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Reduced carbon emission estimates from fossil fuel combustion and cement production in China

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Nearly three-quarters of the growth in global carbon emissions from the burning of fossil fuels and cement production between 2010 and 2012 occurred in China[1,2]. Yet estimates of Chinese emissions remain subject to large uncertainty; inventories of China's total fossil fuel carbon emissions in 2008 differ by 0.3 gigatonnes of carbon, or 15 per cent[1,3–5]. The primary sources of this uncertainty are conflicting estimates of energy consumption and emission factors, the latter being uncertain because of very few actual measurements representative of the mix of Chinese fuels. Here we re-evaluate China's carbon emissions using updated and harmonized energy consumption and clinker production data and two new and comprehensive sets of measured emission factors for Chinese coal. We find that total energy consumption in China was 10 per cent higher in 2000–2012 than the value reported by China's national statistics[6], that emission factors for Chinese coal are on average 40 per cent lower than the default values recommended by the Intergovernmental Panel on Climate Change[7], and that emissions from China's cement production are 45 per cent less than recent estimates[1,4]. Altogether, our revised estimate of China's CO_2 emissions from fossil fuel combustion and cement production is 2.49 gigatonnes of carbon (2 standard deviations = ±7.3 per cent) in 2013, which is 14 per cent lower than the emissions reported by other prominent inventories[1,4,8]. Over the full period 2000 to 2013, our revised estimates are 2.9 gigatonnes of carbon less than previous estimates of China's cumulative carbon emissions[1,4]. Our findings suggest that overestimation of China's emissions in 2000–2013 may be larger than China's estimated total forest sink in 1990–2007 (2.66 gigatonnes of carbon)[9] or China's land carbon sink in 2000–2009 (2.6 gigatonnes of carbon)[10].

Reports of national carbon emissions[7,11–14] are based on activity data (that is, amounts of fuels burned) and emission factors (that is, amount of carbon oxidized per unit of fuel consumed), with these factors estimated as the product of the net carbon content (that is, tonnes carbon per joule), net heating value (that is, joules per tonne fuel), total carbon content (that is, tonnes carbon per tonne fuel) and oxidation rate (that is, carbon oxidized per carbon content; see Methods). The uncertainty of China's emissions estimates is typically reported as ±5% to ±10% (refs 4, 13, 15), but this range is somewhat arbitrary because neither the activity data nor the accuracy of emission factors is well known. For instance, national activity data are substantially different from the sum of provincial activity data[16], and the emissions factors used are not based on up-to-date measurements of the fuels actually being burned in China, of which the quality and mix are known to vary widely from

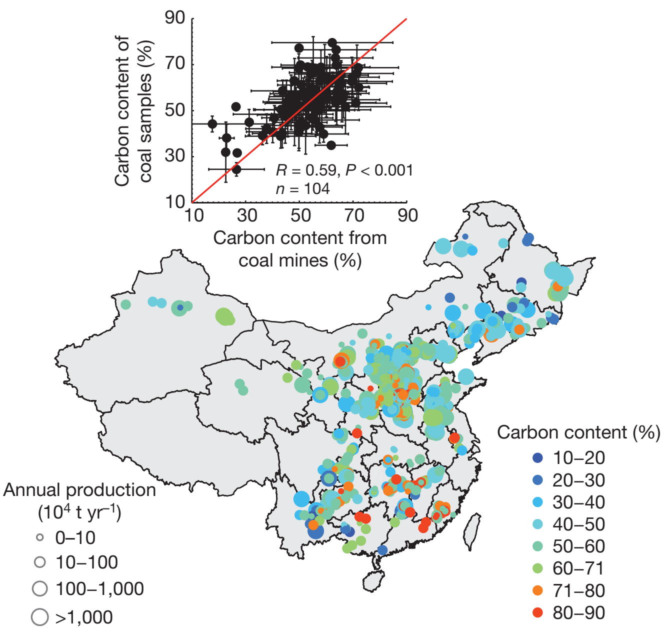

Figure 1 | Total carbon content and production of coal mines. The inset shows the comparison between carbon content from 602 coal samples and 4,243 coal mines ($R = 0.59$, $P < 0.001$, $n = 104$). Each dot in the inset indicates the average of carbon content from 602 coal samples and 4,243 coal mines in the same 1° by 1° grid. The nearly one-to-one correlation indicates that samples and mines capture the same spatial variability of coal carbon content across China.

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year to year, especially for coal[17]. Indeed, using different official sources of activity data and emissions factors can result in estimated emissions that vary by up to 40% in a given year (see Methods).

Here, we present revised estimates of Chinese carbon emissions from the burning of fossil fuels and cement production during the period 1950–2013 using independently assessed activity data and two sets of comprehensive new measurements of emission factors. Results suggest that Chinese CO_2 emissions have been substantially overestimated in recent years: 14% less than the estimates by the Emissions Database for Global Atmospheric Research (EDGAR) version 4.2 (EDGAR being adopted by the Intergovernmental Panel on Climate Change (IPCC) as the emission baseline) in 2013 and 12% less than the latest inventory China reported to the United Nations Framework Convention on Climate Change (UNFCCC; in 2005). The difference is due primarily to the emission factors used to estimate emissions from coal combustion; our measurements indicate that the factors applicable to Chinese coal are on average about 40% lower than the default values recommended by the IPCC[7,11] and used by previous emissions inventories[1,4,18].

In re-evaluating Chinese energy consumption, we adopt the 'apparent consumption' approach[13,15], which does not depend upon energy consumption data (that previous studies have shown to be not very reliable[16,19]). Instead, apparent energy consumption is calculated from a mass balance of domestic fuel production, international trade, international fuelling, and changes in stocks, data about which are less subject to 'adjustment' by reporting bodies and accounting errors related to either energy consumed during fuel processing or assumptions about the mix of fuel types (especially coal) being used by individual consumers. Furthermore, this approach allows imported and domestically produced fuels to be tracked separately so that appropriate emission factors can be applied to these fuels (see Methods).

Apparent consumption of coal, oil and natural gas in China in 2013 was 3.84 Gt, 401.16 Mt and 131.30 Gm^3, respectively. Between 1997 and 2012, we estimate that cumulative energy consumption was 10% greater than the national statistics and 4% lower than provincial statistics (Extended Data Fig. 2). In addition, our results indicate a higher annual growth rate of energy consumption than national statistics between 2000 and 2010 (9.9% yr^{-1} instead of 8.8% yr^{-1}); the high growth rate is consistent with satellite observations of NO_x[20,21], although NO_x to fuel emission factors change with time as well.

