Open Access

Earth System
Science
Data

Global CO$_2$ emissions from cement production

Robbie M. Andrew

CICERO Center for International Climate Research, Oslo 0349, Norway

Correspondence: Robbie M. Andrew (robbie.andrew@cicero.oslo.no)

Abstract. The global production of cement has grown very rapidly in recent years, and after fossil fuels and land-use change, it is the third-largest source of anthropogenic emissions of carbon dioxide. The required data for estimating emissions from global cement production are poor, and it has been recognised that some global estimates are significantly inflated. Here we assemble a large variety of available datasets and prioritise official data and emission factors, including estimates submitted to the UNFCCC plus new estimates for China and India, to present a new analysis of global process emissions from cement production. We show that global process emissions in 2016 were $1.45 \pm 0.20 \, \mathrm{Gt} \, CO_2$, equivalent to about 4 % of emissions from fossil fuels. Cumulative emissions from 1928 to 2016 were $39.3 \pm 2.4 \, \mathrm{Gt} \, CO_2$, 66 % of which have occurred since 1990. Emissions in 2015 were 30 % lower than those recently reported by the Global Carbon Project. The data associated with this article can be found at https://doi.org/10.5281/zenodo.831455.

1 Introduction

Anthropogenic emissions of carbon dioxide to the atmosphere come from three main sources: (i) oxidation of fossil fuels, (ii) deforestation and other land-use changes, and (iii) carbonate decomposition. Cement – the largest source of emissions from the decomposition of carbonates – is a binding material that has been used since ancient times. But it was following World War II that the production of cement accelerated rapidly worldwide, with current levels of global production equivalent to more than half a tonne per person per year (Fig. 1). Global cement production has increased more than 30-fold since 1950 and almost 4-fold since 1990, with much more rapid growth than global fossil energy production in the last 2 decades. Since 1990 this growth has largely been because of rapid development in China where cement production has grown by a factor of almost 12 such that 73 % of global growth in cement production since 1990 occurred in China (van Oss, 2017).

There are two aspects of cement production that result in emissions of CO$_2$. The first is the chemical reaction involved in the production of the main component of cement, clinker, as carbonates (largely limestone, CaCO$_3$) are decomposed into oxides (largely lime, CaO) and CO$_2$ by the addition of

heat. Stoichiometry directly indicates how much CO$_2$ is released for a given amount of CaO produced. Recent estimates are that these so-called "process" emissions contribute about 5 % of total anthropogenic CO$_2$ emissions excluding land-use change (Boden et al., 2017). The second source of emissions is the combustion of fossil fuels to generate the significant energy required to heat the raw ingredients to well over 1000 °C, and these "energy" emissions, including those from purchased electricity, could add a further 60 % on top of the process emissions (IEA, 2016). Total emissions from the cement industry could therefore contribute as much as 8 % of global CO$_2$ emissions. These process (sometimes called "industry" or "industrial process") and energy emissions are most often reported separately in global emissions inventories (Le Quéré et al., 2016, 2017; IPCC, 2006).

The Global Carbon Project annually publishes estimates of global emissions of CO$_2$ from the use of fossil fuels and cement production, and these estimates are used by the global carbon modelling community as part of the development of the global carbon budget (Le Quéré et al., 2016, 2017). It is therefore important that the emissions estimates are as accurate as possible. This emissions database covers all emissions of CO$_2$ resulting from the oxidation (not only energy use) of fossil fuels, including those that occur in the IPCC sec-
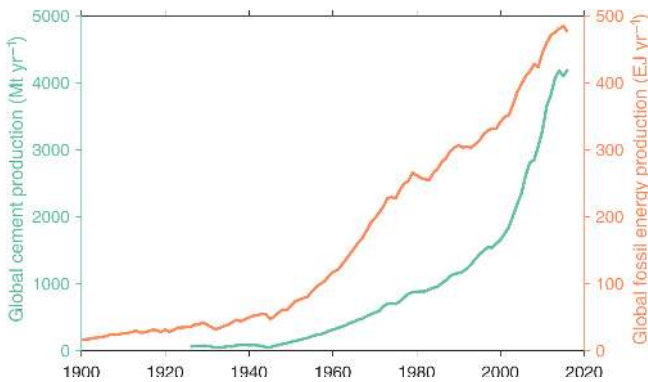
Figure 1. Global cement and fossil energy production to 2016 (USGS, 2014; Mohr et al., 2015).

tor Industrial Processes and Product Use, such that including cement emissions means that the vast majority of CO_2 emissions are covered.

In this work we investigate the process emissions from cement production, develop a new time series for potential use by the Global Carbon Project, and present plans for future continued updates, revisions, and development. The focus on process emissions here is because both direct fossil fuel emissions and electricity emissions are already accounted for in other parts of the global carbon budget.

2   Previous estimates of global cement emissions

Early estimates of emissions from global cement production effectively assumed that almost all cement was of the ordinary Portland cement (OPC) type, which uses a very high proportion of clinker and very small amounts of other ingredients, such as gypsum to control setting time. For at least the first half of the 20th century this assumption was quite reasonable, with the vast majority of cement being produced in industrialised countries, which followed carefully developed and tested standards regarding strength and other important qualities.

In 1970, Baxter and Walton presented estimates of global CO_2 emissions from fossil fuels and cement production for 1860–1969 in which the "mean calcium oxide content of cements was taken to be 60 % ... and the carbon content of limestone assumed to be 12 % with 100 % kilning efficiency. Thus the ... manufacture of 1 t of cement yields ... 4.71 × 10^5 g of carbon dioxide ..." (i.e. 0.471 t CO_2 (t cement)$^{-1}$ (Baxter and Walton, 1970). Assuming that their estimate of global cement production in 1969 was the same as that reported by the USGS (USGS, DS140, etc.), their estimate of emissions from cement production in 1969 would have been 256 Mt CO_2.

In a landmark paper of 1973, Charles Keeling presented a systematic analysis of emissions from fossil fuel combustion for 1860–1969 and cement production for 1949–

1969 (Keeling, 1973). Using an average CaO content of cement of 64.1 %, Keeling's emission factor was 0.50 t of CO_2 (t cement)$^{-1}$, giving an estimate for emissions from cement production in 1969 of 272 Mt. While both Keeling (1973) and Baxter and Walton (1970) cited Lea and Desch (1940) as the source for their estimates of the CaO content of cement, they nevertheless used different fractions. Importantly, these fractions were assumed to be time invariant.

Marland and Rotty (1984) presented further estimates for 1950–1982 using a global average CaO content of cement of 63.8 % taken directly from US data for 1975. From this they derived a time-invariant emission factor of 0.50 t CO_2 (t cement)$^{-1}$.

The estimates made by Marland and Rotty (1984) combined with the earlier estimates of Keeling (1973) were included in the archive of the Carbon Dioxide Information Analysis Center (CDIAC) in 1984 (Rotty and Marland, 1984). Later, CDIAC modified the cement emission factor very slightly based on a study by Griffin (1987), who (in turn based on Orchard, 1973) said that "the range of lime (CaO) content in cement is 60–67 %" and based on discussion with experts recommended the use of 63.5 %, which was calculated as the midpoint of the range (Boden et al., 1995). This time-invariant, global emission factor of about 0.50 was still in use in CDIAC's 2016 data release.

CDIAC's method was directly adopted by the Intergovernmental Panel on Climate Change (IPCC) in their 1996 guidelines (Haukås et al., 1997) for cases in which clinker production data were not available. The IPCC subsequently revised its methods for cases in which clinker production are not available in the 2006 guidelines (p. 2.8):

"(I)n the absence of data on carbonate inputs or national clinker production data, cement production data may be used to estimate clinker production by taking into account the amounts and types of cement produced and their clinker contents and including a correction for clinker imports and exports. Accounting for imports and exports of clinker is an important factor in the estimation of emissions from this source."

In addition, the IPCC guidelines now recommend the use of a default clinker ratio of 0.75 when it is known that significant amounts of blended cements are produced.

The Emissions Database for Global Atmospheric Research (EDGAR) presents estimates of CO_2 and other climate-important gases by country. For cement they initially used the emission factor from Marland and Rotty (1984) of 0.50 t CO_2 (t cement)$^{-1}$ (Olivier et al., 1999). With the release of version 4.1 of the database in 2010, they modified their emission factor to account for changing rates of blending (i.e. lower clinker ratios) in cement production in response to work by the World Business Council for Sustainable Development (WBCSD), who released sample-based estimates of the clinker ratio in a range of countries (Anonymous, 2010). In version 4.3.2, EDGAR used official estimates from Annex I parties to the UNFCCC, specific clinker

production data for China, and the WBCSD database for all remaining countries (Olivier et al., 2016; Janssens-Maenhout et al., 2017). Since 2003, countries that are listed in Annex 1 of the UN Framework Convention on Climate Change (UN-FCCC) have been required to submit annual inventories of greenhouse gas emissions in considerable detail, including estimates of emissions from cement production (UNFCCC, 2017). Other parties to the convention are requested to submit less detailed and less frequent national communications and, more recently, biennial update reports (BURs).

3 Methods

While cement production data are available by country (van Oss, 2017), it is the production of clinker that leads to process CO$_2$ emissions, and the amount of clinker in cement varies widely. With no available source of clinker production data for all countries, other options must be considered. The direct use of cement production data without adjustment for clinker trade or clinker ratios that vary by country and over time leads to poor emissions estimates (see Appendix A) and should therefore be used only as a last resort. The World Business Council for Sustainable Development (WBCSD), through its Getting the Numbers Right initiative, has collected cement data, including clinker production data, directly from firms, but their survey-based approach leaves many parts of the world poorly sampled (WBCSD, 2014).

The main rationale of our approach, therefore, is to prioritise officially reported emissions, recognising that these generally make use of data and knowledge unavailable elsewhere. Then we use officially reported clinker production data and emission factors, IPCC default emission factors, industry-reported clinker production, and finally survey-based clinker ratios. These are applied to cement production data where no better data are available. Full details are provided in Appendix D and in the associated data files. For the 42 Annex I countries that report their greenhouse gas inventories annually to the UNFCCC, we extract official estimates of cement production emissions from 1990 onwards. Some eastern European countries submit data for years before 1990: Poland and Bulgaria from 1988, Hungary from 1986, and Slovenia from 1987. These are all based on clinker production data and largely use Tier II methods. This dataset covers about 10 % of current global cement production and is available as consistently structured spreadsheet files for each year. In addition, clinker production data were available for the US from 1925 (Hendrik van Oss, USGS, personal communication 2015).

Some non-Annex I parties have begun to include time series of cement emissions in their national communications, national inventory reports, and biennial update reports to the UNFCCC, and these estimates have been used directly. At the time of writing, the following countries reported useable time-series data: Armenia, Azerbaijan, Brazil, Chile, In-

donesia, Jamaica, Mexico, Moldova, Namibia, South Africa, and Uzbekistan. In addition, Mauritania reports that all of its clinker is imported.

For China, which currently produces almost 60 % of global cement, clinker production data are available from 1990. China's emission factor is reported by NDRC (2014) as 0.5383 t CO$_2$ (t clinker)$^{-1}$, and this is used both in the second national communication (NDRC, 2012) and the first biennial update report (NDRC, 2016). Some studies have estimated other emission factors based on factory-level sampling (Liu et al., 2015; Shen et al., 2014), but here we use the officially sanctioned factor until or unless that is changed.

India, the world's second-largest cement producer with about 7 % of global production in recent years, does not officially report clinker production statistics. Data from the Cement Manufacturers' Association (CMA) are useful only until the 2009–2010 financial year when two large producers discontinued membership in the organisation (CMA, 2010). Clinker production data are also reported by business consultancies in their annual overviews of the industry in India. Data on the types of cement produced, combined with their likely clinker contents, can also be used to support this evidence base.

While Jamaica reported cement emissions for 2006–2012, the data source was clearly identified and additional clinker production data have been obtained to cover 1995–2015. Meanwhile, clinker production data for the Republic of Korea were readily available from its cement association for 1991–2015. Emissions estimates from these data matched those reported in official communications to the UNFCCC during overlapping periods.

Finally, for all remaining countries we have used survey-based clinker-ratio data from the WBCSD's Getting the Numbers Right initiative (WBCSD, 2014) combined with historical cement production data from the USGS. In many cases these clinker ratios are presented only for groups of countries but indicate the best available information about clinker ratios in those countries.

