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Sharing emission space at an equitable basis: Allocation scheme based on the equal cumulative emission per capita principle

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HIGHLIGHTS

- An allocation scheme based on equal per capita cumulative emission is presented.
- This scheme enables the considerations of different historical responsibilities.
- Country-specific trajectories are adjusted according to the global emission pathway.
- Allowances and peaking years are quantitatively analyzed.
- This new allocation scheme is compared with five others.

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ABSTRACT

This paper proposes an allocation scheme based on cumulative emission per capita to achieve a globally equitable carbon emission space. Within this scheme, each country has an equal cumulative emission per capita during the considered time period, and their annual emission per capita would reach the same level in the converged year. It is quantified by assuming a quadratic annual emission per capita for each country in the allocation interval. The country-specific emission trajectories are provided based on long-term targets, and then adjusted to strictly follow the global emission pathway. We analyze the peak years and associated abatement costs with different starting years under this scheme. Compared with three other schemes, this new allocation scheme considers historical emissions and future needs for developed and developing countries simultaneously.

1. Introduction

Global climate change has been a critical issue in the international community. In order to avoid dangerous climate impact, the world has agreed on a target to limit the global average temperature rise to 2 °C or even lower [1]. Such target would require a reduction by at least one half of current global emissions until 2050. In this condition, future emission space would be extremely stringent within a relatively long period, and most countries would face a severe emission space shortage. Hence, the means of setting reasonable principles and applying a proper methodology to allocate this restricted space among countries would certainly affect their fundamental interests.

International climate negotiations have focused on the allocation of emission rights (resource-sharing) and reduction commitments (burden-sharing) over the years. The United Nations Framework Convention on Climate Change (UNFCCC) has affirmed the principles of equity, common but differentiated responsibilities and respective capabilities in coping with climate change [2]. Consistent with their responsibilities and capabilities, both developed and developing countries therefore need to contribute on an equitable basis, taking active mitigation actions to control and reduce the current and future greenhouse gas (GHG) emissions.

Validated by UNFCCC, these principles should likewise serve as the preconditions to discuss future space allocation. Research institutions and scholars from numerous countries have proposed a variety of allocation schemes in different views so far. Among these schemes, several tend to allocate space based on emission convergence or the status quo [3,4]. However, others, particularly those put forward by developing countries, advocate that the allocation must fully consider different historical responsibilities, economic levels, and development needs. Duties and obligations on climate change must be correctly distinguished [5,6]. Specifically, the main existing schemes can be roughly divided into six categories, as summarized in Table 1.

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Table 1
Main allocation schemes.

Principles	Allocation schemes
Capacity/responsibility [7–11]	Ability to pay approach Brazilian proposal, extended to historical responsibility approach Greenhouse development rights framework Multi-stage approach South African approach
Current emission [12,13]	Grandfathering rule One billion high emitters approach
Emission intensity [14,15]	Emission intensity convergence Emission intensity targets approach
Emission per capita [16–21]	Adjusted equal annual emission per capita Contraction and convergence Common but differentiated convergence Equal annual emission per capita The convergence proposed by Centre for Science and Environment The Indian prime minister's proposal
Multi-indicator [22–24]	Multi-criteria convergence Preference score approach South-North dialogue proposal
Sector emission [25,26]	Multi-sector emission convergence Triptych approach

Given that the atmosphere is a common resource for all human beings, many studies suggested considering per capita as the basis of equity. The equal per capita annual emission (EPC) scheme provides each citizen in the world an equal emission right in each year straightway [27]. A well-known variant, namely, contraction and convergence (CC), is proposed by the Global Commons Institute [28]. In this scheme, the annual emission per capita in developed countries gradually descends, whereas it ascends yearly in developing countries. Eventually, the annual emission per capita in both developed and developing countries would converge at the same level at a certain time. Nevertheless, such implementation of future allocation would allow the per capita emission in developing countries to be always lower than that in developed countries.

As a scheme based on the status quo, grandfathering rule (GF) refers to an essential economic idea of public goods distribution. In this scheme, the global space would be allocated top-down among countries, proportional to their actual emissions in the reference year [29]. The Brazilian proposal suggested that reduction obligations should be allocated only among Annex I countries according to their responsibilities on the temperature rise. But developed countries insist that developing countries, particularly emerging economies or large emitters, must be also included in the absolute reductions [30]. As a result, a threshold can be introduced to identify the participation time of developing countries, e.g. GDP per capita, emission per capita, or a start year pre-defined. The triptych is a bottom-up approach that considers emissions from the energy-intensive industry, the domestic sector and the power production sector. Each sector has its own convergence criterion [31]. The South–North dialogue proposal divides countries into six groups with the weighted indicator of capacity, responsibility and mitigation potential. Each group has a differentiated reduction commitment [32]. In contrast to these proposed schemes, we propose an allocation scheme based on the equal cumulative emission per capita (EPCCE) principle, which is translated into a country-specific, year-to-year carbon allowance.

The remainder of this paper is organized as follows. Section 2 proposes the converged scheme based on EPCCE in the global equity scope. Section 3 discusses allocation results under this new scheme, including emission allowances, peak years and associated abatement costs. Section 4 presents comparative analyses with three other classical schemes. Section 5 performs sensitivity analyses. Lastly, Section 6 provides the conclusions.