Given the large fraction of CO_2 emissions from coal combustion (80% between 2000 and 2013), estimates of total emissions are heavily dependent on the emission factors used to assess coal emissions. Thus, we re-evaluate each of the variables that determine these emission factors. The mean total carbon content of raw coal samples from 4,243 state-owned Chinese coal mines (4,243 mines represent 36% of Chinese coal production in 2011)[22] (Fig. 1) is 58.45% (Fig. 2a), and the production-weighted total carbon content is 53.34%.

These results straddle the results of an independent set of 602 coal samples from the 100 largest coal-mining areas in China (these areas together represent 99% of Chinese coal production in 2011)[22] (Extended Data Fig. 3), which reveal a similarly low mean carbon content of 55.48% (Fig. 2b) and a production-weighted mean total carbon content of 54.21%. The net carbon content per energy produced of these same samples is 26.59 tC TJ^{-1}, or 26.32 tC TJ^{-1} if weighted by production (Fig. 2c), and their net heating value is 20.95 PJ Mt^{-1}, or 20.6 PJ Mt^{-1} if weighted by production (Fig. 2d). Although the measured net carbon content per energy produced of these samples is within 2% of the IPCC default value (25.8 tC TJ^{-1}), the heating value from these coal samples (20.95 PJ Mt^{-1}) is significantly less than either the IPCC default value (coking coal) of 28.2 PJ Mt^{-1} or the mean value of US coal of 26.81 PJ Mt^{-1} (ref. 23). The lower heating value of Chinese coal reflects its generally low quality and high ash content (Fig. 2e, f). For example, the average ash content of our 602 coal samples was 26.91% compared to the average ash content of US coal, 14.08% (ref. 23), but is consistent with recent studies[24].

Finally, we assessed the oxidation rate (carbon oxidized per carbon content) of the fossil fuels consumed by 15 major industry sectors in

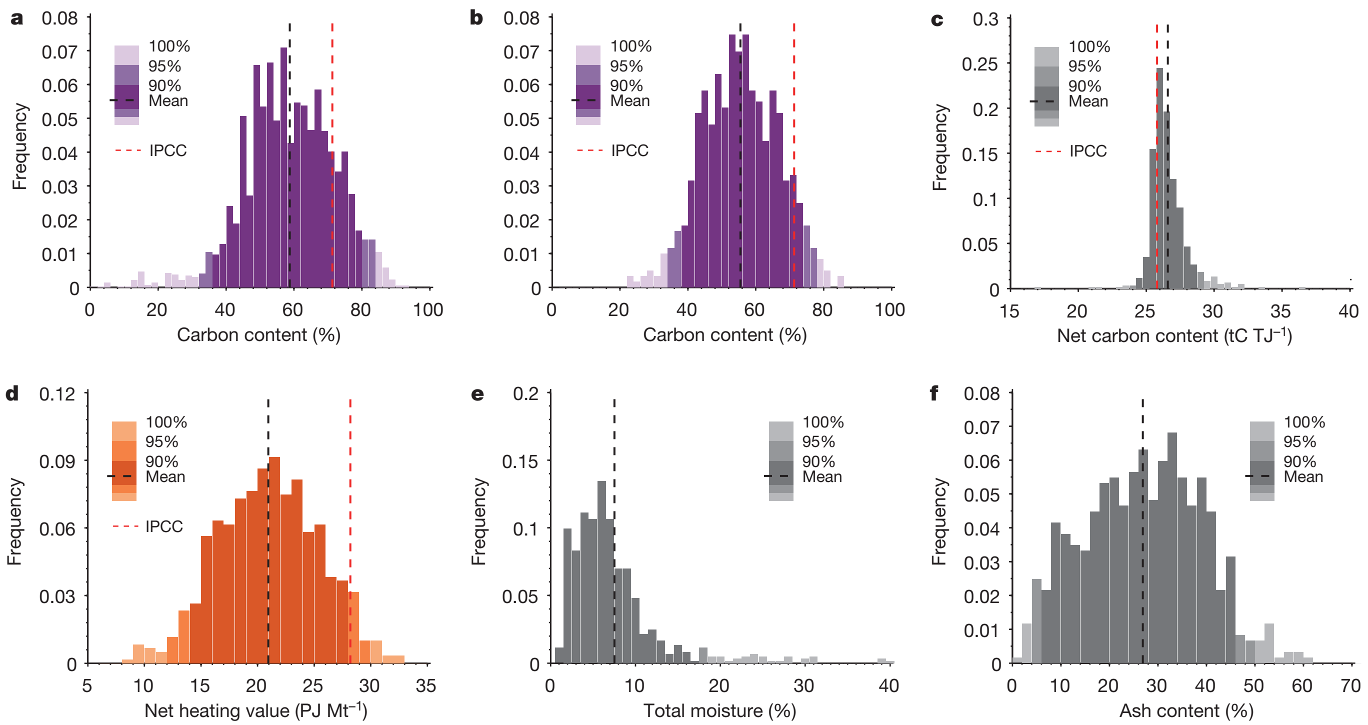

Figure 2 | Histograms of Chinese coal properties. a, **b**, Total carbon content of 4,243 coal mines (**a**) and 602 coal samples (**b**). Dashed lines show mean, and shading indicates 90% and 95% intervals. **c**, **d**, Net carbon content (**c**) and net heating values (**d**) of the 602 coal samples. Carbon content for coal mines (**a**) and samples (**b**) are significantly lower than IPCC values, which is mainly because of the lower net heating values of China's coal (**d**); net carbon content is close to the IPCC value (**c**). **e**, **f**, Total moisture (**e**) and ash content (**f**) further proved the low quality of China's coal, which in general has high ash content but low carbon content.

China with 135 different combustion technologies (see Supplementary Data), as analysed by the National Development and Reform Commission (NDRC; ref. 25). We calculate a production-weighted average oxidation rate for coal of 92%, somewhat lower than the IPCC default value of 98%, but generally consistent with China-specific values reported by the NDRC (94%)[25], China's National Communication that reported to UNFCCC (92%)[8], and the estimate from a previous study (on average 93%)[26]. Our estimates of the oxidation values of oil and natural gas in China (98% and 99%, respectively) are each within 1% of the IPCC default value.

Combining our revised estimates of carbon content, heating value and oxidation value, we derive new emission factors for coal, natural gas and oil burned in China. The revised emission factors differ from IPCC defaults by −40%, +13% and −1%, respectively (Fig. 3). In turn, applying these lower emission factors to our revised estimates of energy consumption, our best estimate of Chinese carbon emissions from fossil fuel combustion in 2013 is 2.33 GtC using the carbon content of 4,243 coal mine samples, and 2.31 GtC if the carbon content of 602 coal samples is used. On the basis of the residual scatter of carbon contents from these independent sets of coal samples (Fig. 1), the associated 2σ uncertainty related to coal carbon content is of the order of 3%. Additional uncertainty about Chinese emissions is provided by varying the estimates of coal consumed, by ±10% as evidenced by the range between national and provincial activity data[16,19]. Combining these two numbers gives the 7.3% uncertainty range of Chinese fossil fuel carbon dioxide emissions.