Most of these methods provide estimates only back to 1990 at best, and we therefore extrapolate for earlier years using cement production data combined with assumptions about how clinker ratios have changed over time. We make the basic assumption that most countries began their cement industries by producing ordinary Portland cement, a strong and very common cement type with a clinker ratio of 0.95, and over time introduced other types of cements with lower clinker ratios. This assumption reflects available observations. Specifically, the clinker ratio was set to 0.95 in 1970 with the IPCC default emission factor and linearly interpolated to the implied ratio and emission factor in the earliest year for which data are available for each country. For large cement producers covering more than 80 % of global production, USGS provides an estimate of cement production for 2016 (USGS, 2017), and this is used to estimate 2016 emissions for those countries. For other countries, emissions
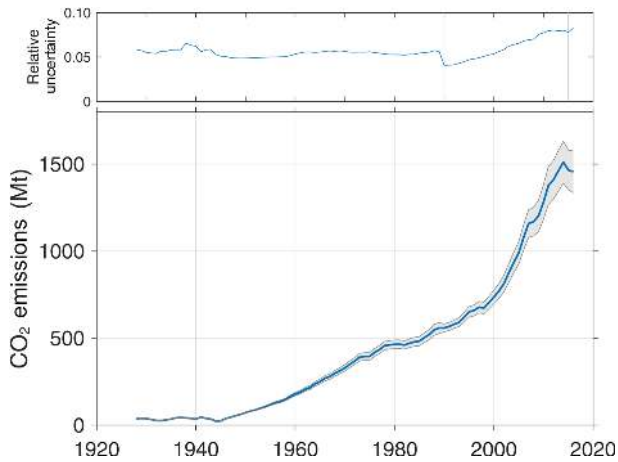
Figure 2. Global process emissions from cement production, with 95 % confidence interval. A step change in uncertainty occurs in 1990, reflecting a significant change in data availability.

Figure 3. Process emissions from Chinese cement production, 1980–2016. 1NC refers to China's first national communication, 2NC the second, and BUR1 the first biennial update report. Also shown are estimates from CDIAC (Boden et al., 2017), Liu et al. (2015), and EDGAR v4.3.2 FT2015.

Figure 4. Comparing new cement emissions estimates (dashed lines) for the top four cement producers after China with those from CDIAC (solid lines) and official estimates (crosses, India and Vietnam) as reported to the UNFCCC (see text). The new estimates for the USA and Turkey come directly from national official estimates. Estimates from EDGAR v4.3.2_FT2015 are shown for India and Vietnam with round markers.

are assumed to be the same as in 2015. While this extrapolation is clearly not ideal, not extrapolating would result in very large discontinuities and frustrate any attempt at trend analysis, particularly any assessment of cumulative emissions. Extrapolating necessarily affects derived growth rates, but these growth rates are dominated by the changes in cement production much more than the extrapolation method.

It is clear from this that data quality is significantly higher from 1990 onwards, and estimates before then will have higher uncertainty. However, emissions prior to 1990 are also less important in the global policy debate, and because only about 30 % of historical cement production occurred before 1990, emissions from that period are also of lower importance for global carbon modelling and budget calculations. In addition, the rate of change of technology was much slower before 1990, with most adjustments to, for example, the clinker content of cement occurring in more recent times so that estimates for earlier years are less sensitive to assumptions. We estimate uncertainty in global cement emissions using a Monte Carlo approach, as described in Appendix C.

4 Results

Process emissions from cement production reached a peak in 2014 of 1.51 ± 0.12 Gt CO_2, subsequently declining slightly to 1.46 ± 0.19 Gt CO_2 in 2016 (Fig. 2). In comparison, CDIAC's estimate for 2014 is 2.08 Gt CO_2 (Boden et al., 2017). The most recent estimate currently available from EDGAR is for 2015 at 1.44 Gt CO_2 (Olivier et al., 2016), which is in very good agreement with our estimate for the same year of 1.47 ± 0.11 Gt CO_2. Cumulative emissions over 1928–2016 were 39.3 ± 2.4 Gt CO_2. The global average clinker ratio has declined from approximately 0.83 in 1990 to 0.66 in 2016 (Fig. E1), which is consistent with an estimate of 0.65 made by the IEA (IEA, 2017).
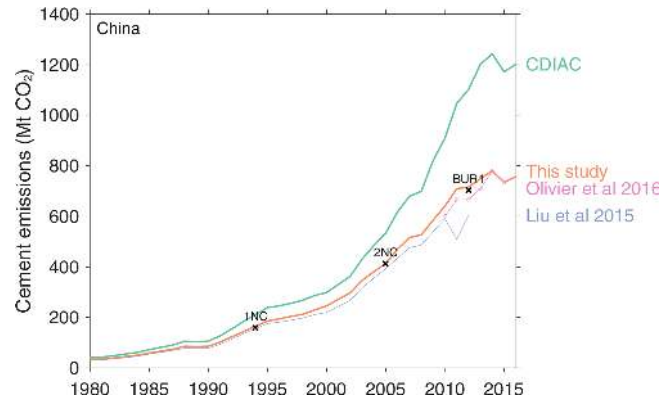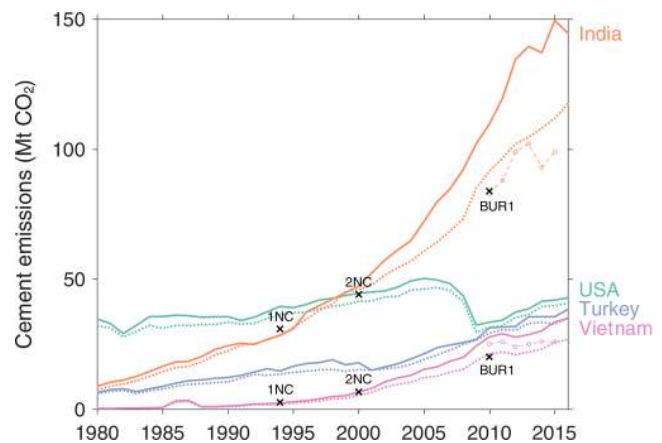
For China, emissions reached just under 800 Mt CO_2 in 2014 (Fig. 3). The emissions estimated here show high agreement with the few official estimates reported, a direct consequence of our use of official data and emission factors. While China produced 57 % of the world's cement in 2016, its emissions were 52 % of the total, a consequence of its clinker ratio being less than 0.60 in recent years, which is below the world average. The results for a number of other countries are presented in the appendices.

Indian emissions are quite uncertain, but the methods used here produce results reasonably close to the few officially reported estimates (Fig. 4). In 2010 there is some divergence from the estimate in India's first biennial update report. In

that year the data provided by the Indian Cement Manufacturers' Association are known to be incomplete, while other data sources indicate substantially higher clinker production in that year; this discrepancy is yet to be resolved (see Appendix D).

Aggregate uncertainty is relatively low through most of the historical period (Fig. 2, top panel), partly as a direct consequence of the choice of the Monte Carlo method with symmetric distributions and no correlation: errors tend to cancel. In 1990, with the beginning of most Annex I countries' detailed reporting to the UNFCCC, global uncertainty declines slightly but then gradually increases as more cement production occurs in developing countries where uncertainty is higher.

5 Data availability

All data used in producing this dataset and the resulting dataset itself are available on Zenodo at the following DOI: https://doi.org/10.5281/zenodo.831455.

The exception is the Getting the Numbers Right dataset from WBCSD, which is available from their website at http://www.wbcsdcement.org/GNR-2014/index.html.

6 Conclusions

Estimating global process emissions from cement production is fraught with problems of data availability and has always required strong assumptions. Over the last 3 decades, countries around the world have increasingly been producing blended cements with lower clinker ratios, and the use of cement production data with constant emission factors has become untenable.

The new global cement emissions database presented here increases the reliance on official and reliable data sources and reduces the reliance on assumptions compared with previous efforts. It is intended that the database will be used in the global carbon budget and updated annually with both data updates and methodological improvements. As more countries estimate their emissions and report them to the UNFCCC in detail, more data will replace assumptions in producing this dataset. Work is still required in improving estimates of cement emissions from both China and India, in particular, as these are the world's two largest cement producers and official time-series estimates are lacking.

Appendix A: Reasons for different estimates

Released annually, CDIAC's emissions estimates are widely reported, including in the IPCC Fifth Assessment Report (Ciais et al., 2013). However, recently there have been some questions raised about the accuracy of these cement emissions estimates, particularly for China (e.g. Lei, 2012; Ke et al., 2013; Liu et al., 2015). According to Ke et al. (2013), CDIAC's estimates of cement emissions for China were 36 % higher than those obtained from an IPCC Tier II method for 2007, amounting to an "error" of 181 Mt CO_2, noting that "CDIAC's relatively higher emission factor is equivalent to the assumption of a high clinker-to-cement ratio" (p. 175).

A1   Clinker ratios

The most obvious reason that CDIAC's estimates are higher than those produced elsewhere is that the formula they have used obscures an assumption about the ratio of clinker to cement in production.

CDIAC's method for estimating process emissions from cement production by country is taken from a report by Griffin (1987) and requires that cement production data in tonnes are multiplied by a fixed factor 0.136 to obtain tonnes of carbon emitted as CO_2, i.e. 1 t of cement produced $0.136 \times 3.667 = 0.50$ t of CO_2 (Boden et al., 1995).

According to Griffin (1987), the emissions factor for the production of cement, E_{cem}, from the calcination of limestone is given as

$$E_{cem} = f_{cem}^{CaO} \frac{M_r^{CO_2}}{M_r^{CaO}},$$

where f_{cem}^{CaO} is the fraction of CaO in cement, $M_r^{CO_2}$ is the molecular weight of CO_2 (44.01), and M_r^{CaO} is the molecular weight of CaO (56.08). Based on discussion with experts, Griffin (1987) recommended $f_{cem}^{CaO} = 0.635$, calculated as the midpoint of the range 0.60–0.67 given by Orchard (1973).

According to the IPCC's more recent 2006 guidelines (Hanle et al., 2006), when using cement production data adjusted for clinker trade, the formula should read

$$E_{cem} = f_{cem}^{clink} f_{clink}^{CaO} \frac{M_r^{CO_2}}{M_r^{CaO}},$$

where f_{cem}^{clink} is the clinker ratio, and f_{clink}^{CaO} is the fraction of CaO in clinker. In the earlier 1996 IPCC guidelines, the information sourced from CDIAC stated that the average CaO content of cement is 0.635, while the CaO content of clinker is 0.646, yielding an implicit average clinker ratio of cement of 0.98.

This high implicit clinker ratio appears to be based on the assumption that the majority of cement produced in the world is (was) ordinary Portland cement: "Other speciality cements are lower in lime, but are typically used in small quantities.
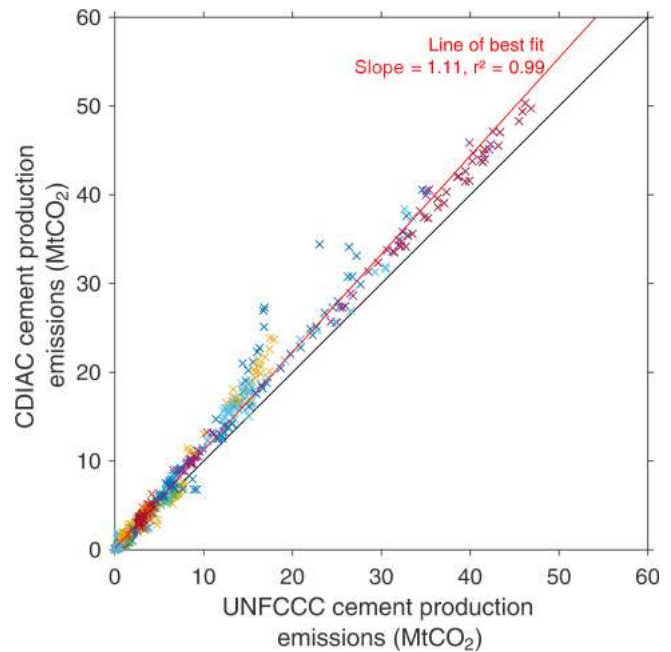

Figure A1. Comparison of CO_2 emissions in 43 countries as estimated by CDIAC (Boden et al., 2017) and those officially reported to the UNFCCC, 1990–2015 (UNFCCC, 2017).

... The differences between the lime content and production of clinker and cement, *in most countries*, are not significant enough to affect the emission estimates" (Houghton et al., 1996, p. 2.5; emphasis in original). Indeed, Orchard (1973) made his statement about lime content in reference to Portland cements, which are the type that is composed of at least 95 % clinker, rather than cement in general.

In the USA, the average clinker ratio was most likely about 0.95 for much of the 20th century, possibly dropping to about 0.90 or slightly lower after about 1970 (Hendrik van Oss, personal communication, 7 May 2015). However, the International Energy Agency (IEA) recently estimated the global average clinker ratio to be 0.65 (IEA, 2017), and the dataset presented in this work agrees with that assessment. In China where almost 60 % of cement is produced, the clinker ratio is currently below 0.60.