2. Approach and methodology

2.1. EPCCE approach

Central to many claims, especially those arguing for equal per capita emission allocation rights is the idea that based on the premise of shared humanity and equal value of all humans, all humans, regardless of distinguishing characteristics, have equal claims to global collective goods. The underlying idea of this argument is that there are no relevant distinguishing characteristics amongst humans that would dictate that some humans should have more and other less access to any good that is indivisible and collective. In the climate change context this argument often is linked to an equal individual rights to atmospheric space.

Table 1 indicates that most schemes are presented from the perspectives of emission per capita or capacity/responsibility. As we have known, an allocation based on per capita directly reflects equal rights, so it is relatively acceptable in this field. For the scheme based on responsibility, a country's responsibility on global climate change is generally described by its contribution to the temperature rise, radiative forcing, sea level rise, or realist actual emissions [33]. Considering data availability, this paper chooses emissions. Since GHGs could persistently remain in the atmosphere for even over 100 years, the adoption of cumulative emissions is evidently preferable. Now combining the per capita basis with the responsibility described by cumulative emissions, we deem the cumulative emission per capita a more reasonable index to design the future space allocation scheme.

From the reliable instrumental records of near-surface temperature in 1850 until 1999, cumulative emissions (CO_2 related to energy and industry activities) produced in developed countries accounted for 78.6% (World Resources Institute, Climate Analysis Indicators Tool (CAIT) version 9.0 [34]); however, the population share of these countries was only 20.6% in 1999 (World Population Prospects, the 2010 Revision [35]). During 1850–1999, the cumulative emission per capita exceeded 1000 tCO_2 in the United Kingdom (UK) and the United States (US). In Germany, Russia, Australia and France, it was over 500 tCO_2. But for developing countries such as China, India, and Brazil, it was even less than 100 tCO_2, as listed in Table 2. The huge amount of cumulative emission per capita in developed countries has unduly occupied global emission space. Since a certain per capita emission is essential for all countries to achieve their industrialization and modernization, from the perspective of equity, future allocation undoubtedly requires considerations on both the historical responsibilities of developed countries and the development needs of developing countries.

We now propose the converged scheme based on EPCCE to embody the equity as a guiding principle. In the long-term, under EPCCE, future allocation must ensure that (1) cumulative emission per capita in all countries is equal; and (2) the annual emission per capita of all countries converges at the same level by the specified end year. In general, given the relatively lower cumulative emission per capita in the past, the annual emission per capita in most developing countries would outstrip that in developed countries at some time in the future. This difference would provide them with more space for social and economic improvement. After reaching a certain level, these developing countries would begin to share reduction obligations, as illustrated in Fig. 1. After the end year, EPCCE fully degenerates into EPC.

Several studies from developing countries have proposed the idea of a cumulative equal per capita convergence to discuss the future space allocation [36–38]. The central argument for this principle is that the atmosphere is a global commons that are essential to all human beings. Thus, all people should hold the equal use right. Based on this concept, Pan [39] further proposed a carbon budget

Table 2
Cumulative emissions in 1850–1999.

Country	Cumulative emission ($GtCO_2$)	Cumulative emission share (%)	Population in 1999 (10^6)	Population share in 1999 (%)	Cumulative emission per capita (tCO_2/cap)	Annex I (Y/N)
UK	64.5	6.7	58.7	1.0	1098.0	Y
US	293.3	30.5	284.4	4.7	1031.1	Y
Germany	74.5	7.7	82.0	1.4	908.4	Y
Russia	82.2	8.5	147.0	2.4	559.3	Y
Australia	10.1	1.1	19.0	0.3	534.3	Y
France	29.6	3.1	59.0	1.0	501.9	Y
Japan	35.7	3.7	126.5	2.1	282.6	Y
South Africa	10.6	1.1	44.2	0.7	239.0	N
China	67.7	7.0	1255.8	20.9	54.0	N
Brazil	7.1	0.7	171.7	2.9	41.4	N
India	19.4	2.0	1024.7	17.1	19.0	N
Annex I	756.2	78.6	1231.7	20.6	614.0	
Non-Annex I	206.2	21.4	4777.2	79.4	43.2	

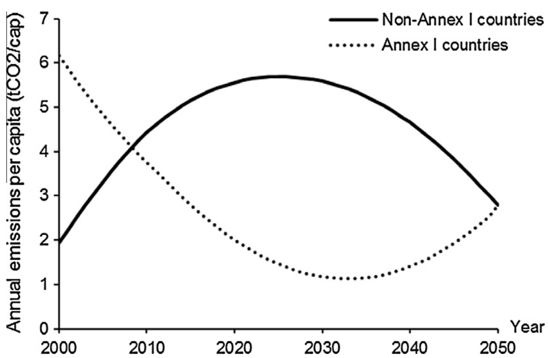

Fig. 1. Schematic plot of EPCCE scheme.

scheme. The Indian approach [11] developed an optimization model to calculate the physical availability of the emission space for various countries, which was analogous to the carbon budget scheme. Unfortunately, the abovementioned studies only assigned total allowances in the whole interval, but none discussed the important issue of quantifying an annual allowance trajectory for each country. Bode [40] provided a proposal based on an equal emission per capita over time. In his work, the allowance trajectories were obtained for each country with the assumption that all countries had a quadratic form of annual emission per capita in the future. However, the study ignored another pivotal issue, the compatibility with the global emission pathway in the long-term targets for concentrations stabilization. This compatibility is significant in two aspects. First, although the total emissions in a period are the same, varied distributions over the years are likely to have different effects on the future temperature rise which is the major characteristic of climate change. Hence, global emissions coinciding with the global pathway are essential to stabilize the expected concentrations with the maximum probability. Second, whether they are consistent with the global pathway is important to discuss the emission peaks which greatly impact the development processes and abatement costs.

