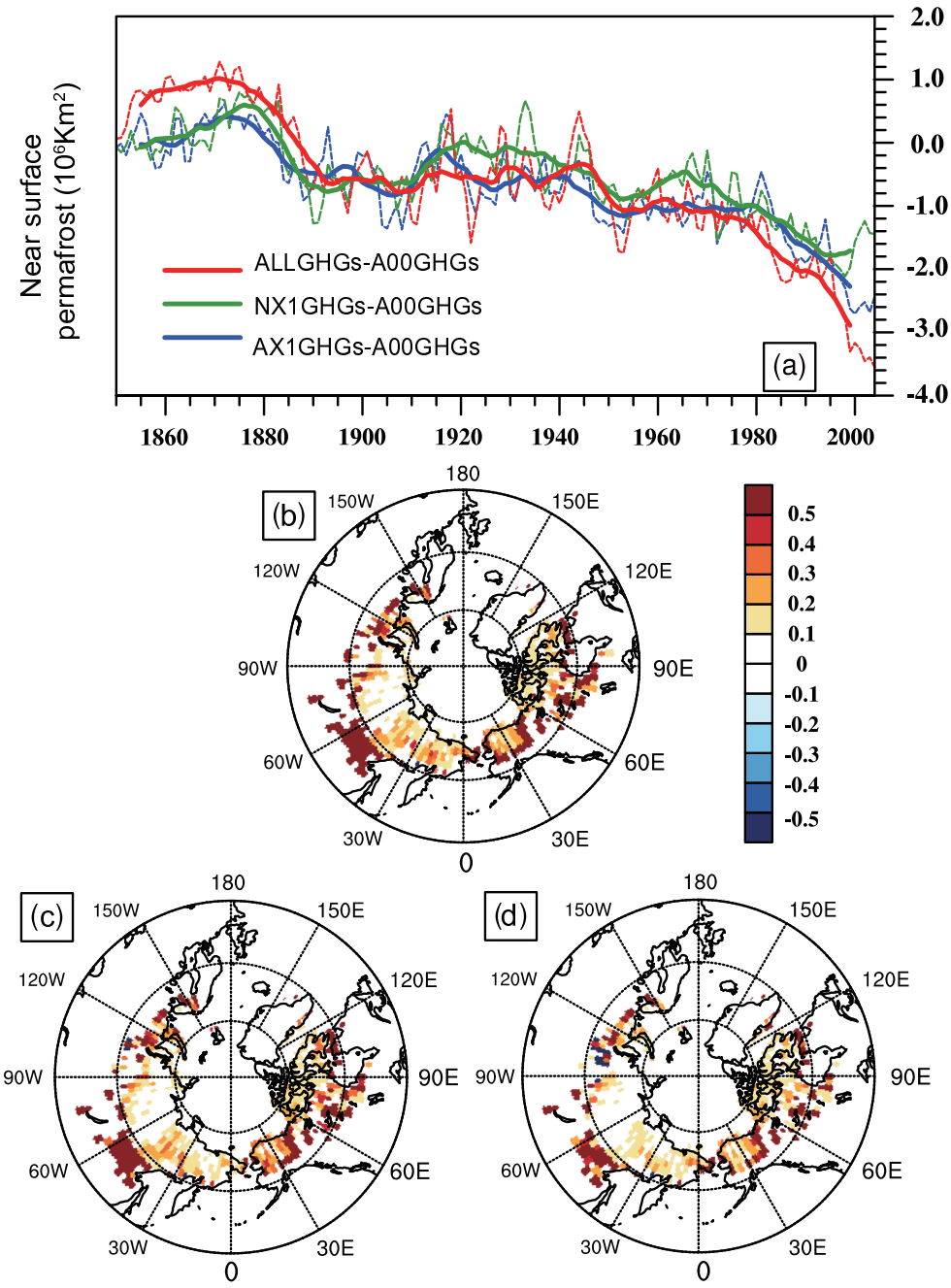

Fig. 5. Similar to Fig. 2 but for the time series of surface (0–4.7 m) permafrost area (units: $\times 10^6$ km^2) and the patterns of the active layer over the permafrost (units: m).

tive GHG emissions, den Elzen et al. (2013) calculated the relative contribution to be 54.1% from developed countries and 45.9% from developing countries, from 1850 to 2000. The discrepancy between the two studies may be because of the different metrics applied. den Elzen et al. (2013) compared cumulative emissions of CO_2-equivalents, whereas we are comparing climate variables. Liu et al. (2015) argued that China emitted 2.9 GtC less than previously thought over the period 2000 to 2013. However, the amount of overestimated carbon emissions is ignorable compared to the difference in cumulative carbon emissions (∼67.1 GtC) between developed and developing countries from 1850 to 2013, and hence has limited influence in attributing historical responsibility for developed and developing countries. As a preliminary step, we investigated the relative contribution of developed and developing countries in this study. To provide a more useful reference for climate negotiations and the formulation of emissions reduction policy, assessments of individual countries' responsibilities for climate change is urgently needed.