We also used clinker production data[27] to recalculate CO_2 emissions from cement production (which accounts for roughly 7%–9% of China's total annual emissions in recent years[4]). This direct method avoids use of default clinker-to-cement ratios (for example, 75% and 95% in the IPCC guidelines[7,11]), and results in emissions estimates that are 32%–45% lower than previous estimates (0.17 GtC in 2012 compared to 0.30 GtC reported by the Carbon Dioxide Information Analysis Center (CDIAC) and 0.24 GtC by EDGAR; Extended Data Fig. 4). The clinker-to-cement ratio calculated by clinker production is 58%, or ~23% lower than the latest IPCC default values. The new, lower estimated cement emissions are consistent with factory-level investigations[28] and several other recent studies[29,30].

Together, our revised estimate of fossil fuel and cement emissions in 2013 is 2.49 GtC ($2\sigma = \pm7.3\%$); the new estimate is 12% less than the latest inventories China reported to the UNFCCC (1.63 GtC in 2005, $2\sigma = \pm8$) and 14% less than the estimate by EDGAR version 4.2 (2.84 GtC in 2013, $2\sigma = \pm10\%$) (Fig. 4). By t-test, our revised estimates of fossil fuel and cement emissions during 2000–2013 are generally lower (at the 90% level) than estimates by EDGAR ($P = 0.016$) and CDIAC ($P = 0.077$).

Our new estimate represents a substantial revision of annual global carbon emissions, reducing the global emissions in 2013 by 0.35 GtC, an amount larger than the reported increase in global emissions between 2012 and 2013 (ref. 31). A systematic reduction of fossil fuel and cement emissions of 0.35 GtC translates into a 15% smaller land sink when this term is calculated as a residual between anthropogenic carbon emissions, atmosphere carbon growth and the ocean carbon sink[31], and is two times the estimated carbon sink in China's forests (0.18 GtC y^{-1})[9]. Thus it implies a considerable revision of the global carbon budget[31]. Over the full period 2000 to 2013, the downward

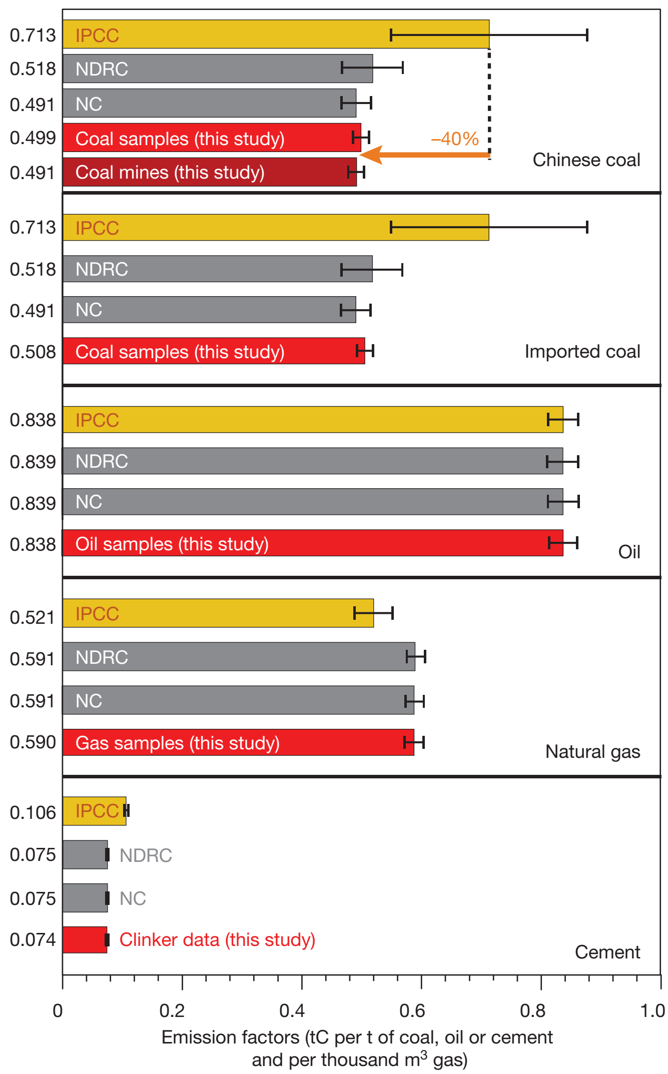

Figure 3 | Comparison of emission factors in 2012. IPCC: default value from IPCC guidelines for national emission inventories (1996, 2006)[7,11]. NDRC: value reported by the NDRC (ref. 25). NC: China's National Communication, which reported to the UNFCCC (2012 for value in 2005)[8]. All error bars are 2σ errors.

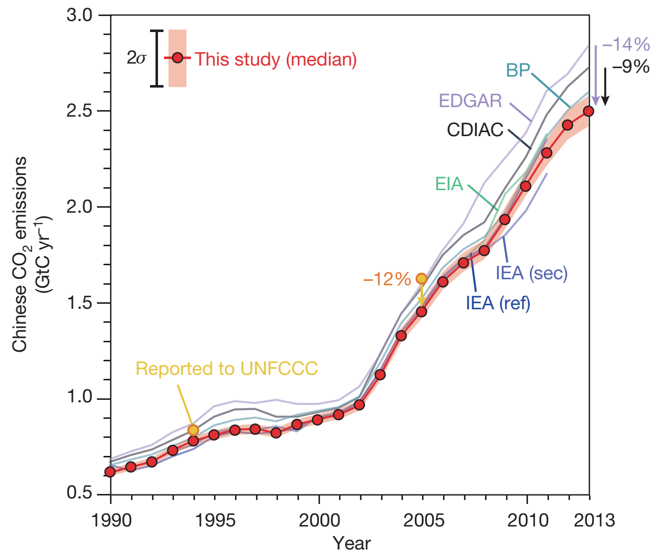

Figure 4 | Estimates of Chinese CO_2 emissions 1990–2013. Total carbon emissions from combustion of fossil fuels and manufacture of cement in China from different sources (International Energy Agency (IEA; sec, sectoral; ref, reference)[3], Energy Information Administration (EIA; http://www.eia.gov/) and BP[18] estimates do not include the emissions from cement production). The yellow dots are the numbers China reported to the UNFCCC in the years 1994 and 2005 (ref. 8). The red-shaded area indicates the 95% uncertainty range of carbon emissions calculated by this study, assuming the emission factors during the period 1990–2013 are the same as those determined for 2012 in this study.

revision of cumulative emissions in China by 2.9 GtC (13%) is larger than the cumulative forest sink in 1990–2007 (2.66 GtC)[9] or China's land carbon sink in 2000–2009 (2.6 GtC)[10]. Depending upon how the remaining quota of cumulative future carbon emissions is shared among nations, a correction of China's current annual emissions by 10% suggests a 25% (inertia basis) or 70% (blended basis) difference in the cumulative future emissions that can be emitted by China under a 2 °C warming target[32]. Evaluating progress towards national commitments to reduce CO_2 emissions depends upon improving the accuracy of annual emissions estimates and reducing related uncertainties[33].