Our EPCCE scheme synthetically considers the following three elements: (1) cumulative emission per capita that reflects responsibilities and rights equity; (2) annual allowance trajectory; and (3) in step with the global emission pathway. Based on rational assumptions and adjustments, the country-specific allowance trajectories that strictly meet the global pathway in the long-term targets are appropriately quantified. These considerations allow the EPCCE scheme to differ from those of existing studies in essence.

2.2. Methodology

The main procedure to implement the EPCCE scheme contains three steps.

Step 1: the remaining allowance in the allocation interval for each country is determined.

With no threshold in this scheme, all countries participate immediately. Before calculation, the allocation interval (from the year s to the year e) and the cumulative start year (s_0, it has been confirmed that an earlier start year reflects historical responsibilities of different countries more accurately [41]), as input parameters, should be pre-defined. Then the remaining allowance $A(i)$ of country i ($i = 1, \ldots, I$) in the allocation interval can be determined by Eq. (1). As input data, $hE(i)$ denotes the historical cumulative emissions of country i from the year s_0 up to the year $(s-1)$, $P(i,t)$ denotes the population of country i in the year t, and $Q(t)$ denotes the global emission cap in the year t. We set out to choose a static population to calculate cumulative emission per capita, and let t^* denote the population reference year (the other input parameter). A snapshot of population is actually often used due to uncertainties, e.g. experts from South Africa [11], German Advisory Council on Global Change [42] and Pan [39]. Due to the availability of data, we mainly considered CO_2 emissions relevant to energy and industry activities, while those produced from international marine, air and land transport are excluded.

$$\begin{cases} [hE(i) + A(i)]/P(i,t^*) = constant \\ \sum_{i=1}^{I} A(i) = \sum_{t=s}^{e} Q(t) \end{cases} \quad (1)$$

Step 2: the remaining allowance of each country is decomposed into annual values. The country-specific trajectories are now obtained.

The first period commitment under the Kyoto Protocol is temporarily ignored. To acquire the country-specific allowance trajectories, similar to Bode's work [40], we assume that the future annual emission per capita of each country fits a quadratic polynomial $\Phi_i(t) = a_i t^2 + b_i t + c_i$ which is determined by Eq. (2).

$$\begin{cases} \sum_{t=s}^{e} \Phi_i(t) = A(i)/P(i,t^*) \\ \Phi_i(s-1) = E(i,s-1)/P(i,t^*) \\ \Phi_i(e) = Q(e)/\sum_i P(i,t^*) \end{cases} \quad (2)$$

For simplification, the first condition can be also approximated as an integral form $\int_s^e \Phi_i(t)dt = A(i)/P(i,t^*)$ In addition, employing other formulas or curves to simulate $\Phi_i(t)$ is indeed possible, just like CC which could be expressed as a linear or exponential convergence. $\Phi_i(t)$ then indicates the allowance of country i in year t by $E(i,t) = \Phi_i(t) \times P(i,t^*)$.

Step 3: the country-specific trajectories are adjusted so that the global total emission per year strictly follows the global pathway.

The trajectory of global total emissions obtained from the first two steps may not severely satisfy the global pathway. General approaches to solve this problem include: (1) an equal per capita adjustment; (2) a scaling factor; and (3) an adjustment based on a specific indicator in the scheme. Since EPCCE is related to a per capita basis, we can adjust based on equal per capita, as indicated by Eq. (3).

$$E(i,t) = E(i,t) + [Q(t) - \sum_i E(i,t)] \times P(i,t^*)/\sum_i P(i,t^*) \quad (3)$$

This adjustment provides the following advantages: (1) For each country, $\sum_{t=s}^{e} E(i,t) = A(i)$ ensures the realization of EPCCE; and (2) for each year, $\sum_{i=1}^{I} E(i,t) = Q(t)$ guarantees the consistency.

3. Results

3.1. Emission allowances

In this paper, according to the availability of data, we mainly considered CO_2 emissions relevant to energy and industry activities, while those produced from international marine, air and land transport are excluded (In fact, these emissions have not been factored in most studies on emission status analysis or future space allocation [43–49]). We respectively set 1850, 1950 and 1990 as the cumulation start year s_0, and the years 2001–2050 as the allocation interval. Historical cumulative emissions $hE(i)$ under different start years in Eq. (1) are from CAIT [34]. The global emission pathway toward the 450 ppm of concentration stabilization levels (S450 [50]) is adopted to give values to $Q(t)$. With 2000 as the population reference year t^*, $P(i,t^*)$ is given by World Population Prospects [35]. Now the remaining emission allowances $A(i)$ of some representative parties are indicated in Fig. 2.