WBCSD demonstrates that the clinker ratio has been declining in every region, and based on the data they have available, the world average for 2012 was about 0.75. Furthermore, between 2000 and 2006 the clinker ratio decreased more quickly in developing countries than developed countries. WBCSD puts the primary reason for a lack of decline in developed countries as the acceptance of common practice and fixed product standards, which act as a barrier to reduction in clinker content. This is in contrast to India and China particularly where fly ash from coal-fired power stations and slag from the iron and steel industry are widely used as clinker substitutes (WBCSD, 2009). Interestingly, it may simply be more common practice in developed countries
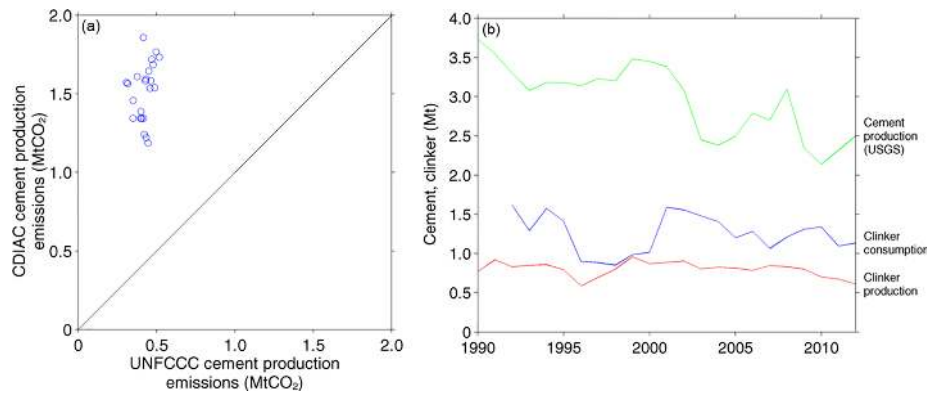
Figure A2. The Netherlands. **(a)** CDIAC vs. UNFCCC. **(b)** Clinker, cement. Note that "clinker consumption" is production plus imports less exports, but excludes stock changes. Sources: UNSD, 2015; UNFCCC, 2014; van Oss, 1994–2012; Boden et al., 2013.

for the construction industry to blend in other ingredients before use (AT Kearney, 2014).

A2 Use of cement production data

The best available data on CO_2 emissions from cement production at a national level come from official submissions to the UNFCCC, with about 40 countries submitting annually (UNFCCC, 2017). Figure A1 compares CO_2 emissions from CDIAC with those from UNFCCC specifically for the process of calcination. Over the 26-year period covered by the UNFCCC submissions (1990–2015), CDIAC's estimates are on average 11 % higher than those estimated by these countries. All countries reporting to the UNFCCC use clinker production data to estimate CO_2 emissions.

CDIAC's estimates are produced using cement production data obtained from the USGS. However, according to the IPCC guidelines (Hanle et al., 2006, p. 2.8),

"(C)alculating CO_2 emissions directly from cement production (i.e. using a fixed cement-based emission factor) is not consistent with good practice. Instead, in the absence of data on carbonate inputs or national clinker production data, cement production data may be used to estimate clinker production by taking into account the amounts and types of cement produced and their clinker contents and including a correction for clinker imports and exports. Accounting for imports and exports of clinker is an important factor in the estimation of emissions from this source."

There is clearly some noise around the line of best fit comparing CDIAC's estimates to emissions reported to the UNFCCC, as shown in Fig. A1, such that simply adjusting estimates down by 11 % (implying an average clinker ratio of about 0.87 for these countries) would still leave considerable differences from official estimates for some countries. These deviations could be explained as the effects of varying clinker ratios and the international trade of clinker. The more clinker is imported for cement production (or exported), the poorer

cement production data become for the purpose of estimating cement emissions.

The Netherlands provides a clear example of how poor the use of cement production data and a global average clinker ratio can be. CDIAC's emissions estimates are at least double those reported to the UNFCCC and as much as 4 times as high (Fig. A2a). The reason for this is significant net imports of clinker and a particularly low clinker ratio (Fig. A2b). The low clinker ratio is because most of the country's production is of cement type CEMIII, which is specifically suitable for use in marine conditions (CEMBUREAU, 2013), and this type of cement uses a much lower clinker ratio (European standard 197-1).

A3 System boundaries

As has been identified by others, one of the reasons for divergences between estimates of cement emissions is that different system boundaries have been used (e.g. Shen et al., 2014; Ke et al., 2013). Studies vary on whether they include process emissions from clinker production, other process emissions, direct fuel combustion emissions, and emissions from the generation of purchased electricity. The IPCC guidelines clearly delineate types of emissions, and process emissions from electricity generation or direct fuel combustion by clinker-producing firms are allocated to the energy sector (Eggleston et al., 2006). Sometimes lime is produced and mixed with clinker, and emissions from this process are also allocated to the IPPU sector but listed separately from cement emissions.

It is not widely understood that CDIAC's emissions estimates do not follow the IPCC delineations, and instead CDIAC estimates emissions result from all oxidation of fossil fuels plus those from cement production (Boden et al., 1995; Marland and Rotty, 1984; Andres et al., 2012). Therefore, CDIAC's estimates of emissions from coal oxidation include the non-energy use of coal, such as when used for anodes in aluminium production, in contrast to the IPCC

methodology. CDIAC's system boundary is therefore much broader than generally understood, including as it does not only all energy emissions but also most industrial process emissions.

Appendix B: Cement production data

In this work, historical cement production data in tonnes are sourced from CDIAC's cement emissions data. Because CDIAC uses a constant emission factor based on cement production, the reverse calculation of cement production data is straightforward. Those production data came originally from USGS (formerly Bureau of Mines; Marland and Rotty, 1984). This is significantly less time-consuming than replicating CDIAC's work of assembling USGS's various datasets.

Appendix C: Uncertainty analysis

Our uncertainty analysis leans heavily on the officially estimated uncertainty of cement emissions provided in submissions to the UNFCCC, whether in national inventory reports, national communications, or biennial update reports. These uncertainties, which follow the methods outlined in the IPCC's guidelines (Eggleston et al., 2006), represent 2 SD of a normal distribution (95 %). For countries without official estimates of uncertainty, estimates have been made based on the approaches used and other information. The greatest uncertainty is when only cement production data and average clinker ratios have been used, and for these cases the uncertainty (2 SD) has been set at 25 %. See the accompanying uncertainty dataset for details.

We have also allowed uncertainty to vary by time, with much higher uncertainties outside of the time covered by official estimates. For example, Annex I countries report emissions for 1990–2015, while outside of that period clinker ratios and cement production data have been used with higher uncertainty.

The uncertainty estimates by country and by time are used in a Monte Carlo analysis with 10 000 runs to give estimates of uncertainty for global cement emissions. This method effectively uses the combined uncertainty of all underlying factors, such as method, clinker ratios, emission factors, cement kiln dust factors, and so on.

Uncertainties are assumed to be uncorrelated between countries and across time. The latter assumption means that the uncertainty of any derived growth rates would be overestimated.

The results of the uncertainty analysis at the global level are shown in the main text in Fig. 2.

Appendix D: Country-specific analyses

D1   Annex I parties to the UNFCCC

The following countries report annual emissions inventories to the UNFCCC using the common reporting format (CRF), and these were downloaded on 7 June 2017. UNFCCC parties sometimes submit revisions through the year, and the specific date of each country's submission as used in this study is shown here.

Australia: 27 May 2017, Austria: 11 April 2017, Belgium: 11 April 2017, Bulgaria: 11 April 2017, Belarus: 14 April 2017, Canada: 3 April 2017, Switzerland: 22 March 2017, Cyprus: 8 May 2017, Czech Republic: 13 April 2017, Germany: 11 January 2017, Denmark: 25 May 2017, Spain: 12 April 2017, Estonia: 12 April 2017, Finland: 11 April 2017, France: 13 April 2017, UK: 13 April 2017, Greece: 10 April 2017, Croatia: 22 May 2017, Hungary: 8 May 2017, Ireland: 12 April 2017, Iceland: 13 April 2017, Italy: 11 April 2017, Japan: 12 April 2017, Kazakhstan: 14 April 2017, Liechtenstein: 23 March 2017, Lithuania: 13 April 2017, Luxembourg: 6 April 2017, Latvia: 13 April 2017, Monaco: 20 April 2017, Malta: 8 May 2017, the Netherlands: 12 April 2017, Norway: 6 April 2017, New Zealand: 25 May 2017, Poland: 8 May 2017, Portugal: 5 May 2017, Romania: 13 March 2017, Russia: 14 April 2017, Slovakia: 7 April 2017, Slovenia: 11 April 2017, Sweden: 28 March 2017, Turkey: 13 April 2017, Ukraine: 24 May 2017, United States of America: 14 April 2017.

These inventories explicitly state process emissions from cement production from 1990 onwards (IPCC sector 2A1). The 2017 submissions include emissions data up to 2015. Monaco's emissions have been combined with those of France, following CDIAC.

The following figures compare cement emissions for Annex I parties as reported by CDIAC (Boden et al., 2017) with those reported here.

D1.1   China

As by far the largest producer of cement worldwide, estimating China's emissions from cement production is critical to having a robust global estimate. In 1982 China overtook Japan to become the world's largest producer of cement and in 2016 accounted for about 57 % of global production (Fig. D4; USGS, 2017).

China has released several official estimates of process emissions from cement production in reporting to the UNFCCC. In its first national communication to the UNFCCC, China reported[1] process emissions from cement production of 157.8 $Mt CO_2$ in 1994 from about 300 Mt of clinker (SDPC, 2004). In its second national communication, China
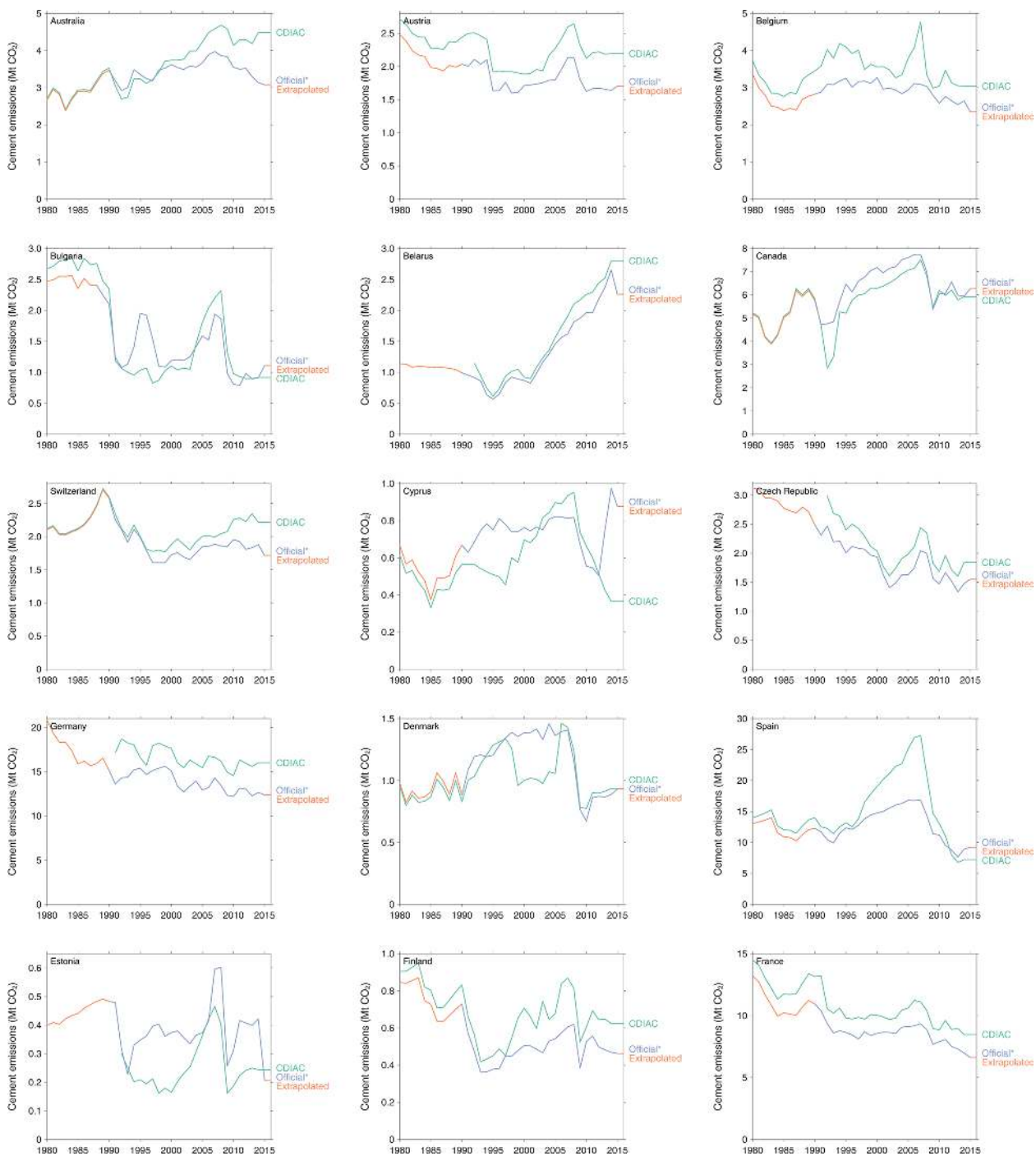
---

[1]P. 32.