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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Author Contributions Z.L. and D.G. designed the paper. Z.L. conceived the research. Z.L. provided the data from 4,243 coal mines. W.W. and J.B. provided the measurement data from 602 coal samples. S.J.D., J.B., Q.Z., R.J.A. and T.A.B. provided the reference data. Z.L., D.G., S.J.D., P.C., S.P., J.L., H.Z., C.H., Y.L. and Q.Z. performed the analysis. S.J.D., S.P., Z.L., H.Z. and K.F. drew the figures. All authors contributed to writing the paper.

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METHODS

Calculation of carbon emissions from fossil fuel combustion and cement production. Carbon emissions are calculated by using activity data, which are expressed as the amount of fossil fuels in physical units used during a production processes (activity $data_{clinker}$ is the amount of clinker produced) multiplied by the respective emission factor (EF):

$$\text{Emission} = \text{activity data} \times \text{EF} \quad (1)$$

Emissions from cement manufacturing are estimated as:

$$\text{Emission}_{cement} = \text{activity data}_{clinker} \times \text{EF}_{clinker} \quad (2)$$

If data on sectorial and fuel-specific activity data and EF are available, total emission can be calculated by:

$$\text{Emission} = \sum\sum\sum \left(\text{activity data}_{i,j,k} \times \text{EF}_{i,j,k}\right) \quad (3)$$

where i is an index for fuel types, j for sectors, and k for technology type. Activity data are measured in physical units (tonnes of fuel expressed as t fuel).

EF can be further separated into net heating value of each fuel v, the energy obtained per unit of fuel (TJ per t fuel), carbon content c (tC TJ^{-1} fuel) and oxidization rate o (in %, the fraction of fuel oxidized during combustion and emitted to the atmosphere). The values of v, c and o are specific for fuel type, sector and technology:

$$\text{Emission} = \sum\sum\sum \left(\text{activity data}_{i,j,k} \times v_{i,j,k} \times c_{i,j,k} \times o_{i,j,k}\right) \quad (4)$$

For the coal extracted in China (for example, for the 4,243 coal mines analysed in this study), net heating v and carbon content c values are not directly available, and a more straightforward emission estimate for coal emissions can be obtained using the mass carbon content (C_{ar} in tC per t fuel) of fuels, defined by $C_{ar} = c \times v$ so that the total emission can be calculated as:

$$\text{Emission} = \sum\sum\sum \left(\text{activity data}_{i,j,k} \times C_{ar_{i,j,k}} \times o_{i,j,k}\right) \quad (5)$$

Apparent energy consumption calculation. The activity data can be directly extracted as the final energy consumption from energy statistics, or estimated based on the mass balance of energy, the so-called apparent energy consumption estimation:

$$\text{Apparent energy consumption} = \text{domestic production} + \text{imports} - \text{exports} \pm \text{change in stocks} - \text{non-energy use of fuels} \quad (6)$$

Calculation of carbon emission from cement production. The carbon emission from cement production is due to the production of clinker, which is the major component of cement. When clinker is produced from raw materials, the calcination process of calcium carbonate ($CaCO_3$) and cement kiln dust (CKD) releases CO_2: $CaCO_3 \rightarrow CaO + CO_2$. The amount of emission can be calculated from the molar masses of CaO (55.68 g $mole^{-1}$) and carbon (12 g $mole^{-1}$) and the proportion of their masses in clinker production. Furthermore, the emission associated with CKD that is not recycled to the kiln is calculated using the CKD correction factor, CF_{cdk}.

Carbon emission from cement production can be calculated the by clinker emission factor ($EF_{clinker}$) and clinker production.

$$\text{Emission}_{cement} = \text{activity data}_{clinker} \times \text{EF}_{clinker} \quad (7)$$

$$\text{EF}_{clinker} = \text{EFCaO} \times (1 + \text{CF}_{cdk}) \quad (8)$$

$$\text{EF CaO}_{clinker} = \text{fraction CaO} \times (12/55.68) = \text{fraction CaO} \times 0.2155 \quad (9)$$

Fraction CaO is the mass proportion of CaO per unit clinker (in %). EF $CaO_{clinker}$ is the mass of total carbon emission released as CaO per unit of clinker (unit: tC per t clinker). CF_{cdk} is the CKD correction factor (in %). $EF_{clinker}$ is the mass of total carbon emission per unit of clinker (tC per t clinker)

Clinker is the major component of cement. However, data on clinker production is less widely reported than that of cement production. Where data about clinker production are not available, the clinker-to-cement ratio $R_{clinker-cement}$ (in %) can be used to estimate the cement emission factor (EF_{cement}) and to further estimate the emission based on cement production.

$$R_{clinker-cement} = \text{activity data}_{clinker} / \text{activity data}_{cement} \quad (10)$$

$$\text{EF}_{cement} = R_{cement-clinker} \times \text{EF}_{clinker} \quad (11)$$

$$\text{Emission}_{cement} = \text{EF}_{cement} \times \text{activity data}_{cement} \quad (12)$$

The IPCC default Fraction CaO (clinker) is 64.6%, and the fraction CaO (cement) is 63.5%; thus, the IPCC default $EF_{clinker}$ is 0.1384 (tC per t clinker). In the IPCC 1996 guidelines, the clinker-to-cement ratio is 95%, which assumes that most cement is Portland cement and that the corresponding default EF_{cement} is 0.1360 (tC per t clinker). In the IPCC 2006 guidelines, the clinker-to-cement ratio is 75% when no direct clinker production data are available, and the corresponding default EF_{cement} is 0.1065 (tC per t clinker). In this study, the clinker-to-cement ratio is calculated using clinker production statistics and cement production statistics. The cement production and clinker production statistics are listed in Supplementary Information.