Under the common but differentiated responsibilities of EPCCE, the basic rights and interests of developing countries are protected. For instance, with different cumulation start years, the total allowances in 2001–2050 for China and India are 271–390 $GtCO_2$ and 234–348 $GtCO_2$, respectively. The developing countries obtain 1057–1524 $GtCO_2$ space in all. On the contrary, the space for the European Union (EU) and US during the same period is respectively −107 to 71 $GtCO_2$ and −196 to −10 $GtCO_2$, indicating that developed countries must quickly perform deep reductions. Fig. 2 also visually illustrates that a later start year would result in a milder distribution of future reduction obligations across countries due to the neglect of emissions in the early industrialization of developed countries.

Since all countries have their own definite caps $A(i)$ within the period, this EPCCE scheme can effectively avoid the incentives of carbon leakage. In addition, the global pathway to stabilize concentrations is severely maintained, which would lead to the best control of the temperature rise.

3.2. Peaks

Another highly important factor in emission space allocation is the occurrence of the peak year. Fig. 3 implies that during the years

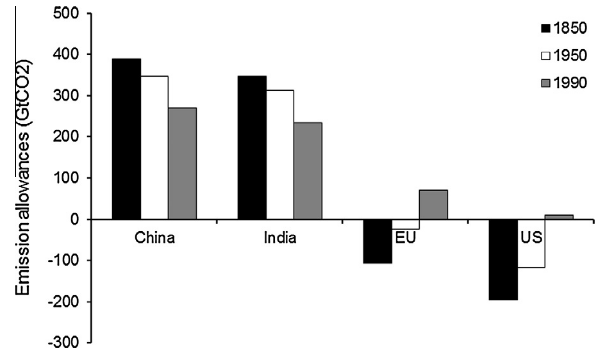

Fig. 2. Allowances of representative parties based on EPCCE in 2001–2050.

2001–2050, the annual allowances of most developing countries would gradually increase based on the emissions in 2000, and reach their peaks in 15–30 years from 2000. After which, their allowances would begin to decrease and converge to the same level (allowances of several least-developed countries would monotonously increase). For EPCCE1850 and EPCCE1950, China would peak in 2021 and 2020, respectively. For EPCCE1990, with the latest start year, it has to peak in 2016. However, according to the World Bank [51], the per capita GDP of China is less than 10% of that of the US in 2011. Hence, from this day onwards, China must accelerate the transition to a low carbon economy in at most 10 years. The peak year for India is between 2020 and 2025, indicating this country would have nearly 10–15 years for free developments.

Theoretically, developed countries and several developing countries with fairly high historical emissions have already passed their peaks. These countries must continuously mitigate in the next 30 years or so (from 2000) to make space for the developing world. Then, with abatements of most developing countries, particularly large emitters (e.g. China), their allowances would slowly return to the converged level in 2050. Unfortunately, according to CAIT [34], their real emissions still remain extremely high, so those peak years mentioned above are in reality quite challenging for developing countries.

3.3. Economic accessibility

It should be noted that allowances presented above are merely results of an initial resource endowment allocation, which could be followed by a secondary trade. Thus, they do not necessarily reflect actual emissions in the future. To further consider the economic feasibility of EPCCE, we employ marginal abatement cost curves (MACs) (Similar works are given by Ellerman and Decaux [52], Criqui et al. [53]). The MACs adopted in this paper are derived from the Global Change Assessment Model (GCAM). As a partial equilibrium model developed by the Joint Global Change Research Institute, GCAM has been widely used in a number of assessment and modeling activities, e.g. the Intergovernmental Panel on Climate Change (IPCC) assessment reports and Energy Modeling Forum [54].

The strengths and weaknesses of using this MACs-based methodology to estimate abatement costs have been profoundly discussed in the literature [14,31,52,53]. In order to account for the dynamics (technology developments, learning effects, etc.) in the system triggered by earlier abatements as much as possible, we have referred to the method which Elzen and Lucas [55] used in the development of the Framework to Assess International Regimes for the differentiation of commitments model (the most famous policy decision-support tool to analyze environmental and costs implications of international climate regimes [56]). That is,

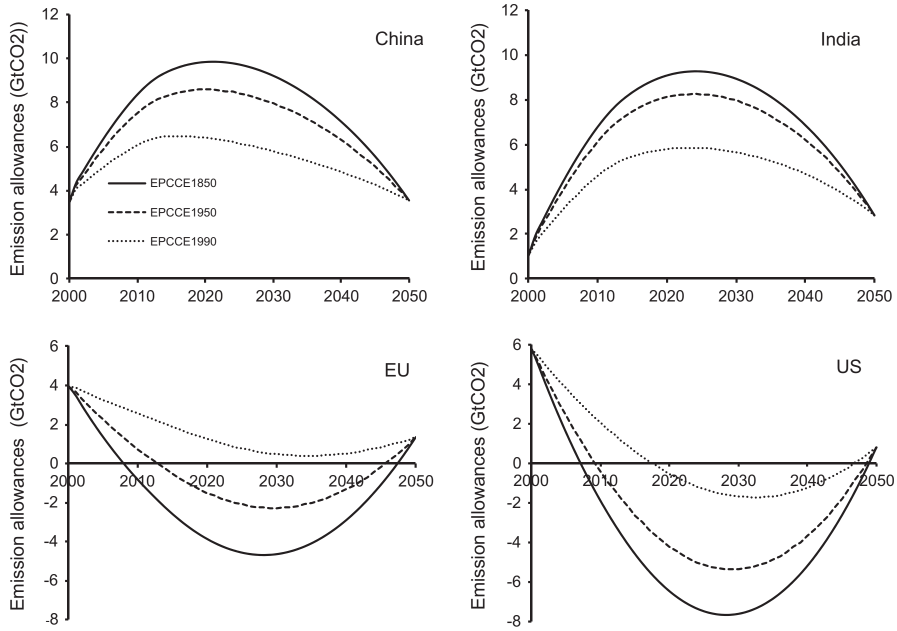

Fig. 3. Allowance trajectories based on EPCCE.