Figure D1. Revised cement emissions for Annex I parties to the UNFCCC.

reported[2] 411.7 Mt CO_2 in 2005 from about 765 Mt[3] of

[2]P. 59.

[3]P. 39 of the second national communication actually reports 674, but this is a typographic error. The NDRC's 2005 GHG inventory research book gives 764.71 Mt of clinker production in 2005 NDRC: the People's Republic of China National Greenhouse Gas Inventory 2005, National Development and Reform Commission,

clinker (NDRC, 2012, 2014). In its first biennial update report, China does not report emissions from cement production separately, but does report[4] clinker production of 1303.9 Mt in 2012 (NDRC, 2016), which with China's emis-

Beijing, 2014, which agrees with both the figure given by CCA – 764.72 Mt – and with the reported emissions.

[4]Tables 2–3 on p. 20 in the English section (p. 152).
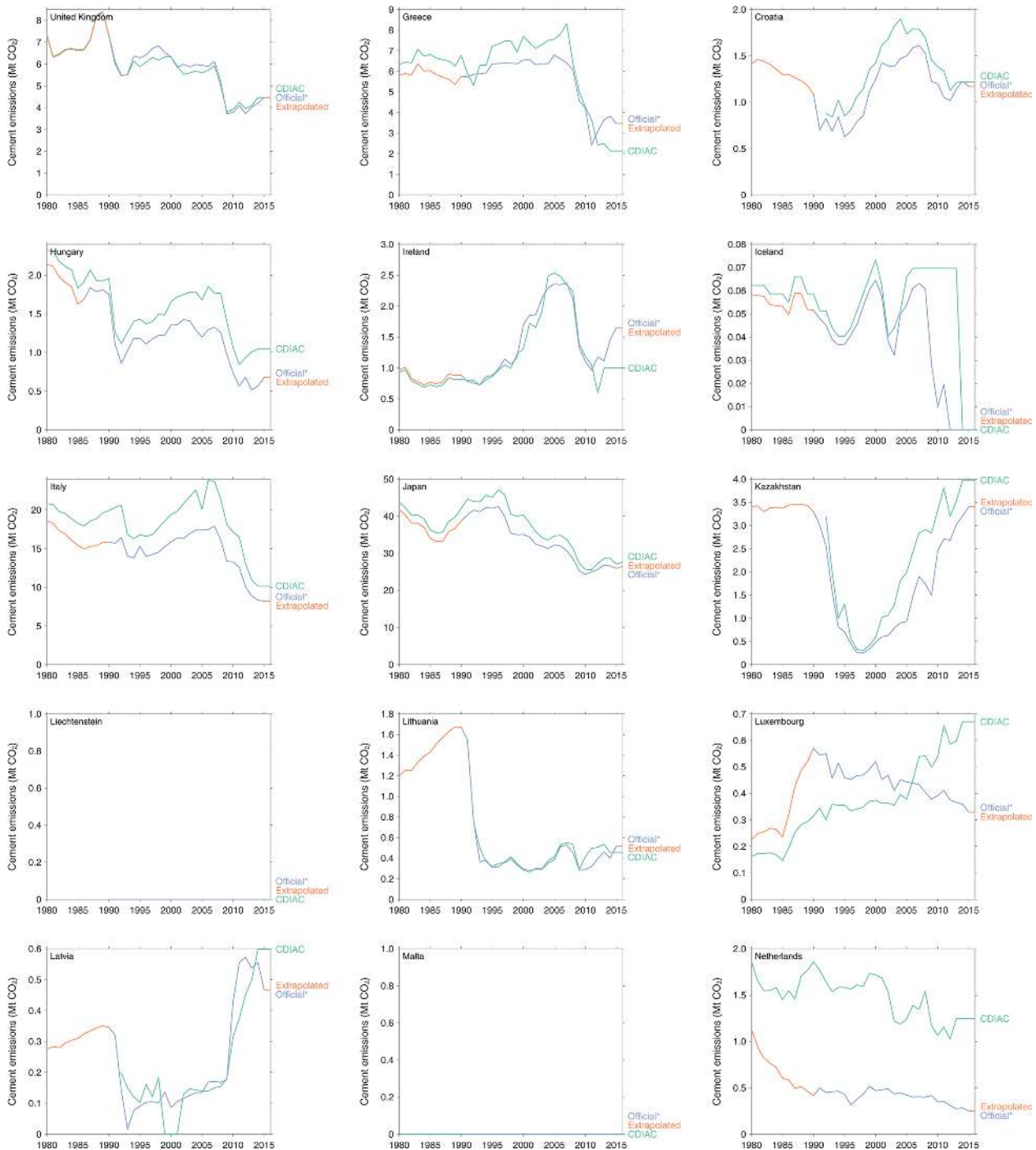
Figure D2. Revised cement emissions for Annex I parties to the UNFCCC.

sion factor of 0.5383, would have led to about 702 $Mt\,CO_2$. In all three cases, China has used firm-level surveys to determine the emission factor.

In 2016 the China Cement Association (CCA) annual Cement Almanac 2015 presented much lower historical clinker production for some years than previous editions (CCA, 2016). These are not revisions, but a change in the coverage

of the data presented: previous almanacs presented national totals, while the 2015 edition presents production enterprises with revenues over a specified threshold (so-called "above-sized" enterprises (a correspondent at CCA, personal communication, 2017). The differences between these two figures has diminished considerably over time, such that clinker production from above-sized enterprises in 2013 was 98 % of

Figure D3. Revised cement emissions for Annex I parties to the UNFCCC.

all clinker production reported by CCA in the previous edition.

National clinker production data for 1990–2004 were provided by Shaohui Zhang, who received them directly from CCA (Zhang et al., 2015); 2005–2013 data are from the 2015 edition of CCA's almanac; 2014–2016 data are from NBS via the China Cement Research Institute (CCRI), and these have been scaled up very slightly so that the 2013 figure matches the national total provided by CCA.

Figure D5 shows clinker ratios (the ratio of clinker production to cement production) from this and a number of other sources. Some authors do not adjust for clinker trade before calculating the ratio. The numbers from WBCSD are unreliable because of a very small sample size in China ($\sim 4\%$ of all clinker production) and likely to be biased toward producers of higher-quality cement. The data sourced from the

CCA by Zhang are used in this study and supplemented by later data from CCA's almanac.

The clinker ratio in China has been below 0.8 since at least 1990 and has declined rapidly in the last decade to about 0.62 in recent years (Fig. D5). Along with the use of clinker substitutes mentioned above, the use of modern kiln types also contributes. The new suspension preheater (NSP) type, which allows lower clinker ratios to be used in cement production given the same strength requirements, was used for about one-seventh of production in 2000, a share which had grown to about four-fifths in 2010 (Xu et al., 2012).

The default factor for the average lime (CaO) content of clinker given by the IPCC 2006 guidelines is 65 %. Liu et al. (2015) used 62 %, being the weighted average derived
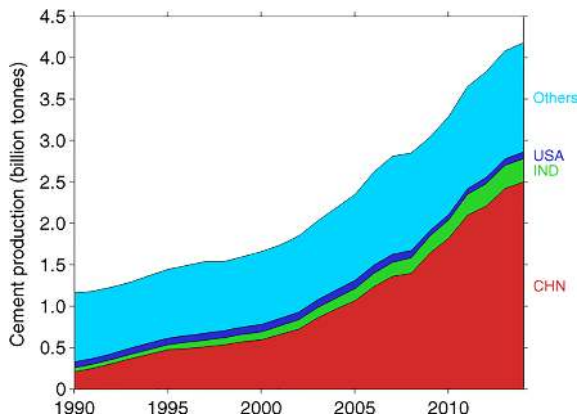
Figure D4. Production of cement by country, 1990–2014 (van Oss, 1994–2012; USGS, 2015).
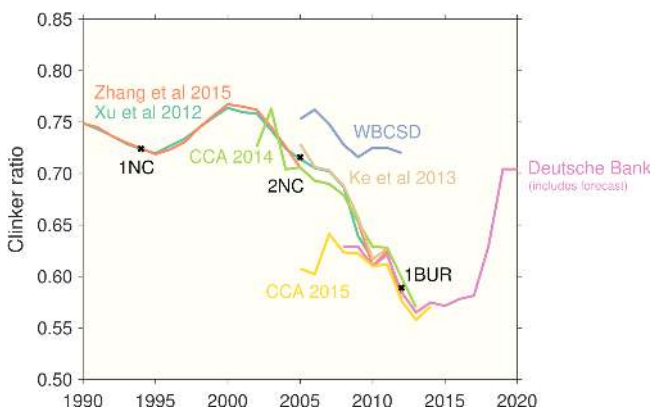

Figure D5. China's clinker ratio since 1990 from a number of different sources. The three official estimates are marked in black: 1NC is the first national communication, 2NC the second national communication, and 1BUR is the first biennial update report.

from the factory-level study made by Shen et al. (2014)[5]. However, clinker production also involves the decomposition of $MgCO_3$ to MgO, and emission factors derived only from the CaO content (including Liu et al., 2015) omit this source of CO_2 emissions, which Annex I parties include in their inventories.

China's second national communication used emission factors "derived from in situ surveys" (p. 60), while the first biennial update report used factors "obtained through typical enterprise survey" (p. 19). The factor used for the second national communication is provided in the NDRC's report: 0.5383 (NDRC, 2014). This factor excludes clinker kiln dust, stated to be negligible, but does include emissions from the decomposition of $MgCO_3$.

For years before 1990, the assumption is made here that the clinker ratio was 0.8 until 1970 and then linearly declined to the estimated value in 1990.

[5]Confirmed by Z. Liu, personal communication, 2017.

The cement emissions derived in this study are shown in Fig. 3, which also compares with several other available estimates. The 2011 dip in cement emissions presented by Liu et al. (2015) appears to be spurious based on an unlikely low clinker ratio of 0.49 in that year. Recent data from CCA indicate a ratio of 0.63 in that year with no particular discontinuity.

D1.2 India

India is the second-largest producer of cement in the world, with about 300 000 t in 2016 (USGS, 2017). The 47 % of India's cement production covered by WBCSD's data used a clinker ratio of 0.70 in 2014 (WBCSD, 2012).

In India's first national communication to the UNFCCC with data for 1994, process emissions from cement production are reported as 30 767 kt CO_2 using an emission factor of 0.537 t CO_2 t^{-1} clinker (p. 41), implying clinker production of 57 294 kt in that year (Ministry of Environment and Forests, 2004). USGS reports Indian cement production in that year as 57 000 kt. Allowing for rounding, the implied clinker ratio was therefore surprisingly high at approximately 1.0 in 1994. WBCSD data indicate that the clinker ratio in 1990 was 87 % for the cement manufacturers from which there were data (WBCSD, 2014). These data are inconsistent, but it is unclear where the error lies.

Similarly, in India's second national communication with data for 2000, process emissions are reported as 44 056 kt CO_2 using the same emissions factor (p. 53), implying clinker production of 82 041 kt (Ministry of Environment and Forests, 2012). USGS reports cement production in 2000 of 95 000 kt. The clinker ratio was therefore most likely about 0.86 in 2000, agreeing closely with that reported by WBCSD (0.85).

India's first biennial update report give cement process emissions of 83 851.74 kt CO_2 in 2010 (Ministry of Environment, Forest and Climate Change, 2015). Energy emissions were about the same as in 2000, implying vastly improved efficiency. The BUR does not indicate what emission factor was used, but assuming 0.537 as before would suggest 156 Mt of clinker production in 2010.

With no complete official time series of either clinker production or clinker ratio, a multi-source approach has been used here. We make use of data from the Indian Cement Manufacturers' Association (CMA), consultancy reports from CRISIL and IBEF, WBCSD, and other sources. Data include clinker production, blending ratio (the inverse of clinker ratio), and cement types. When calculating clinker ratios from clinker and cement production data, clinker trade has been taken into account.