It should be noted that the non-energy use of fossil fuels and other industrial processes such as ammonia production, lime production and steel production will also produce carbon emissions. To be consistent with the scope of the international data set we are comparing, those emissions are not included in this study. On the basis of a previous study the total emissions of these non-energy fuel use and industry processes was equivalent to 1.2% of China's emissions from fossil combustion in 2008 (ref. 14).

The uncertainty range of China's emission estimates. We conduct analysis to show the uncertainty range of China's emission estimates based on emission factors (EFs) reported in the literature. We collected 12 sets of EF data for fossil fuel combustion from the six following official sources: IPCC (1996, 2006)[7,11], China National Development and Reform Commission (NDRC)[34], UN Statistics (UN)[35], China National Communication on Climate Change (NC)[8], China National Bureau of Statistics (NBS)[22] and Multi-resolution Emission Inventory for China (MEIC; http://www.meicmodel.org). There are three sets of EFs in the NDRC data, corresponding to three tiers of fuel classifications, four sets in NC and two sets in UN. We combined these 12 sets of EFs with two sets of energy statistics derived from national and provincial data[6,36]. This yielded 24 possible inventories for China's carbon emissions of fossil fuel combustion for 1997–2012 (Extended Data Table 1). The underlying data used in the commonly used data sets (IEA, CDIAC, BP, EDGAR) is either listed in this data assembly (NBS and IPCC) or not publically available.

The mean value of 24 possible inventories is 2,523 MtC in 2012, and the standard deviation is 376 MtC (15%); the detailed data are listed in the Extended Data Table 1. The 2σ standard deviation range suggested by 24 possible inventories is 30%, which is larger than the reported range of 10% by current emission data sets such as EDGAR.

A Monte Carlo (Extended Data Fig. 1) approach was adopted to assess the distribution range of the emissions by assuming that all reported EF values have the same probability (values have been randomly selected with equal probabilities and calculated for 100,000 times). The mean value of the 24 members' ensemble is 2.43 GtC in 2012 (95% confidence interval is +20%, −11% and maximum–minimum range of +27%, −15%). The uncertainty is attributed to the activity data (about 40% of total uncertainty) and EF (60%). The variability of EF for coal dominates the total uncertainty (55% for total uncertainty and 90% for the uncertainty by EF), whereas the EF for other fuels are more comparable. Different EF values for coal mainly reflect variation in v and hence C_{ar} ($C_{ar} = v \times c$) values, whereas the variation of c and o are comparatively smaller (less than 10%).

The distribution range of the emissions is listed in Extended Data Fig. 1.

We assumed the equal possibility for various EFs when conducting the Monte Carlo analysis; this will expand the uncertainty range. However, both the standard deviation of 24 possible inventories and the Monte Carlo analysis show a significant uncertainty range, implying the considerable system error of the emission estimates by using reported EFs; thus it is critical to perform emission estimates based on a measurement-based EF.

Apparent consumption calculation. We adopted the 'apparent consumption' approach to recalculate China's energy consumption. The apparent energy consumption is the mass balance of fuels produced domestically for energy production, trade, international fuelling and change in stocks:

$$\text{Apparent energy consumption} = \text{domestic production} + \text{imports} - \text{exports} \pm \text{change in stocks} - \text{non-energy use of fuels} \quad (13)$$

The calculated apparent energy consumption is usually different from the reported energy consumption in China. For example, our recalculated energy consumption is higher (17% for coal, 2% for oil and 3% for gas) than the national reported energy consumption for 2013.

We believe the resulting estimates of energy consumption to be more accurate than both national and provincial energy statistics, because of the following reasons.

First, national energy statistics may be biased[16,37,38] because of underreported fuel use in boilers from small factories and workshops[17,37,38]. In addition, the adjustment of national statistics by the Chinese government has been discussed in the literature[39–41].

Second, provincial energy statistics are also not reliable because of the considerable inconsistencies in provincial aggregated final-consumption energy statistics. When comparing energy consumption with total available energy supply (production plus imports and changes in stocks) in provincial statistics for 2012, coal and oil show differences of 0.25 Gt coal and 81 Mt oil[6,22], respectively. In addition, after removing international trade, the amount of exported and imported coal within all provinces should be equal to each other, whereas, in fact, we found an unexplained mismatch of 0.37 Gt coal in provincial aggregated energy statistics, equal to 21% of total domestically traded coal.

Third, the apparent energy consumption is based on production and trade statistics. Chinese data on fuel production and trade statistics are more reliable and consistent than data on final energy consumption. After many years of policies to reduce or close private coal mines, 97% of the coal production in China (3.40 Gt coal in 2011) is from government-owned companies (including central and local governments) that keep good records of the mass of coal extracted[42,43]. This reliability is supported by the fact that national and provincial statistics on coal production differed by only 10% in 2012 (refs 6, 22), while the same sources reported coal consumption rates that differed by 37% (3.19 Gt for national data versus 4.36 Gt for provincial data). Moreover, coal production and trade data are consistently released earlier than coal consumption data, suggesting that the production data are the original data and therefore less prone to 'adjustment' for political or other proposes. Finally, trade data have also been monitored internationally, so the numbers can be verified by different nations.

Fourth, compared with the final energy consumption approach that involves 20 kinds of primary and secondary energy products, the apparent consumption approach is much simpler: it considers only three primary fuel types (raw coal, crude oil and natural gas) in order to avoid accounting errors due to energy consumed during fuel processing (for example, mass loss in coal washing and coking).

Fifth, the apparent energy consumption approach uses energy production data, which avoids having to deal with uncertain estimations of the mix of different coal types used by each final consumption category. When considering the variation of EFs for different fuel types and sectors, analysis of the sources of uncertainty is more complex. It is difficult to assess specific coal-burning EFs for a myriad of small consumers, and to scale these data up to the national level. Large energy consumers such as power plants continuously mix coal from different sources, which also makes it very difficult to assess national consumption-weighted average EF (weighted by share of different kinds and quality of coal consumed) from a consumption point of view. In contrast, production data can provide the national production-weighted average EF, and thus the national consumption-weighted average EF can be calculated by excluding the coal used for exports, non-energy use and stock changes.

Sixth, the apparent consumption approach allows us to track imported and domestically produced fuels, so that a different EF can be applied.

Between 1997 and 2012, the calculated apparent energy consumption was 10% greater (14% for 2012) than the one reported in national statistics and 4% lower than provincial statistics (Extended Data Fig. 2). The growth rate of apparent energy consumption is consistent with the growth rate of industrial productions (Extended Data Fig. 5).

Sample selection. China's coal resources are mainly concentrated in 100 major coal mine areas from 24 coal mine bases, and there are about 4,000 stable coal mines among these 100 coal mine areas that record coal production. The location of coal sampling is consistent with the distribution of coal mines (Extended Data Fig. 3).