In recent years, the GHG emissions of developing countries have continuously increased due to rapid industrializa-

tion and have even exceeded the emissions of developed countries. This result challenges previous attribution studies that have excluded recent carbon emissions. A recent study demonstrated that carbon emissions from 2006 to 2011 that accounted for the largest proportion of GHGs have a limited influence (1%–2%) on the attribution of historical contributions from developed and developing countries (Wei et al., 2015). den Elzen et al. (2013) found that the contribution of developed countries to global GHGs emissions was approximately 54.1% (51.9%) during the period 1850–2010 (1850–2000). Taking into account changes in GHGs, ozone precursors, aerosols and land cover, Ward and Mahowald (2014) pointed out that developed countries were the major contributor to observed temperature changes during 1850–2010. The aforementioned results indicate that the rapidly increasing GHGs emissions from developing countries in recent years do not significantly alter the developed/developing countries contribution to long-term climate change.

Additionally, throughout the second half of the 20th century, developed economies effectively exported their carbon emissions through their imports of manufactured products from developing countries (Davis et al., 2011; Peters et al., 2011). The transferred carbon emissions and the contributions from the developed world to the developing world through international trade have been largely ignored. Therefore, the influence of transferred emissions on the attribution of historical contribution must be investigated to partially solve the disputes in climate negotiations.

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REFERENCES

Allen, M. R., D. J. Frame, C. Huntingford, C. D. Jones, J. A. Lowe, M. Meinshausen, and N. Meinshausen, 2009: Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature*, **458**, 1163–1166.

Andres, R. J., T. A. Boden, and G. Marland, 2013: Annual fossil-fuel CO_2 emissions: Isomass of emissions gridded by one degree latitude by one degree longitude. CDIAC, doi: 10.3334/CDIAC/ffe.AnnualIsomass.

Andronova, N., and M. Schlesinger, 2004: Importance of sulfate aerosol in evaluating the relative contributions of regional emissions to the historical global temperature change. *Mitigation and Adaptation Strategies for Global Change*, **9**, 383–390.

Davis, S. P. , G. P. Peters, and K. Caldeira, 2011: The supply chain of CO_2 emissions. *Proc. Natl. Acad. Sci. USA*, **108**, 18554–18559.

den Elzen, M. G. J., M. Berk, M. Schaeffer, J. Olivier, C. Hendriks, and B. Metz, 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, 129 pp.

den Elzen, M. G. J., M. Schaeffer, and P. L. Lucas, 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. *Climatic Change*, **71**, 277–301.

den Elzen, M. G. J., J. G. J. Olivier, N. Höhne, and G. Janssens-Michel, 2013: Countries' contributions to climate change: Effect of accounting for all greenhouse gases, recent trends, Basic needs and technological progress. *Climatic Change*, **121**, 397–412.

Ding, Z. L., X. N. Duan, Q. S. Ge, and Z. Q. Zhang, 2009: Control of atmospheric CO_2 concentrations by 2050: A calculation on the emission rights of different countries. *Science in China Series D: Earth Sciences*, **52**, 1447–1469.

Feng, J. M., T. Wei, W. J. Dong, Q. Z. Wu, and Y. L. Wang, 2014: CMIP5/AMIP GCM simulations of East Asian summer monsoon. *Adv. Atmos. Sci.*, **31**, 836–850, doi: 10.1007/s00376-013-3131-y.

Flato, G., and Coauthors, 2013: Evaluation of Climate Models. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker et al., Eds. Cambridge University Press, 741–866.

Frank, D. C., J. Esper, C. C. Raible, U. Büntgen, V. Trouet, B. Stocker, and F. Joos, 2010: Ensemble reconstruction constraints on the global carbon cycle sensitivity to climate. *Nature*, **463**, 527–530.

Fung, I. Y., S. C. Donry, K. Lindsay, and J. John, 2005: Evolution of carbon sinks in a changing climate. *Proc. Natl. Acad. Sci. USA*, **102**, 11 201–11 206.

Gent, P. R., and Coauthors, 2011: The community climate system model version 4. *J. Climate*, **24**, 4973–4991.

Giorgi, F., and R. Francisco, 2000: Uncertainties in regional climate change prediction: A regional analysis of ensemble simulations with the HADCM2 coupled AOGCM. *Climate Dyn.*, **16**, 169–182.

Harvey, D., and Coauthors, 1997: An introduction to simple climate models used in the IPCC second assessment report, T. H. John et al., Eds. *IPCC technical paper II-February 1997*, IPCC, Geneva, Switzerland, 52 pp.

He, J. K., W. Y. Chen, F. Teng, and B. Liu, 2009: Long-term climate change mitigation target and carbon permit allocation. *Advances in Climate Change Research*, **5**, 362–368. (in Chinese)

Höhne, N., and K. Blok, 2005: Calculating historical contributions to climate change-discussing the "Brazilian Proposal". *Climatic Change*, **71**, 141–173.

Höhne, N., and Coauthors, 2011: Contributions of individual countries' emissions to climate change and their uncertainty. *Climatic Change*, **106**, 359–391.