The cement-type data (OPC, PPC, etc.) indicate a dramatic shift to OPC between 1986 and 1990, suggesting an improvement in quality. This appears to have been a result of decontrol in 1989, which removed many regulations from the industry. Since 2000 the cement types have begun to change
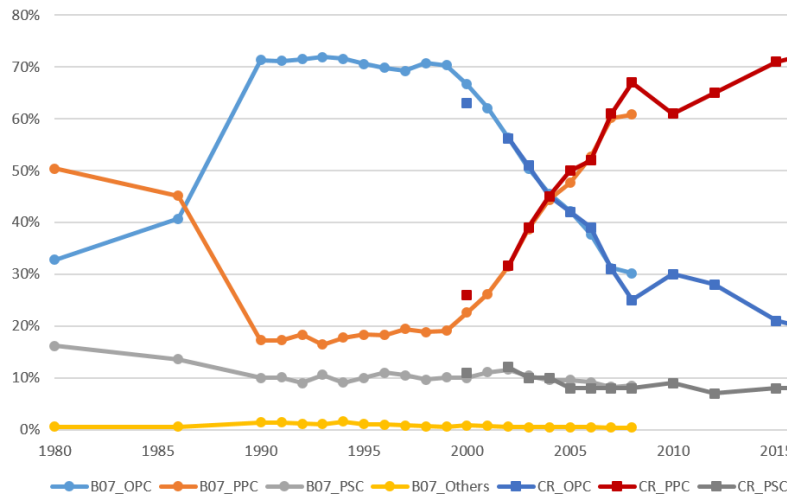
Figure D6. Proportions of cement production by type. B07: Bapat et al. (2007), CR: CRISIL (various years). OPC: ordinary Portland cement, PPC: Portland pozzolana cement, PSC: Portland slag cement.
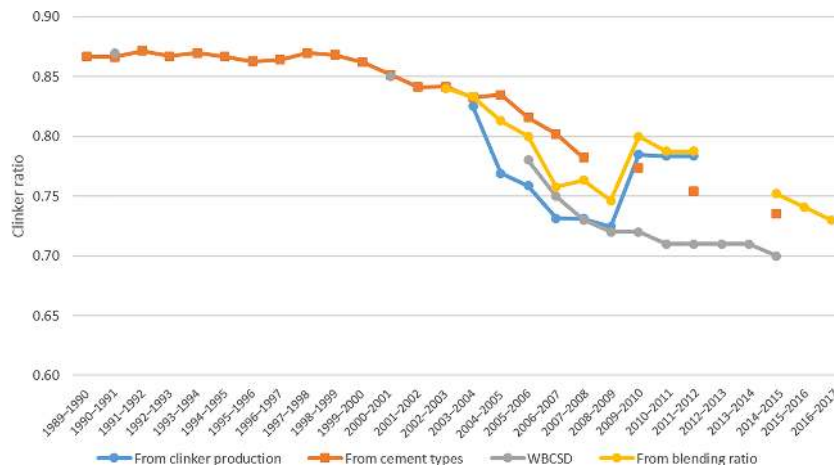

Figure D7. Estimates of clinker ratio in India from various sources.

again, a result of growing acceptance of other types of cement as being of sufficient quality (CRISIL, 2016, p. 21).

Using the cement types combined with the proportion of clinker in each cement type, one can derive the overall clinker ratio from a weighted average. The proportions of clinker in each cement type change over time, and only two sets of estimates were available: one from the WBCSD and IEA (2013), assumed to represent 2012 and later, and another from IBEF (2005), assumed to represent 2005 and earlier. The clinker ratios by cement type were interpolated linearly between these two years.

The WBCSD survey data for India cover close to half of Indian cement manufacturing. These data show that the clinker ratio declined from 0.86 in 1990 to 0.70 in 2014.

Various reports on the Indian cement industry by the consultancy CRISIL give data on both clinker production and blending ratios for various years.

The CMA also provides clinker production data, but in the 2009–2010 financial year two members discontinued their membership in the association, so production data from that year onwards are incomplete (CMA, 2010).

There unfortunately remains some disagreement between the clinker ratios derived from different sources (Fig. D7). The data from the WBCSD represent just under half4of cement production in India, most likely the larger producers. There is a significant divergence in 2009–2010 between WBCSD and the other data sources. CRISIL reports that "the blending ratio dipped significantly to around 1.25 from 1.34 in 2008–2009. Cement players had lowered the blending ratio during the year on account of decline in cement demand
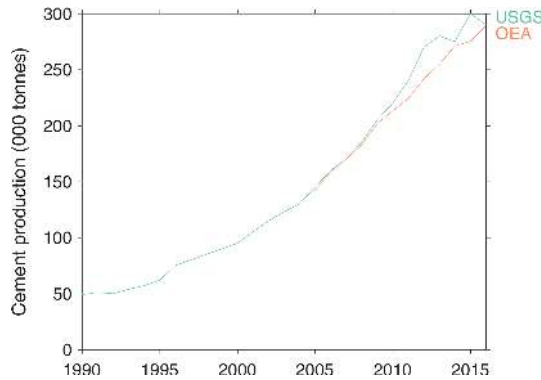
Figure D8. Comparison of Indian cement production data (in kilotonnes) from USGS and OEA, the latter from 2005.

and increased clinker production" (CRISIL, 2013, pA-19). The cement-type data also show a sharp increase against the trend in the amount of OPC produced at that time, from 25 % in 2007–2008 to 30 % in 2009–2010. It may be that the survey-based approach of WBCSD did not capture this adjustment in the industry.

The use of clinker production data is clearly preferred. When clinker production data were not available in earlier years, we have used the analysis based on cement types. In later years we use the reported blending ratios (reciprocal of the clinker ratio). Data were adjusted from financial to calendar years by using a simple weighting of 0.75 : 0.25 for the two overlapping financial years. In a later revision monthly cement production statistics may be used to improve this weighting.

The clinker ratio must be applied to cement production data, but there is some divergence between USGS data and those from the Office of the Economic Advisor (OEA), which are reported by the CMA (Fig. D8). This divergence has not yet been explained. In this work we rely on the official data from the OEA, although this only affects the emissions estimate for 2016 because clinker production estimates are used for 2004–2015.

Indian analyses have shown emission factors $(tCO_2 (tclinker)^{-1})$ similar to the default IPCC factor of 0.52 (Arceivala, 2014), so we use that factor here.

The final emissions time series lies very close to the three available official estimates (Fig. D9).

D1.3   USA

The USA reports annual emissions from cement production to the UNFCCC, along with all other Annex I parties. However, in addition to this series, which starts in 1990, the US Geological Survey (USGS) has an unpublished time series of clinker production in the US starting in 1925 (Hendrik van Oss, personal communication, 2015). This allows for very good estimates of CO_2 emissions from historical clinker production. Furthermore, while USGS clinker data begin in
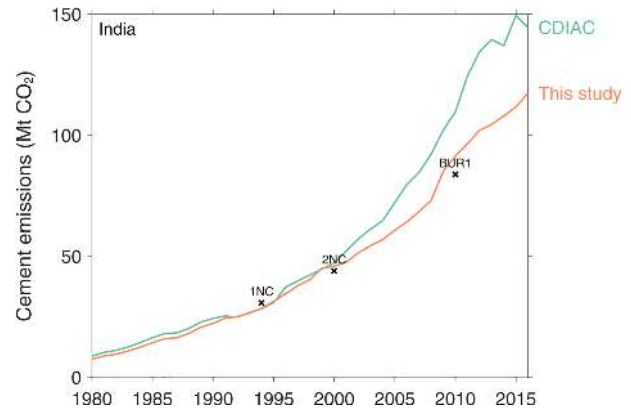

Figure D9. Revised cement emissions for India. 1NC: first national communication; 2NC: second national communication; BUR1: first biennial update report.
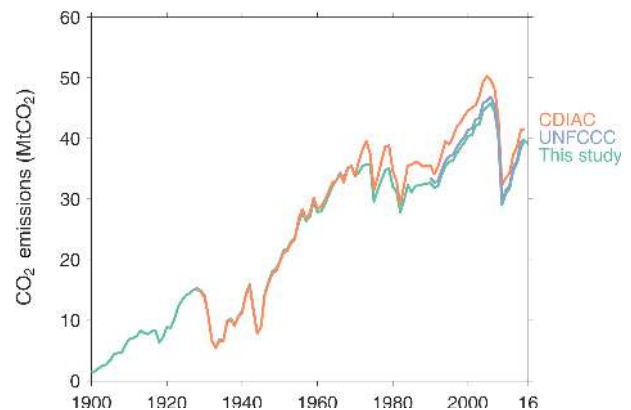

Figure D10. Revised cement emissions for the USA.

1925, the clinker ratio was very close to 1 between 1925 and 1970. By assuming that it was also 1 between 1900 and 1924, the data series can be extended back to 1900 when cement production data begin (Fig. D10).

Until about 1970, CDIAC's estimates of US cement emissions show good correspondence with estimates calculated directly from clinker production data. However, after about 1970 significant deviations appear as the clinker ratio of US cement began to drop below unity (Fig. D10). The same method is used here to calculate emissions from clinker production data as is used in the US national inventory report. The reason for the divergence seen in Fig. D10 is that the UNFCCC submission includes cement production in Puerto Rico, while the estimates in this study do not.

D1.4   Armenia

Armenia's 2010 national inventory report provides emissions from cement production for 1990–2010 (Ministry of Nature Protection, 2014). The implied emission factor is nearly constant, at around 0.507 every year. The second national in-
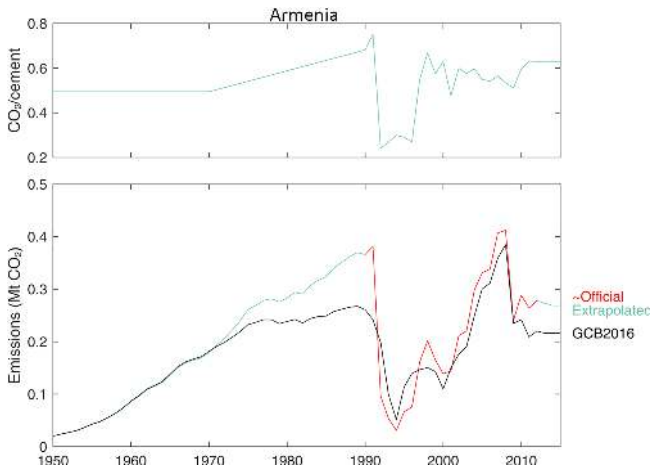
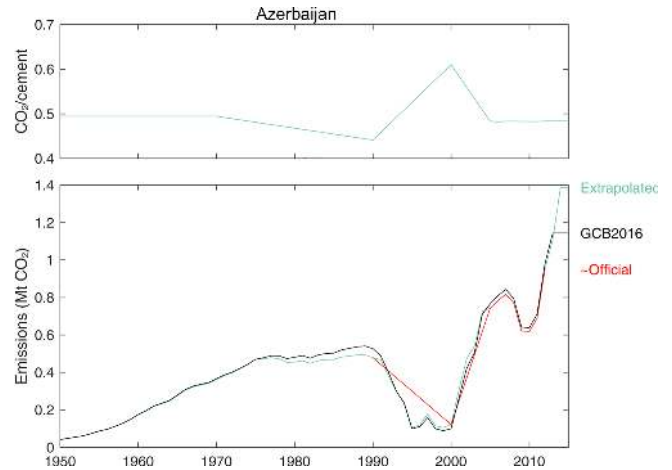**Figure D11.** Revised cement emissions for Armenia.

Figure D13. Revised cement emissions for Azerbaijan.
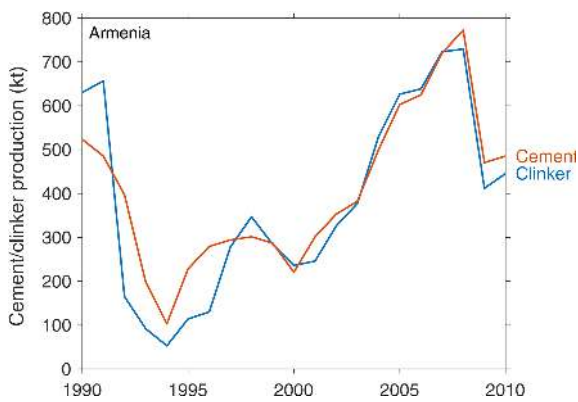

Figure D12. Clinker and cement production in Armenia, 1990–2010 (Ministry of Nature Protection, 2014; van Oss, 2017).
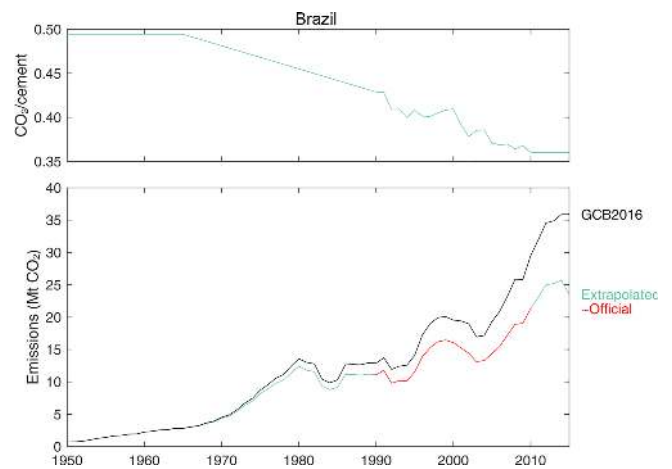

Figure D14. Revised cement emissions for Brazil.

ventory report for 2012 provides emissions for 2000–2012 using Tier III methodology (Ministry of Nature Protection, 2015). These have been combined with the earlier estimates to give a longer data series from 1990–2012. The introduction of Tier III methodology raised emissions in the overlapping period by an average of 14 %, and this was used to adjust the emissions from the first NIR.