By collecting the coal samples, the following principles are adopted.

First, the sampling spot is based on coal seams under production in one coal mine district, because the properties of coal from within a coal seam are almost the same. It is guaranteed that at least one sample is collected from each coal seam in one coal mine district.

Second, every coal mine area is sampled, so the 602 samples are across 100 mine areas that cover the majority of the nation's coal production.

Third, there are at least three samples for each coal mine with a production over 5 million tonnes.

Fourth, in the same coal mine district, coal mines with high production are selected preferentially.

Fifth, for sampling within a location, if the samples are collected from a coal pile, they should be collected from at least three different coal piles. If the samples are collected from a conveyor belt, they should be collected three times with several hour intervals from each other. All these three-times-collected samples are merged together and considered as one sample data point (in total 602 sample data points) for further analysis. All samples are stored in sealed plastic bags for further analysis.

Sample analysis. For the sample measurements, we measured the air dry moisture, total moisture, net heating value, and the ash, carbon, hydrogen, nitrogen and total sulfur content. Carbon, hydrogen, nitrogen and total sulfur are determined by combustion using an Elementar elemental analyser. Coal samples are weighed into a tin capsule and burned in a tube furnace at 1,350 °C. Carbon dioxide, water, nitrogen dioxide and sulfur oxide are released from the samples and measured by a thermal conductive detector (TCD). Two parallel samples were tested together each time. The analysis is performed based on ISO standards:

Measurement process (ISO 18283:2006: Hard coal and coke—Manual sampling).

Air dry moisture (ISO 11722:2013: Solid mineral fuels. Hard coal. Determination of moisture in the general analysis test sample by drying in nitrogen).

The total moisture (ISO 589:2008: Hard coal. Determination of total moisture).

Carbon, hydrogen and nitrogen contents (ISO 625:1996: Solid mineral fuels. Determination of carbon and hydrogen. Liebig method; ISO 29541:2010: Solid mineral fuels. Determination of total carbon, hydrogen and nitrogen content. Instrumental method).

Ash content and volatile matter (ISO 11722:2013: Solid mineral fuels. Hard coal. Determination of moisture in the general analysis test sample by drying in nitrogen; ISO 1171:1997: Solid mineral fuels. Determination of ash; and ISO 562:2010: Hard coal and coke. Determination of volatile matter).

The net calorific value (ISO 1928:2009: Solid mineral fuels. Determination of gross calorific value by the bomb calorimetric method and calculation of net calorific value).

Total sulfur contents (ISO 334:2013: Solid mineral fuels. Determination of total sulphur. Eschka method).

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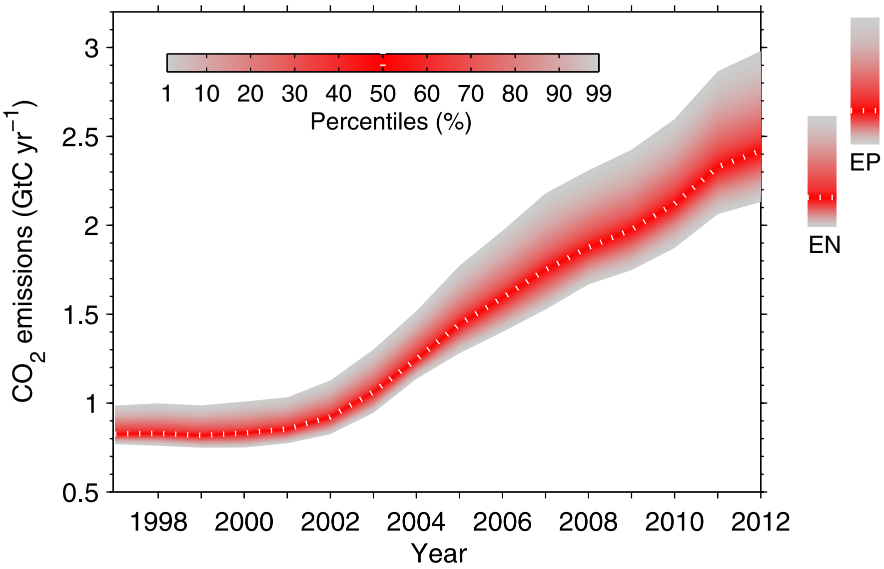
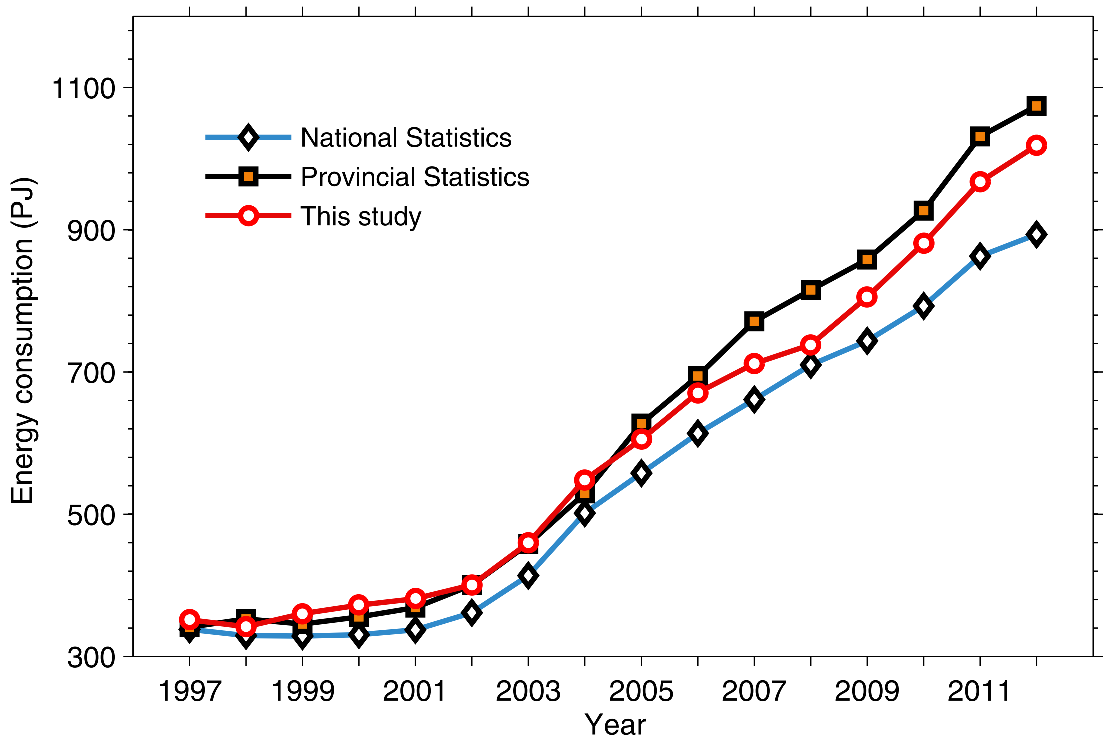
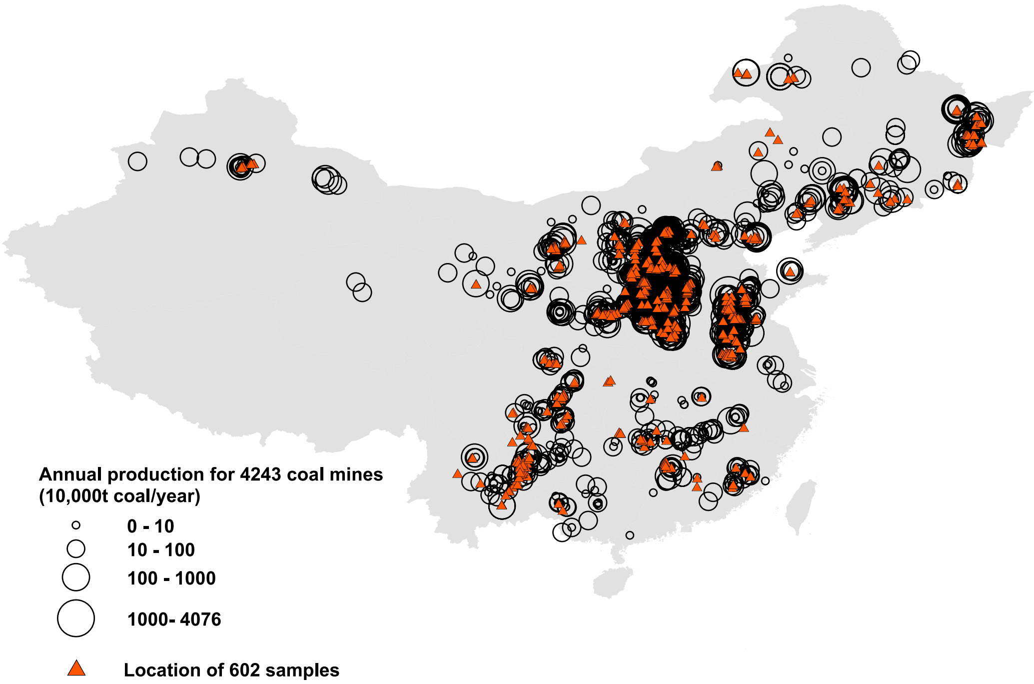