IPCC, 1996: *Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, J. T. Houghton et al., Eds. Cambridge University Press, 572 pp.

IPCC, 2013: *Summary for Policymakers. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker et al., Eds. Cambridge Uni-

versity Press, 1–30.

Jones, C., and Coauthors, 2013: Twenty-first-century compatible CO_2 Emissions and airborne fraction simulated by CMIP5 earth system models under four representative concentration pathways. *J. Climate*, **26**, 4398–413.

Lachenbruch, A. H., and B. V. Marshall, 1986: Changing climate: Geothermal evidence from permafrost in the Alaskan Arctic. *Science*, **234**, 689–696.

Le Quéré, C., and Coauthors, 2009: Trends in the sources and sinks of carbon dioxide. *Nature Geoscience*, **2**, 831–836.

Liu, Z., and Coauthors, 2015: Reduced carbon emission estimates from fossil fuel combustion and cement production in China. *Nature*, **524**, 335–338.

Matthews, H. D., N. P. Gillett, P. A. Stott, and K. Zickfeld, 2009: The proportionality of global warming to cumulative carbon emissions. *Nature*, **459**, 829–832.

Matthews, H. D., T. L. Graham, S. Keverian, C. Lamontagne, D. Seto, and T. J. Smith, 2014: National contributions to observed global warming. *Environmental Research Letters*, **9**, 014010.

Neale, R. B., and Coauthors, 2010: Description of the NCAR community atmosphere model (CAM 5.0). NCAR Tech. Note NCAR/TN-486+ STR.

Osterkamp, T. E., 2005: The recent warming of permafrost in Alaska. *Global and Planetary Change*, **49**, 187–202

Peters, G. P., J. C. Minx, C. L. Weber and O. Edenhofer, 2011: Growth in emission transfers via international trade from 1990 to 2008. *Proc. Natl. Acad. Sci. USA*, **108**, 8903–8908.

Prather, M. J., and Coauthors, 2009: Tracking uncertainties in the causal chain from human activities to climate. *Geophys. Res. Lett.*, **36**, L05707, doi: 10.1029/2008GL036474.

Rigor, I. G., J. M. Wallace, and R. L. Colony, 2002: Response of sea ice to the Arctic Oscillation. *J. Climate*, **15**, 2648–2663.

Rosa, L. P., S. K. Ribeiro, M. S. Muylaert, and C. P. de Campos, 2004: Comments on the Brazilian proposal and contributions to global temperature increase with different climate responses—CO_2 emissions due to fossil fuels, CO_2 emissions due to land use change. *Energy Policy*, **32**, 1499–1510.

Shu, Q., Z. Song, and F. Qiao, 2015: Assessment of sea ice simulations in the CMIP5 models. *Cryosphere*, **9**, 399–409.

Slater, A. G., and D. M. Lawrence, 2013: Diagnosing present and future permafrost from climate models. *J. Climate*, **26**, 5608–5623.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2012: An overview of CMIP5 and the experiment design. *Bull. Amer. Meteor. Soc.*, **93**, 485–498.

Trudinger, C., and I. Enting, 2005: Comparison of formalisms for attributing responsibility for climate change: Non-linearities in the Brazilian Proposal. *Climatic Change*, **68**, 67–99.

UNFCCC, 1997: Paper No. 1: Brazil; proposed elements of a protocol to the United Nations framework convention on climate change. No. UNFCCC/AGBM/1997/MISC.1/Add.3 GE.97. Bonn.

UNFCCC, 2002: Methodological issues. Scientific and methodological assessment of contributions to climate change. Report of the Expert Meeting, Note by the Secretariat. FCCC/SBSTA/2002/INF.14.

Ward, D. S. and N. M. Mahowald, 2014: Contributions of developed and developing countries to global climate forcing and surface temperature change. *Environmental Research Letters*, **9**, 074008.

Wei, T., and Coauthors, 2012: Developed and developing world responsibilities for historical climate change and CO_2 mitigation. *Proc. Natl. Acad. Sci. USA*, **109**, 12 911–12 915.

Wei, T., W. J. Dong, W. P. Yuan, X. D. Yan, and Y. Guo, 2014: Influence of the carbon cycle on the attribution of responsibility for climate change. *Chinese Science Bulletin*, **59**, 2356–2362.

Wei, T., W. J. Dong, B. Y. Wu, S. L. Yang, and Q. Yan, 2015: Influence of recent carbon emissions on the attribution of responsibility for climate change. *Chinese Science Bulletin*, **60**, 674–680. (in Chinese)

Yan, Q., H. J. Wang, O. M. Johannessen, and Z. S. Zhang, 2014: Greenland ice sheet contribution to future global sea level rise based on CMIP5 models. *Adv. Atmos. Sci.*, **31**, 8–16，doi: 10.1007/s00376-013-3002-6.

Zhang, Z. Q., J. S. Qu, and J. J. Zeng, 2008: A quantitative comparison and analytical study on the assessment indicators of greenhouse gases emissions. *Acta Geographica Sinica*, **63**, 693–702. (in Chinese)