Armenia's clinker production was significantly higher than USGS-reported cement production in 1990 and 1991, indicating significant exports of clinker in those years (Fig. D12). While clinker production dropped significantly below cement production in the following few years, there have been a number of years since when clinker appears to have been exported.

While it is quite possible that Armenia was a net exporter of clinker in years prior to 1990, no data have been found to substantiate this. After 2012 we assume that the ratio of clinker production and cement production in 2012 continues with the emission factor of 2012.

D1.5   Azerbaijan

Azerbaijan's third national communication provides estimates of emissions from cement production for 1990, 2000, and 2005–2012.

D1.6   Brazil

Brazil's third national communication to the UNFCCC includes estimates of emissions from cement production from 1990 to 2010 (MSTI, 2016). The emission factor ranges between 0.544 and 0.549 t CO$_2$ (t clinker)$^{-1}$ for the years in which clinker production data are provided. The clinker ratio (assuming zero clinker trade) has declined from 0.78 in 1990 to 0.66 in 2010 (Fig. D15).

The report states that Brazil has been substituting clinker in cement manufacturing "for over 50 years" (p. 100). For years before 1990, the clinker ratio was interpolated linearly from 0.95 in 1965 to the estimated ratio in 1990 from the
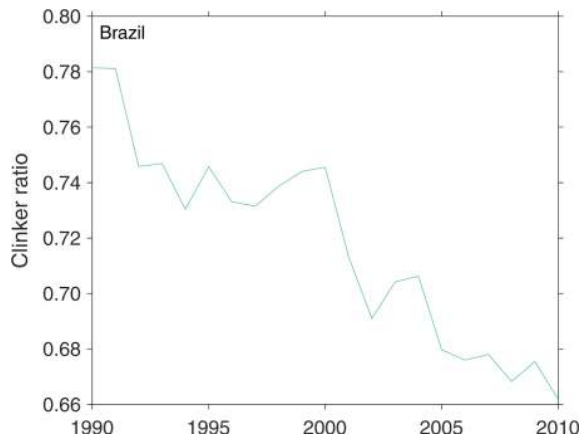
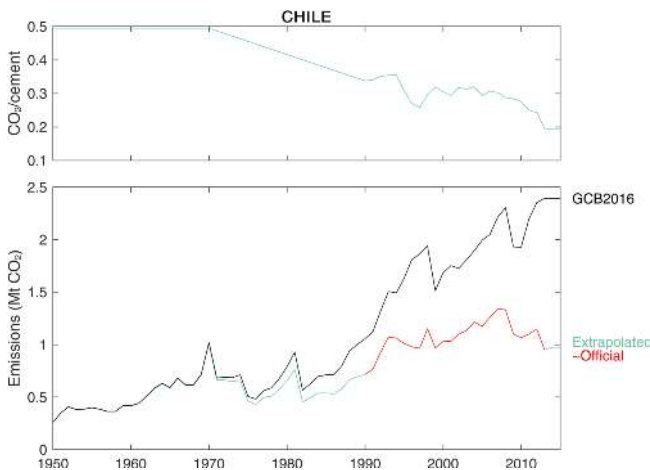**Figure D15.** Brazil's approximate clinker ratio with no account for clinker trade.

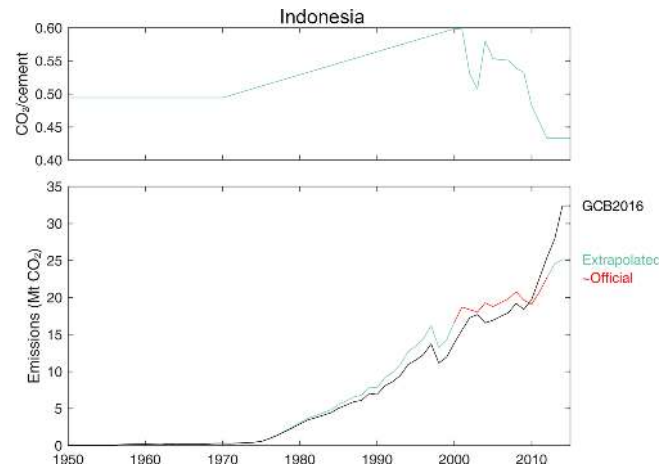**Figure D16.** Revised cement emissions for Chile.

Figure D17. Revised cement emissions for Indonesia.

Figure D18. Net clinker exports from Indonesia, 1999–2016 (source: Statistics Indonesia).

data. After 2010, the clinker ratio was assumed constant at the 2010 level.

D1.7   Chile

The Chilean national inventory report (MdMA, 2017) presents clinker production data for 1990–2013, with 1990–1994 and 2013 estimated based on extrapolated clinker ratios. The country uses IPCC default emission factors in the absence of country-specific data. Significant imports of clinker mean that the resulting emissions are significantly lower than those estimated by CDIAC (Fig. D16).

Imports were negligible in 1990, so an assumption has been made of no imports prior to 1990. For years after 2013, the ratio of clinker production to cement production has been assumed to continue, implicitly assuming the same clinker ratio and clinker trade ratios.

D1.8   Indonesia

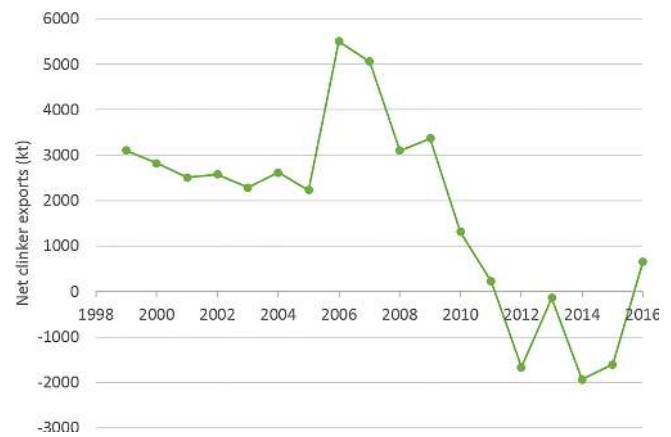Indonesia's first biennial update report provides estimates of process emissions from cement production for 2000–2012 using the IPCC default emission factor. Clinker production is higher than cement production in many years.

The clinker ratio, even after adjustment for clinker trade, is still above 1 in some years, which is impossible (Fig. D20). This uses cement production data from USGS. Clearly there are some inconsistencies in the datasets used, and without clinker production data it appears impossible to generate a reasonable time series of cement emissions for Indonesia.

D1.9   Jamaica

Jamaica's first biennial update report presents clinker production and emissions estimates for 2006–2012 (Mahlung and Dore, 2016). The implied emission factor used is $0.520\,\mathrm{kg\,CO_2\,(kg\,clinker)^{-1}}$.
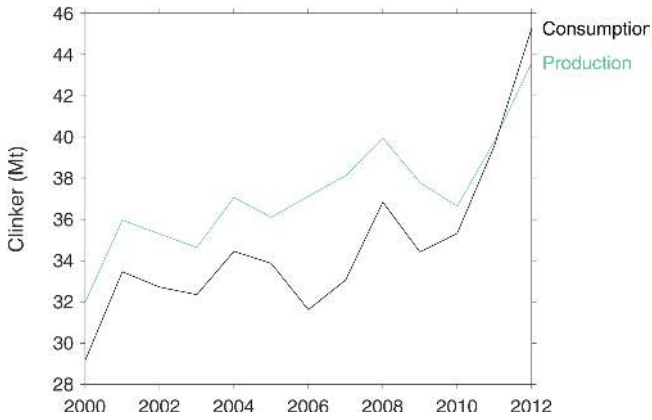
Figure D19. Indonesian clinker production and derived consumption, 2000–2012.
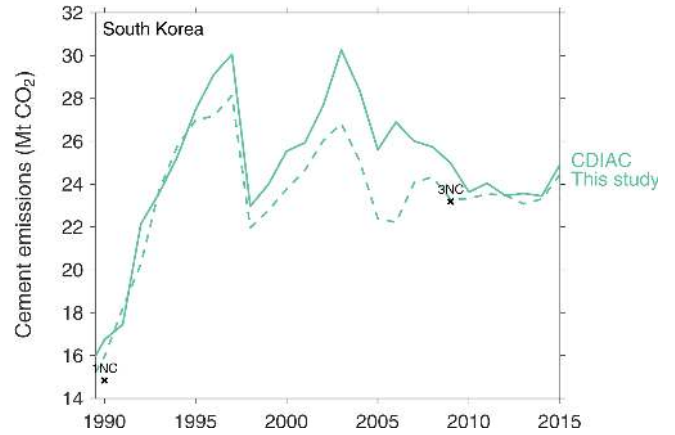

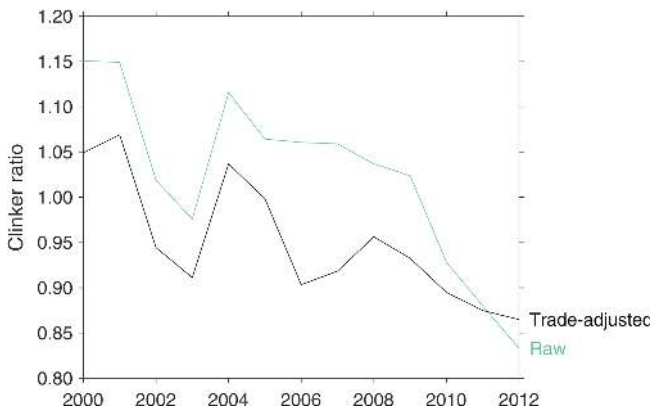**Figure D22.** Revised cement emissions for South Korea.

Figure D20. Indonesian clinker ratio calculated from both clinker production and consumption data.
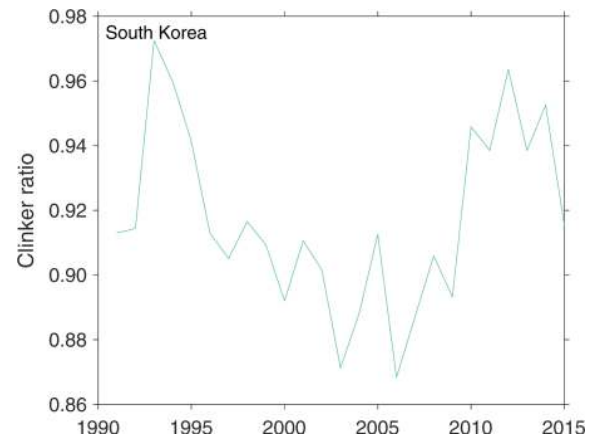

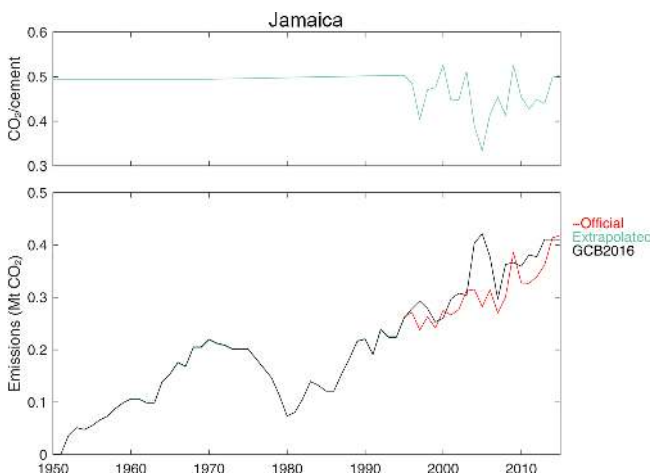**Figure D23.** South Korea's approximate clinker ratio with no account for clinker trade.

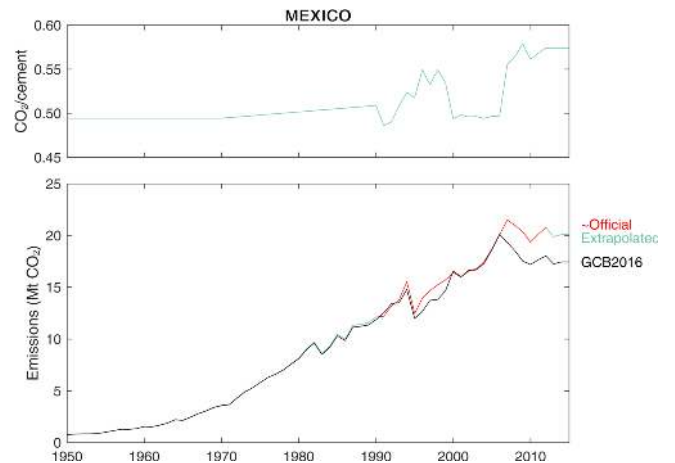**Figure D21.** Revised cement emissions for Jamaica.