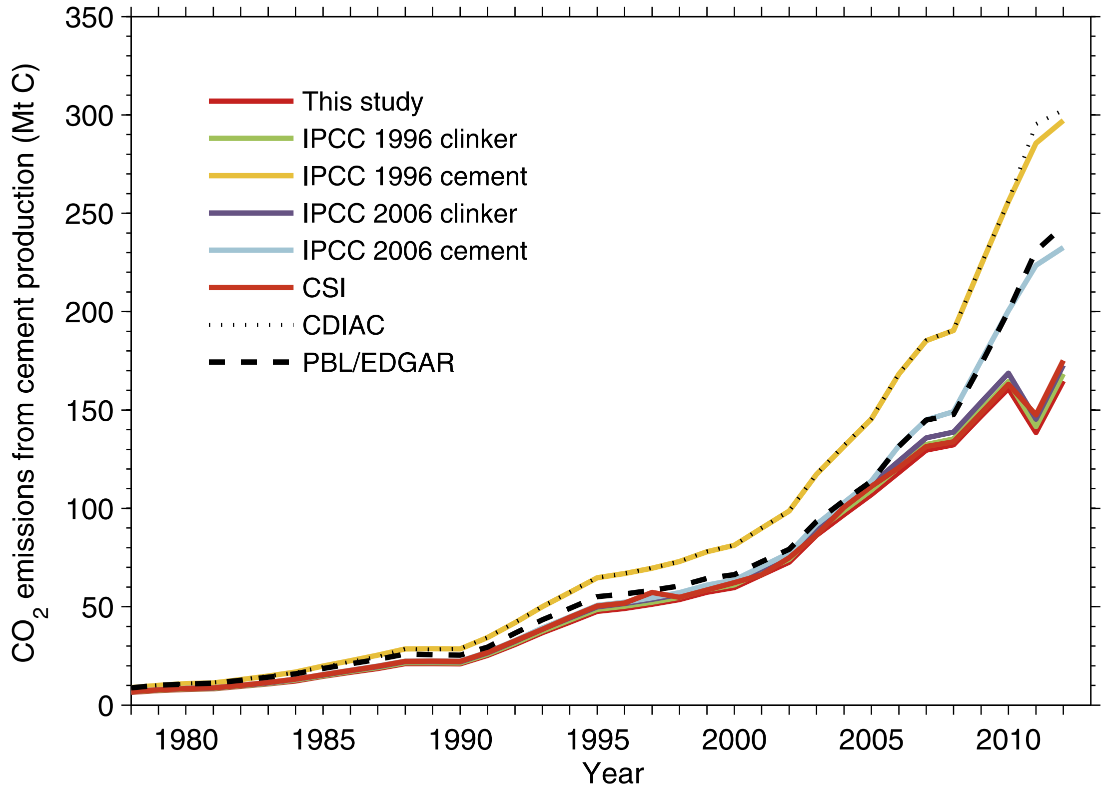
Extended Data Figure 1 | Uncertainty distribution of Chinese CO_2 emissions 1997–2012. Monte Carlo simulations of the Chinese carbon emissions based on a blended activity data set where national and provincial data are assigned equal probabilities ($n = 100{,}000$). Chinese carbon emissions based on national energy activity data (EN) and provincial activity energy data (EP) in 2012 are shown on the right bar.