the MACs are obtained by imposing a linearly increasing carbon tax on CO_2 emissions in time from 0 in 2005 (the base year of GCAM) to the desired value in the evaluation year. To be used in different scenarios, these MACs have been expressed as percentile reductions. Furthermore, more changes (e.g. a major change in energy or industry mix) in the trends over time can be incorporated in GCAM during the process of MACs production, if necessary.

We consider a global free trade market of emission allowances, excluding transaction costs, limits on import or export, non-competitive behaviours in supper, etc. In this perfect market, any region (abatement costs have to be calculated in the region level) could fulfill its obligations through domestic mitigations and international trade. Therefore, by purchasing spare allowances of other regions, a region with low or even negative allowances will have a chance to achieve its tasks. The baseline chosen to give projections of emissions as usual is the A1B scenario of the IPCC special report on emissions scenario (SRES) (the base year of SRES is 2000 [57]). GDP and relevant abatements costs can be expressed in either market exchange rates (MER) or purchase parity power. In this paper, we apply the MER basis which Nordhaus and Boyer [58] has strongly supported especially in a trade system.

By setting an annual discount rate, all abatement costs in 2010–2050 can be converted to net present ones in 2010 (Here we calculate abatement costs after the base year of GCAM). Since there are considerable differences in economy sizes, Fig. 4 adopts the discounted effort rates (calculated as abatement costs divided by GDP) to illustrate the distribution of the overall abatement costs across regions (Negative values mean gains). In the framework of MER-GDP, the Former Soviet Union (FSU) always confronts the highest rates (5.93–9.64%), followed by Eastern Europe (3.55–6.12%), mainly due to their high per capita emissions and medium GDP levels. Africa and India are the two largest sellers in the market. They get extraordinarily large profits as compensations of low historical emissions, which lead to negative effort rates (Africa: −5.56% to −2.68%, India: −5.35% to −2.31%). As the cumulation start year becomes recent, the cost distribution among regions changes approximately in line with the allowance allocation. Developing regions will gain less (or pay more), while developed regions will generally pay less. Above all, this figure verifies that the EPCCE scheme could be economically accessible with an appropriate start year and acceptable financial flows.

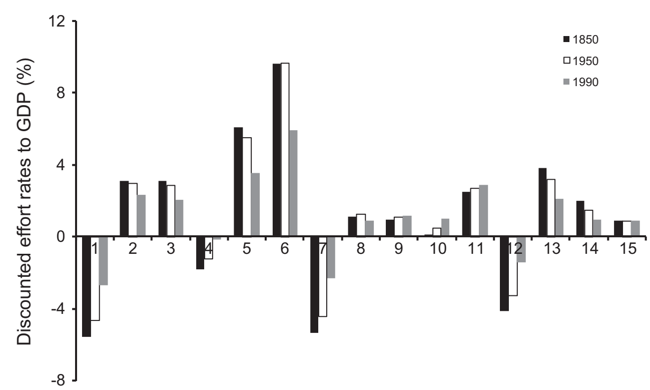

Fig. 4. Abatement costs distribution based on EPCCE with a discount rate 0.05. Regions defined in GCAM: 1-Africa, 2-Australia&NZ, 3-Canada, 4-China, 5-Eastern Europe, 6-Former Soviet Union, 7-India, 8-Japan, 9-Korea, 10-Latin America, 11-Middle East, 12-Southeast Asia, 13-US, 14-Western Europe, 15-The world.

Table 3
Parameter settings.

Scheme	Parameters
CC	Convergence coefficient = 4
EPC	No population cap
GF	Policy delay = 5 years
	Threshold = 30% of Annex I average per capita GDP in 1990

4. Comparative analysis

CC, EPC and GF are the typical and influential allocation schemes, as Section 1 states. In this section, the comparative analyses between EPCCE and them are carried out. We keep using IPSS SRES A1B and S450 to determine global reduction targets. Table 3 gives the parameter settings, and GF is adjusted by a scaling factor to satisfy the global pathway S450.

4.1. Allowance trajectories

In this scenario, due to the population trend, both China and India under EPC peak the earliest with the peak allowance of 5–6 $GtCO_2$, as depicted in Fig. 5. Among these schemes, CC allots China and India the least total allowances during the whole period, only 200 $GtCO_2$ and 145 $GtCO_2$, respectively. In fact, in our study, we find that for most developing countries, EPC appears to provide the earliest peak years, whereas CC constantly provides the least peak allowances.

From the quantitative view, EPCCE1850 is most beneficial for China (390 $GtCO_2$). For India, as the most populated country, EPCCE1850 and EPCCE1950 provide very sufficient emission rights (348 $GtCO_2$ and 314 $GtCO_2$), which even outdistance its baseline emissions. Through trade and cooperation, these surpluses would help it get enormous revenues (see Fig. 4). Under GF, with a relatively low per capita GDP, India only needs to absolutely abate after the year 2037, receiving a relatively long period to develop.