Figure D24. Revised cement emissions for Mexico.

The BUR states that clinker production data were obtained from the Caribbean Cement Company. Accordingly, further clinker production data have been sourced from annual reports of the Caribbean Cement Company (Caribbean Cement Company, various years) to extend this series to 1995–2015 (Fig. D21).

The clinker ratio was 0.96 in 1995. For years before 1995, a clinker ratio of 0.95 has been assumed with the same emission factor of 0.520.

D1.10   Korea

The Korea Cement Association (KCA) has published annual national clinker and cement production from 1991, and at the time of writing data were available to 2015 (KCA, 2017).

The third national communication (Korean Ministry of Environment, 2012) states that cement production was 40.9 % of total industrial process emissions of 56.7 Mt CO$_2$ in 2009, which comes to 23.19 Mt CO$_2$. Using an emission factor of 0.52 and the KCA clinker production figure of 44.774 Mt gives a very close 23.28 Mt CO$_2$ (Fig. D22).

The clinker ratio over 1991–2015 from the KCA data shows no clear trend, varying from year to year probably only in response to clinker trade (Fig. E23).

D1.11   Mexico

Mexico's first biennial update report (INECC and Semarnat, 2015) provides CO$_2$ emissions from cement manufacturing during 1990–2012 (Fig. D24). Mexico has had significant clinker exports over this period such that emissions are in many years higher than the estimates made by CDIAC.

After 2012, the emissions rate was assumed constant at the 2012 level, implicitly assuming a constant clinker ratio and constant international clinker trade.

D1.12   Moldova

Moldova's national inventory report provides cement emissions for 1990–2012 (Ministry of Environment, 2013). Clinker production tracked cement production relatively closely over the entire period, although cement production was rather higher than clinker production in 1990, suggesting either exports of clinker or a lower clinker ratio in that year (Fig. D26).

After 2010 we assume that the ratio of clinker production and cement production in 2010 continues with the emission factor of 2010 (Fig. D25).

The main reason GCB2016 estimates were so low is that the method used to disaggregate emissions from countries of the former Soviet Union assumed that the shares in 1992 represented the shares before 1992.
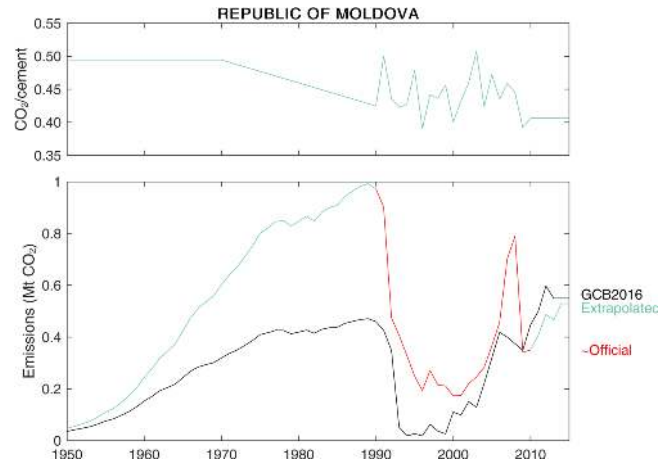

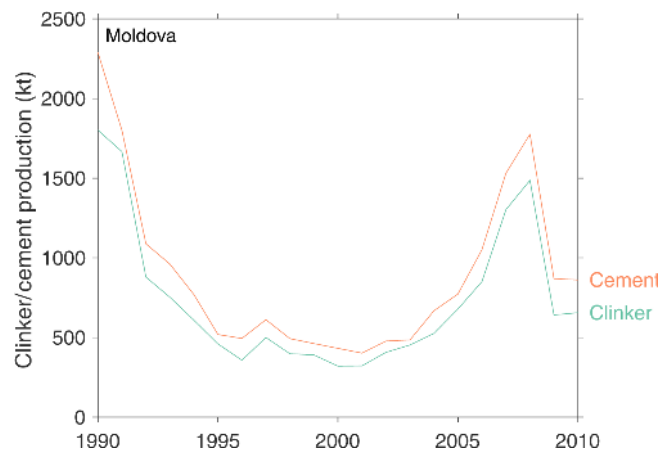**Figure D25.** Revised cement emissions for Moldova.

Figure D26. Clinker and cement production in Moldova (Ministry of Environment, 2013).
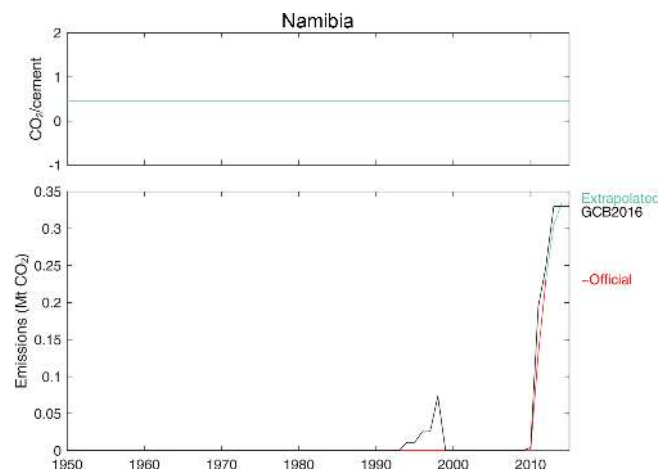

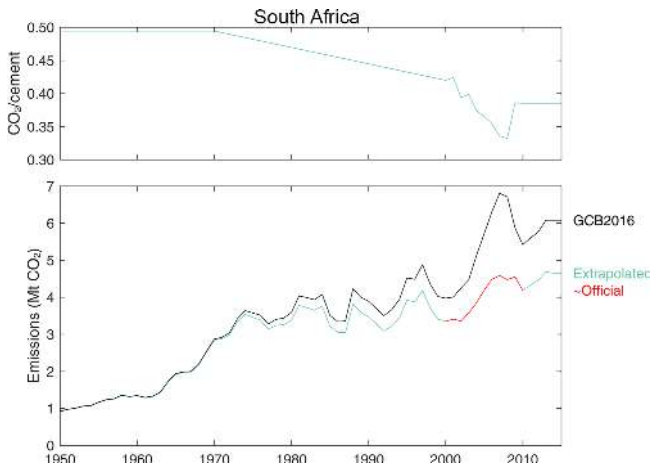**Figure D27.** Revised cement emissions for Namibia.
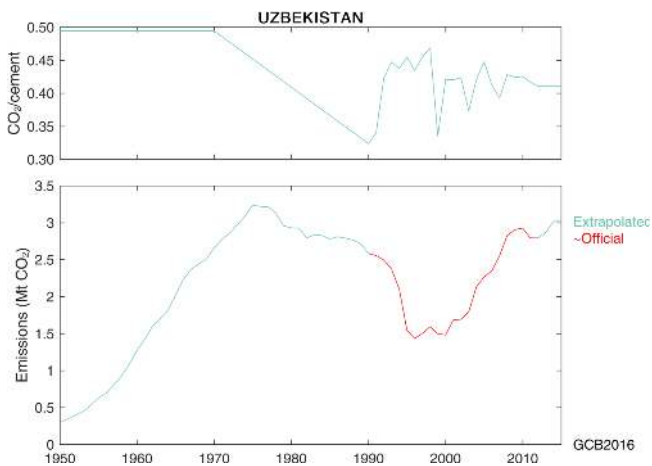
Figure D28. Revised cement emissions for South Africa.

Figure D29. Revised cement emissions in Uzbekistan.

Figure E1. Implied global clinker ratio derived from emissions estimates and cement production data.

Appendix E: Global clinker ratio

The approximate implied global clinker ratio can be derived from emissions and cement production data using default emission factors (Fig. E1). The trend until 1990 is largely artificial, resulting from the assumptions used in extrapolation, although in earlier years the data for the US dominate.

D1.13 Namibia

Namibia's second national inventory report provides estimates for emissions from cement production for 2000–2012 and clearly states that there was no cement production in the country before 2011.

D1.14 South Africa

South Africa's first national inventory report (DEA, 2014) provides estimates of emissions from cement production for 2000–2010.

D1.15 Uzbekistan

Uzbekistan's national inventory report includes a time series of cement emissions for 1990–2012 (Uzhydromet, 2016).

After 2012, the emission factor and clinker ratio of 2012 were assumed constant (Fig. D29).
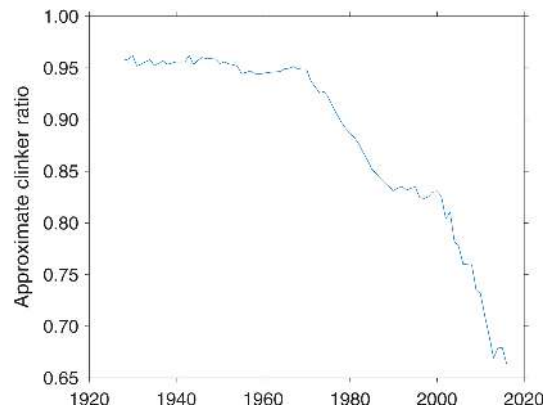
References

AT Kearney: Cement Vision 2025: Scaling New Heights, available at: http://www.atkearney.in (last access: 23 June 2017), 2014.

Andres, R. J., Boden, T. A., Bréon, F.-M., Ciais, P., Davis, S., Erickson, D., Gregg, J. S., Jacobson, A., Marland, G., Miller, J., Oda, T., Olivier, J. G. J., Raupach, M. R., Rayner, P., and Treanton, K.: A synthesis of carbon dioxide emissions from fossil-fuel combustion, Biogeosciences, 9, 1845–1871, https://doi.org/10.5194/bg-9-1845-2012, 2012.

Anonymous: Main differences in greenhouse gas emissions between EDGAR 4.1 and version 4.0, Netherlands Environmental Assessment Agency (PBL), Bilthoven, the Netherlands, available at: http://edgar.jrc.ec.europa.eu/Main_differences_between_EDGAR_version_41and40.pdf (last access: 21 November 2017), 2010.

Arceivala, S. J.: Green Technologies For a Better Future, McGraw Hill, New Delhi, 2014.

Bapat, J. D., Sabnis, S. S., Joshi, S. V., and Hazaree, C. V.: History of Cement and Concrete in India – a Paradigm Shift, American Concrete Institute (ACI) Technical Session on History of Concrete, Atlanta, USA, April 2007, 2007.

Baxter, M. S. and Walton, A.: A theoretical approach to the suess effect, P. Roy. Soc. Lond. A Mat. 318, 213–230, https://doi.org/10.1098/rspa.1970.0141, 1970.

Boden, T. A., Marland, G., and Andres, R. J.: Estimates of Global, Regional, and Naitonal Annual CO_2 Emissions from Fossil-Fuel Burning, Hydraulic Cement Production, and Gas Flaring: 1950–1992, Carbon Dioxide Information Analysis Center (CDIAC), Oak Ridge National Laboratory, Oak Ridge, Tennessee, Technical Report, Report Number(s): ORNL/CDIAC-90; NDP-030/R6, https://doi.org/10.2172/207068, 1995.

Boden, T. A., Marland, G., and Andres, R. J.: Global, Regional, and National Fossil-Fuel CO_2 Emissions, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., USA, https://doi.org/10.3334/CDIAC/00001_V2013, 2013.

Boden, T. A., Andres, R. J., and Marland, G.: Global, Regional, and National Fossil-Fuel CO_2 Emissions, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., USA, available at:

http://cdiac.ess-dive.lbl.gov/trends/emis/meth_reg.html, last access: 28 June 2017.

Caribbean Cement Company: Annual Report, various years, available at: http://www.caribcement.com/, last access: 9 June 2017.

CCA: China Cement Almanac 2015, China Building Material Press, Beijing, 2016 (in Chinese).

CEMBUREAU: Cements For a Low-Carbon Europe, The European Cement Association, Brussels, available at: http://www.cembureau.be/cements-low-carbon-europe (last access: 6 May 2015), 2013.

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M., Jones, C., Quéré, C. L., Myneni, R. B., Piao, S., and Thornton, P.: Carbon and other biogeochemical cycles, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, UK and New York, NY, USA, 2013.

CMA: Annual Report 2009–10, Cement Manufacturers' Association (India), available at: http://www.cmaindia.org/annual-report.html (last access: 28 April 2017), 2010.

CRISIL: Cement: Annual Review, available at: https://www.crisil.com/pdf/research/industry-research-sample-report.pdf (last access: 21 June 2017), 2013.

CRISIL: Cement, available at: https://www.crisil.com/content/dam/crisil/our-analysis/reports/Research/premium-reports/sectors/september/Sector-Report-Cement-September-2017.pdf (last access 12 January 2018), 2016.

CRISIL: Cement Industry Report, various years, available at: https://www.crisil.com/, last access: 31 March 2017.