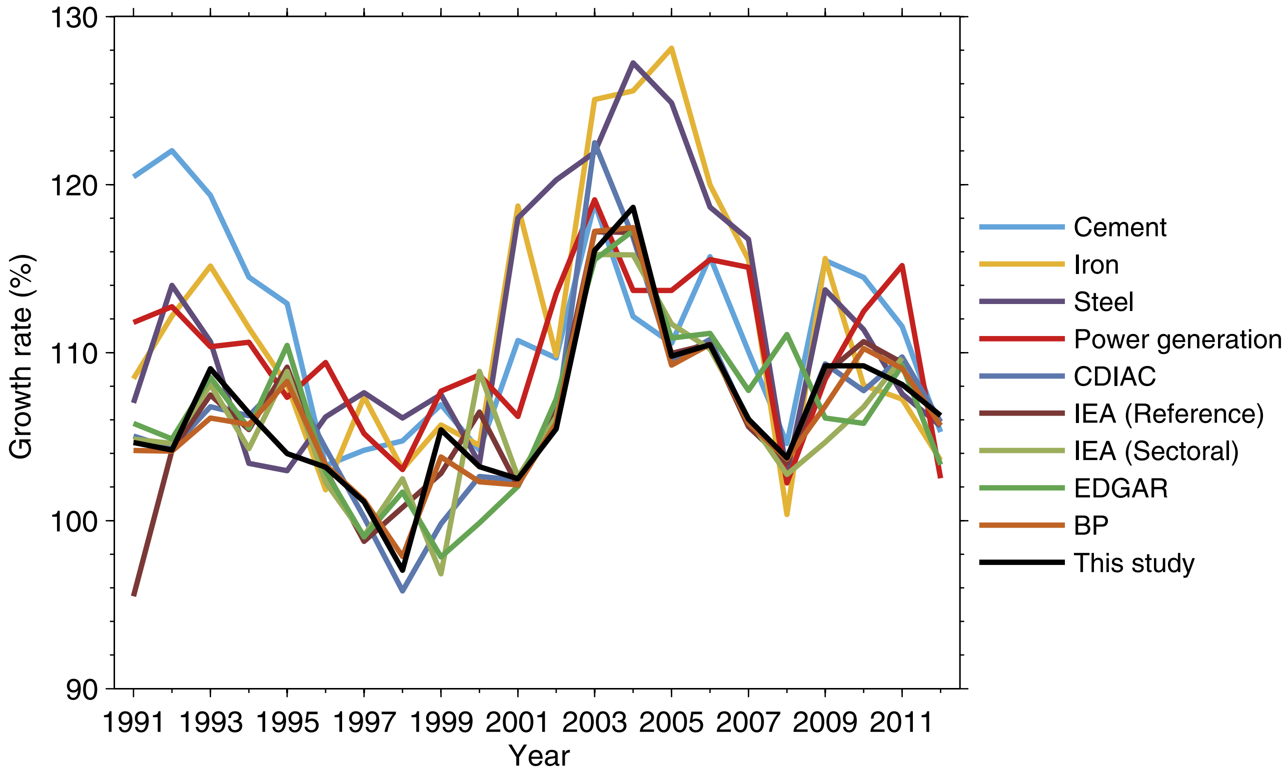
Extended Data Figure 2 | Total fossil fuel energy consumption based upon national statistics, provincial statistics and calculations in this study.



Extended Data Figure 3 | Location of 4,243 coal mines with annual production and 602 coal samples. The coal samples and mines are consistent with spatial distribution.



Extended Data Figure 4 | Emission estimates of China's cement production by different sources.



Extended Data Figure 5 | Growth rate of carbon emissions, based upon BP, EGDAR, IEA and calculations in this study, and industrial products. Industrial products comprise the production of cement, iron, steel and power generation. The emission trends calculated in this study are consistent with the trends of industrial production.

Extended Data Table 1 | Twenty-four emission inventories of fossil fuel combustion based on reported emission factors and fuel inventories in China.

Unit: MtC	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
IPCC EP	1081	1113	1087	1109	1153	1256	1438	1662	1969	2180	2432	2573	2707	2964	3251	3379
IPCC EN	1062	1028	1017	1016	1034	1106	1286	1543	1722	1892	2036	2220	2332	2442	2700	2783
NBS EP	837	862	846	868	902	983	1127	1303	1548	1716	1912	2021	2126	2319	2561	2664
NBS EN	827	805	800	803	819	879	1015	1228	1375	1514	1632	1760	1847	1933	2144	2213
NDRC tier 1 EN	840	817	813	816	832	891	1037	1251	1400	1542	1662	1802	1893	1981	2196	2266
NDRC tier 1 EP	851	877	861	881	918	1000	1148	1330	1580	1753	1958	2070	2181	2392	2626	2737
NDRC tier 2 EP	841	868	849	869	903	984	1128	1305	1550	1718	1918	2030	2139	2346	2573	2685
NDRC tier 2 EN	829	805	800	802	817	874	1016	1225	1370	1506	1622	1762	1850	1934	2143	2212
NDRC tier 3 EP	850	879	858	879	910	995	1137	1319	1555	1723	1924	2037	2137	2340	2564	2675
NDRC tier 3 EN	837	816	806	808	821	880	1019	1236	1370	1505	1620	1763	1843	1926	2133	2201
NC 1994 EN	768	750	746	751	766	822	953	1151	1294	1427	1538	1656	1737	1819	2017	2084
NC 1994 EP	774	798	784	805	838	913	1049	1213	1446	1603	1789	1892	1992	2178	2403	2504
NC 2005 tier 1 EN	819	797	790	791	805	860	999	1206	1348	1481	1594	1734	1821	1903	2107	2174
NC 2005 tier 1 EP	831	858	840	859	892	970	1111	1283	1529	1694	1891	2003	2111	2313	2535	2646
NC 2005 tier 2 EN	816	791	784	783	796	849	985	1189	1330	1459	1570	1711	1796	1876	2075	2141
NC 2005 tier 2 EP	828	856	836	854	885	962	1100	1270	1513	1675	1870	1981	2090	2288	2505	2615
NC 2005 tier 3 EN	817	794	785	787	799	856	991	1199	1331	1462	1573	1713	1791	1872	2072	2138
NC 2005 tier 3 EP	829	859	837	857	887	969	1106	1280	1513	1675	1870	1981	2080	2278	2495	2604
MEIC EN	792	770	765	768	783	838	968	1171	1309	1440	1550	1672	1754	1834	2032	2099
MEIC EP	802	829	810	832	862	938	1074	1241	1475	1633	1817	1923	2024	2204	2437	2537
UN average EN	1103	1063	1051	1048	1064	1134	1319	1575	1737	1895	2031	2258	2372	2490	2740	2818
UN average EP	1126	1160	1134	1152	1200	1305	1487	1725	2042	2257	2518	2663	2804	3108	3353	3483
UN China EN	843	814	808	809	822	876	1014	1215	1342	1464	1567	1747	1836	1929	2124	2186
UN China EP	856	883	867	881	921	1001	1140	1328	1577	1745	1949	2061	2175	2430	2596	2707
Standard deviation	105	109	105	107	113	126	142	155	196	219	260	265	280	339	357	376
Average Value	869	870	857	868	893	964	1110	1310	1509	1665	1827	1960	2060	2212	2432	2523