Table 4
Reductions compared with baseline emissions during 2001–2050 (%).

Scheme	China	India	EU	US	Annex I	Non-Annex I
CC	−52.0	−42.6	−57.0	−59.4	−57.8	−47.4
EPC	−47.2	−19.8	−72.2	−84.8	−77.5	−35.1
GF	−47.5	−33.6	−53.6	−49.9	−52.2	−50.9
EPCCE1850	−6.0	37.6	−136.7	−155.3	−133.9	0.2
EPCCE1950	−16.5	24.2	−108.3	−133.2	−117.1	−10.3
EPCCE1990	−34.7	−7.5	−75.5	−97.1	−84.8	−30.5

In terms of treating developing countries as a group, GF gives the smallest total allowances (747 $GtCO_2$), yet EPCCE1850 provides the largest total (1524 $GtCO_2$) and peak (39.3 $GtCO_2$) allowances as well as a moderate peak year (2023).

For developed countries like EU and US, all schemes require steep reductions. Three EPCCE schemes make them completely compensate their burdens from the selected start year. And under other three schemes, their annual allowances also almost all show monotonically decreasing trends (Local jumping upwards is due to the start of absolute abatements in some large developing countries). Relatively speaking, since the current emissions are high, GF and CC are usually favorable to developed countries. However,

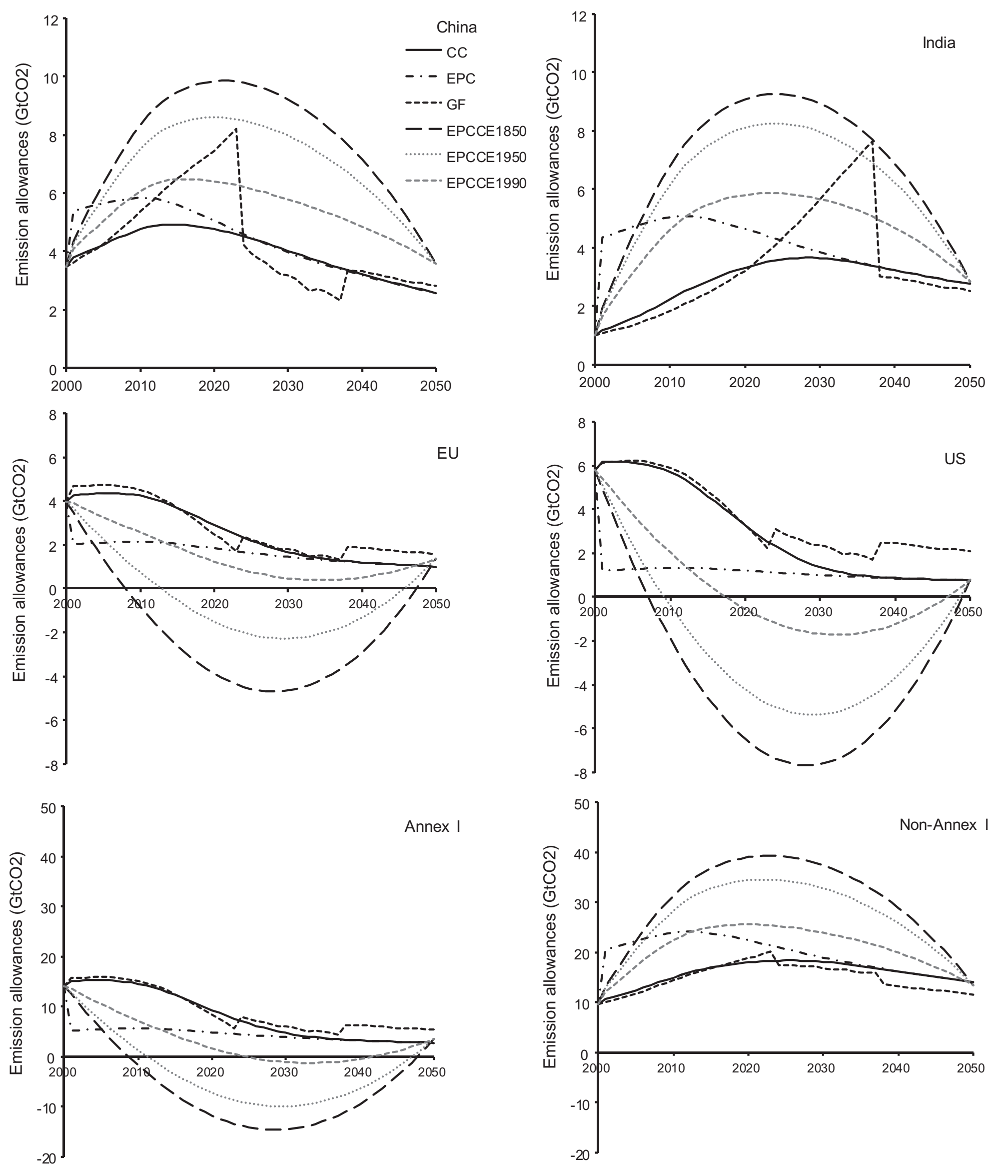

Fig. 5. Allowance trajectories under different schemes.

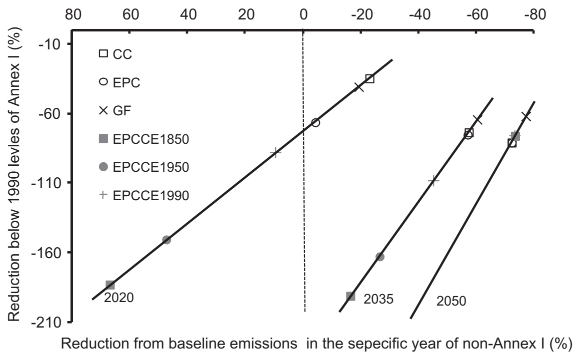

Fig. 6. Reduction tradeoff relationship between Annex I and non-Annex I countries.

Table 5
Peak years and allowances with adjustment (A) versus without adjustment (NA).

Case		Peak year			Peak allowance ($GtCO_2$)		
	Start year	1850	1950	1990	1850	1950	1990
A	Brazil	2023	2022	2020	1.4	1.2	0.9
	China	2021	2020	2016	9.9	8.6	6.5
	India	2024	2024	2023	9.3	8.3	5.9
	Non-Annex I	2023	2022	2020	39.3	34.5	25.5
NA	Brazil	2026	2026	2027	1.4	1.3	0.9
	China	2025	2025	2025	10.0	8.7	6.4
	India	2027	2027	2028	9.5	8.5	6.1
	Non-Annex I	2026	2026	2027	40.0	35.2	26.0

even GF would need EU and US to reduce total emissions during 2001–2050 by 156 $GtCO_2$ and 177 $GtCO_2$, respectively.

4.2. Reduction tradeoff

Table 4 summarizes the reduction shares of allowances during 2001–2050 under these schemes as compared with the baseline levels (Negative value indicates a reduction). For the four representative parties, only India can emit as usual under EPCCE1850 and EPCCE1950. For China, although no current obligations are quantified, its reduction tasks seem to be very severe and urgent. For the developing world, only EPCCE1850 which takes full responsibilities since the instrumental records of temperature into account provides the rare chance to match baseline emissions.

Fig. 6 shapes the tradeoff relationship between the change in emissions of Annex I countries compared with their 1990 levels, as well as the deviation from the baseline emissions of non-Annex I countries in the years 2020, 2035 and 2050. For instant, in 2020, 50% mitigation in developed countries relative to 1990 levels corresponds with about 14% deviation from the baseline in developing countries to stabilize concentrations at a 450 ppm level. If developing countries do not reduce emissions in 2035, developed countries have to abate by 239%. However, the slope implies that as long as developing countries increase their reductions in 2035 by merely 1%, its effect would be equal to almost 3% reductions in developed counties relative to 1990 levels. It can be concluded that to combat global climate change effectively in the long-term, all countries must be involved. But the premise should be adequate support provisions in terms of finance flow, technology transfer, and capacity building from developed countries to developing ones.

According to the Coase theorem [59], in a perfect market, the trade mechanism will always result in the global efficient re-allocation of abatements with the least possible costs regardless of the initial allocation. This means that though the cost distribution across regions varies with different schemes, the global discounted effort rates will always steady at 0.88% (see Fig. 4).

5. Sensitivity ananlysis

5.1. Adjustment

Although the adjustment to match the yearly global total emissions with the global pathway will not alter cumulative emissions, we have pointed out that it is significant for issues on peaks. Since developed countries usually peak in the first year, we concentrate on developing countries.

Table 5 implies that based on the equal per capita adjustment in *Step 3*, the peak allowances of most developing countries remain stable, while the peak years are shown to be dramatically brought forward. For example, China has to peak at around five years ahead if the start year is 1950. Moreover, as the cumulation starts later, the impact of this adjustment becomes greater. For the start year 1850, after the adjustment, the developing countries as a group would peak 3 year earlier. However, for 1990, the group has to reach its peak 7 years in advance.

The significance of this adjustment manifests that under the current situations, both developed and developing countries have to accelerate the mitigation pace earlier than their expectations in order to stabilize the concentrations. Before executing quantified commitments, developing countries must strive for a win–win society for tackling climate change and achieving sustainable development at soon as possible.

5.2. Population

Besides the cumulation start year, emission allowances and accompanying abatement costs under EPCCE are directly related

Table 6
Allowances of non-Annex I countries in 2001–2050.

Start year	Reference year	Brazil	China	India	Non-Annex I
1850	1990	54.7/2023/1.4[a]	403.1/2021/10.2	337.6/2024/9.0	1482.5/2023/38.1
	2000	54.8/2023/1.4	390.4/2021/9.9	347.7/2024/9.3	1524.0/2023/39.3
	2030	52.9/2023/1.4	309.6/2019/7.7	348.7/2024/9.3	1600.1/2023/41.3
	Dynamics[b]				
1950	1990	48.9/2022/1.2	358.4/2020/8.9	304.8/2024/8.0	1326.9/2022/33.5
	2000	49.0/2022/1.2	347.0/2020/8.6	313.9/2024/8.3	1364.4/2022/34.5
	2030	47.3/2022/1.2	274.1/2018/6.7	314.8/2024/8.3	1433.1/2022/36.4
	Dynamic	46.9/2023/1.2	309.7/2018/8.0	306.3/2025/8.1	1366.8/2024/34.3
1990	1990	38.1/2020/0.9	279.6/2017/6.7	227.3/2023/5.7	1030.0/2020/24.8
	2000	38.2/2020/0.9	271.3/2016/6.5	234.0/2023/5.9	1057.4/2020/25.5
	2030	36.9/2020/0.9	218.0/2013/5.3	234.6/2023/5.9	1107.6/2020/26.8
	Dynamics	37.2/2020/0.9	231.0/2014/5.9	233.6/2024/5.9	1092.1/2022/26.1

[a] Total allowances ($GtCO_2$)/peak year/peak allowance ($GtCO_2$).
[b] Population data from 1850 to 1949 lacks.

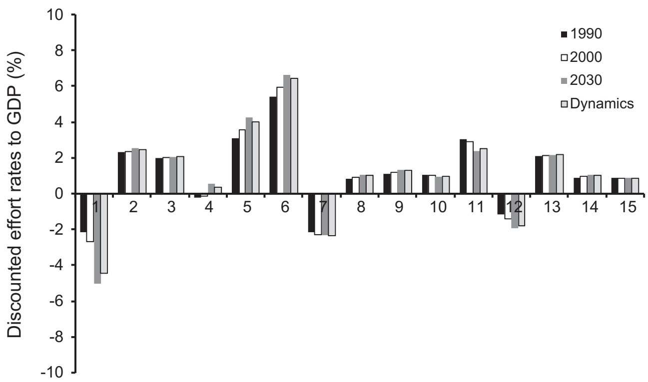

Fig. 7. Abatement costs distribution with different population bases.

to the population basis. In this subsection, we perform the sensitivity analysis on the population. Different reference years of population are considered, including the past (1990) and the future (2030). And beyond these static cases, EPCCE can further cover dynamics with the forecast of population trend given by IPCC SRES A1B.

As Table 6 presents, the cumulation start year is the intuitively dominating factor in the future allocation under EPCCE. If we treat developing countries as a group, the impacts of the reference years (1990, 2000, 2030 and dynamics) seem to be negligible. Given a certain start year, the variation of total allowances is limited within 8% (1850: 1483–1600 $GtCO_2$; 1950: 1327–1433 $GtCO_2$; 1990: 1030–1108 $GtCO_2$). Meanwhile, the peak year and allowance are likely to stay the same. In the country level, Brazil and India are scarcely affected by the selection of population bases. However, for China, the choice of a future reference year (2030) or dynamics would sharply shorten the total allowances in 2001–2050 largely due to a relatively slow growth rate of population compared with other developing countries in the baseline A1B. For developed countries, our findings are basically homologous. Taking them as a group, once the cumulation start year is specified, total allowances are approximately steady. Regarding allocation results of countries, the US is insensitive to the change of population basis, while the reference year 2030 assigns EU extremely low allowances (1850: −143 $GtCO_2$; 1950: −57 $GtCO_2$; 1990: 47 $GtCO_2$).

Following allowances, Fig. 7 show the distribution of abatement costs under different population bases taking 1990 as the cumulation start year. It is illustrated that the future reference year and dynamics of population will cost China, Eastern Europe and FSU more to accomplish their burdens. However, these population bases are indeed profitable for Africa, Middle East and Southeast Asia. For the rest regions, their discounted effort rates are barely affected.

6. Conclusions

With the 2 °C target, the emission rights allocation schemes would directly influence all countries within a relatively long time. Developing countries still require an appropriate growth in emissions. The allocation scheme based on EPCCE in this paper has comprehensively considered the responsibilities and equity rights of all countries. We first frame the debate over allocation principles as a moral issue rather than a cost-benefit analysis, and focus on the fairness of EPCCE principles rather than the likelihood of its being accepted. We then compare EPCCE with other key allocation schemes under different start years, and provide an abatement cost analysis to show the cost distribution of EPCCE. A sensitivity analysis has been provided for two key parameters of EPCCE approach in this paper: the cumulation start year and the reference year of population.

Using the EPCCE scheme to allocate the future emission space in the long-term targets, we has assumed a quadratic annual emission per capita for each country and strictly matched the global emission pathway with an equal per capita adjustment. Numerical analyses have been restricted to energy-industry related CO_2 emissions, which could be extended in the future. Under a severe stabilization levels, the results demonstrate that this scheme may lead to negative allowances in some years for certain countries with high historical emissions as well as considerably large financial transfers in the potential trade market. However, it has particularly safeguarded rational interests of the developing world, satisfying the fundamental principles of equity, common but differentiated responsibilities under UNFCCC.

Emissions of developed countries have already exceeded their allowable space before 2050. Thus, they must deeply and immediately mitigate to set aside the necessary space for developing countries. What's more, the developed countries must also provide adequate technical and financial support to offset their commitments. Fortunately, the 17th Conference of the Parties in Durban has already agreed on a package of measures, mainly including the second commitment period under the Kyoto Protocol as well as the launch of the registry and Green Climate Fund. The successful operation of those instruments would be essential to close the mitigation gap identified by the scientific community.

A certain cumulative emission per capita is indispensable in the development process for all countries. However, according to the results, in order to realize the long-term stabilization targets, most developing countries need to peak within the following 15–30 years (from 2000). Therefore, developing countries, particularly those that are highly populated and are emerging economies, must pay further attention to the coordination of the economy and the environment. Through domestic innovation and international support, they should optimize the energy structure and improve the carbon productivity, thereby accelerate the shift towards a low-carbon development path.

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