DEA: GHG Inventory for South Africa 2000–2010, Department of Environmental Affairs, South Africa, Pretoria, South Africa, available at: http://unfccc.int/national_reports/non-annex_i_natcom/reporting_on_climate_change/items/8722.php, (last access: 10 June 2017), 2014.

Griffin, R. C.: CO_2 release from cement production, in: Estimates of CO_2 Emissions From Fossil Fuel Burning and Cement Manufacturing Based on the United Nations Energy Statistics and the U.S. Bureau of Mines Cement Manufacturing Data, edited by: Marland, G., Boden, T. A., Griffin, R. C., Huang, S. F., Kanciruk, P., and Nelson, T. R., Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1987.

Hanle, L., Maldonado, P., Onuma, E., Tichy, M., and van Oss, H. G.: Mineral industry emissions, in: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, edited by: Eggleston, S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K., IGES, Japan, 2006.

Haukås, H. T., Jaques, A., Neitzert, F., Rosland, A., Rypdal, K., and Weidemann, F.: Chapter 2: Industrial Processes, in: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual, edited by: Houghton, J. T., Meira Filho, L. G., Lim, B., Tréanton, K., Mamaty, I., Bonduki, Y., Griggs, D. J., and Callander, B. A., IPCC/OECD/IEA, Paris, available at: http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.html, (last access: 27 October 2014), 1997.

IBEF: Cement, India Brand Equity Foundation (report prepared by CRISIL), available at: https://www.ibef.org/download/Cement.pdf (last access: 27 April 2017), 2005.

IEA: Energy Technology Perspectives 2016: Towards Sustainable Urban Energy Systems, International Energy Agency, Paris, ISBN 978-92-64-25233-2, available at: www.iea.org/etp2016 (last access: 8 September 2014), 2016.

IEA: Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations, International Energy Agency, Paris, ISBN: 978-92-64-27597-3, available at: www.iea.org/etp2017 (last access: 19 June 2017), 2017.

INECC, and Semarnat: Primer Informe Bienal de Actualización Ante la Convención Marco de las Naciones Unidas Sobre el Cambio Climático, Instituto Nacional de Ecología y Cambio Climático (INECC) and Secretaría de Medio Ambiente y Recursos Naturales (Semarnat), unfccc.int, Mexico City, Mexico, 2015.

IPCC: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, prepared by the National Greenhouse Gas Inventories Programme, edited by: Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K., IGES, Hayama, Japan, available at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html (last access: 21 May 2017), 2006.

Janssens-Maenhout, G., Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Dentener, F., Bergamaschi, P., Pagliari, V., Olivier, J. G. J., Peters, J. A. H. W., van Aardenne, J. A., Monni, S., Doering, U., and Petrescu, A. M. R.: EDGAR v4.3.2 Global Atlas of the three major Greenhouse Gas Emissions for the period 1970–2012, Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2017-79, in review, 2017.

KCA: Annual Production of Clinker and Cement, Korea Cement Association, available at: http://www.cement.or.kr/stati_2015/yy_pro_view_page.asp?sm=2_3_1 (last access: 26 April 2017), 2017 (in Korean).

Ke, J., McNeil, M., Price, L., Khanna, N. Z., and Zhou, N.: Estimation of CO$_2$ emissions from China's cement production: methodologies and uncertainties, Energ. Policy, 57, 172–181, https://doi.org/10.1016/j.enpol.2013.01.028, 2013.

Keeling, C. D.: Industrial production of carbon dioxide from fossil fuels and limestone, Tellus, 25, 174–198, https://doi.org/10.3402/tellusa.v25i2.9652, 1973.

Korean Ministry of Environment: Korea's Third National Communication Under the United Nations Framework Convention on Climate Change, Seoul, available at: www.unfccc.int (last access: 26 April 2017), 2012.

Le Quéré, C., Andrew, R. M., Canadell, J. G., Sitch, S., Korsbakken, J. I., Peters, G. P., Manning, A. C., Boden, T. A., Tans, P. P., Houghton, R. A., Keeling, R. F., Alin, S., Andrews, O. D., Anthoni, P., Barbero, L., Bopp, L., Chevallier, F., Chini, L. P., Ciais, P., Currie, K., Delire, C., Doney, S. C., Friedlingstein, P., Gkritzalis, T., Harris, I., Hauck, J., Haverd, V., Hoppema, M., Klein Goldewijk, K., Jain, A. K., Kato, E., Körtzinger, A., Landschützer, P., Lefèvre, N., Lenton, A., Lienert, S., Lombardozzi, D., Melton, J. R., Metzl, N., Millero, F., Monteiro, P. M. S., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S.-I., O'Brien, K., Olsen, A., Omar, A. M., Ono, T., Pierrot, D., Poulter, B., Rödenbeck, C., Salisbury, J., Schuster, U., Schwinger, J., Séférian, R., Skjelvan, I., Stocker, B. D., Sutton, A. J., Takahashi, T., Tian, H., Tilbrook, B., van der Laan-

Luijkx, I. T., van der Werf, G. R., Viovy, N., Walker, A. P., Wiltshire, A. J., and Zaehle, S.: Global Carbon Budget 2016, Earth Syst. Sci. Data, 8, 605–649, https://doi.org/10.5194/essd-8-605-2016, 2016.

Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Pongratz, J., Manning, A. C., Korsbakken, J. I., Peters, G. P., Canadell, J. G., Jackson, R. B., Boden, T. A., Tans, P. P., Andrews, O. D., Arora, V. K., Bakker, D. C. E., Barbero, L., Becker, M., Betts, R. A., Bopp, L., Chevallier, F., Chini, L. P., Ciais, P., Cosca, C. E., Cross, J., Currie, K., Gasser, T., Harris, I., Hauck, J., Haverd, V., Houghton, R. A., Hunt, C. W., Hurtt, G., Ilyina, T., Jain, A. K., Kato, E., Kautz, M., Keeling, R. F., Klein Goldewijk, K., Körtzinger, A., Landschützer, P., Lefèvre, N., Lenton, A., Lienert, S., Lima, I., Lombardozzi, D., Metzl, N., Millero, F., Monteiro, P. M. S., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S.-I., Nojiri, Y., Padìn, X. A., Peregon, A., Pfeil, B., Pierrot, D., Poulter, B., Rehder, G., Reimer, J., Rödenbeck, C., Schwinger, J., Séférian, R., Skjelvan, I., Stocker, B. D., Tian, H., Tilbrook, B., van der Laan-Luijkx, I. T., van der Werf, G. R., van Heuven, S., Viovy, N., Vuichard, N., Walker, A. P., Watson, A. J., Wiltshire, A. J., Zaehle, S., and Zhu, D.: Global Carbon Budget 2017, Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2017-123, in review, 2017.

Lea, F. M. and Desch, C. H.: The Chemistry of Cement and Concretes, Arnold and Co., London, 1940.

Lei, S.: Key opportunities to reduce emissions in China's cement industry, Joint workshop by MOST and IEA on carbon capture and storage: opportunities in energy-intensive industry, Beijing, China, 2012.

Liu, Z., Guan, D., Wei, W., Davis, S. J., Ciais, P., Bai, J., Peng, S., Zhang, Q., Hubacek, K., Marland, G., Andres, R. J., Crawford-Brown, D., Lin, J., Zhao, H., Hong, C., Boden, T. A., Feng, K., Peters, G. P., Xi, F., Liu, J., Li, Y., Zhao, Y., Zeng, N., and He, K.: Reduced carbon emission estimates from fossil fuel combustion and cement production in China, Nature, 524, 335–338, https://doi.org/10.1038/nature14677, 2015.

Mahlung, C. and Dore, C.: Biennial Update Report for Jamaica, Covering GHG Emissions for 2006–2012, Ministry of Economic Growth and Job Creation, unfccc.int, Kingston, Jamaica, 2016.

Marland, G. and Rotty, R. M.: Carbon dioxide emissions from fossil fuels: a procedure for estimation and results for 1950–1982, Tellus B, 36, 232–261, 1984.

MdMA: Informe del Inventario Nacional de Gases de Efecto Invernadero de Chile, Serie 1990–2013. Versión 2.0, Departamento de Mitigación e Inventarios de Contaminantes Climáticos, División de Cambio Climático, Ministerio del Medio Ambiente, unfccc.int, Santiago, Chile, 2017.

Ministry of Environment: National Inventory Report: Greenhouse Gas Sources and Sinks in the Republic of Moldova 1990–2010, Ministry of Environment of the Republic of Moldova, Chisinau, Moldova, available at: http://unfccc.int/national_reports/non-annex_i_natcom/items/10124.php (last access: 5 May 2017), 2013.

Ministry of Environment and Forests: India's Initial National Communication to the United Nations Framework Convention on Climate Change, available at: www.unfccc.int (last access: 16 March 2017), 2004.

Ministry of Environment and Forests: India: Second National Communication to the United Nations Framework Convention on Climate Change, available at: www.unfccc.int (last access: 13 March 2017), 2012.

Ministry of Environment Forest and Climate Change: India: First Biennial Update Report to the United Nations Framework Convention on Climate Change, available at: www.unfccc.int (last access: 13 March 2017), 2015.

Ministry of Nature Protection: National Greenhouse Gas Inventory Report of the Republic of Armenia (2010), Yerevan, Armenia, available at: http://unfccc.int/national_reports/non-annex_i_natcom/items/10124.php (last access: 5 May 2017), 2014.

Ministry of Nature Protection: National Greenhouse Gas Inventory Report of the Republic of Armenia for 2012, Yerevan, Armenia, available at: http://unfccc.int/ (last access: 5 May 2017), 2015.

Mohr, S. H., Wang, J., Ellem, G., Ward, J., and Giurco, D.: Projection of world fossil fuels by country, Fuel, 141, 120–135, https://doi.org/10.1016/j.fuel.2014.10.030, 2015.

MSTI: Third National Communication of Brazil to the United Nations Framework Convention on Climate Change, Brazilian Ministry of Science, Technology and Innovation, Brasilia, available at: http://unfccc.int/national_reports/non-annex_i_natcom/submitted_natcom/items/653.php (last access: 26 April 2016), 2016.

NDRC: Second National Communication on Climate Change of The People's Republic of China, National Development and Reform Commission, available at: www.unfccc.int (last access: 24 April 2015), 2012.

NDRC: The People's Republic of China National Greenhouse Gas Inventory 2005, National Development and Reform Commission, Beijing, 2014.

NDRC: The People's Republic of China First Biennial Update Report on Climate Change, National Development and Reform Commission, Beijing, available at: www.unfccc.int (last access: 24 March 2017), 2016.

Olivier, J. G. J., Bouwman, A. F., Berdowski, J. J. M., Veldt, C., Bloos, J. P. J., Visschedijk, A. J. H., van der Maas, C. W. M., and Zandveld, P. Y. J.: Sectoral emission inventories of greenhouse gases for 1990 on a per country basis as well as on $1° \times 1°$, Environ. Sci. Policy, 2, 241–263, https://doi.org/10.1016/S1462-9011(99)00027-1, 1999.

Olivier, J. G. J., Janssens-Maenhout, G., Muntean, M., and Peters, J. A. H. W.: Trends in global CO_2 emissions: 2016 report, PBL Netherlands Environmental Assessment Agency, Ispra: European Commission, Joint Research Centre, The Hague, available at: http://edgar.jrc.ec.europa.eu/ (last access: 26 October 2017), 2016.

Orchard, D. F.: Concrete Technology, Applied Science Publishers Ltd., London, 1973.

Rotty, R. M. and Marland, G.: Production of CO_2 from fossil fuel burning by fuel type, 1860–1982, Carbon Dioxide Information Analysis Center (CDIAC), Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1984.

SDPC: The People's Republic of China initial national communication on climate change, State Development Planning Commission, Beijing CHN/COM/1 E COPY 3 ENG, available at: www.unfccc.int (last access: 4 April 2017), 2004.

Shen, L., Gao, T., Zhao, J., Wang, L., Wang, L., Liu, L., Chen, F., and Xue, J.: Factory-level measurements on CO_2 emission factors of cement production in China, Renew. Sust. Energ. Rev., 34, 337–349, https://doi.org/10.1016/j.rser.2014.03.025, 2014.

UNFCCC: National Inventory Submissions 2014, United Nations Framework Convention on Climate Change, available at: http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/8108.php, last access: 28 May 2014.

UNFCCC: National Inventory Submissions 2017, United Nations Framework Convention on Climate Change, available at: http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/10116.php (last access: 1 May 2017), 2017.

UNSD: United Nations Commodity Trade Statistics Database (COMTRADE), available at: https://comtrade.un.org/, last access: 15 May 2015.

USGS: Cement statistics, in: Historical Statistics for Mineral and Material Commodities in the United States, U.S. Geological Survey Data Series 140, edited by: Kelly, T. D. and Matos, G. R., U.S. Geological Survey, available at: https://minerals.usgs.gov/minerals/pubs/historical-statistics/ (last access: 12 January 2018), 2014.

USGS: Mineral Commodity Summaries 2015, United States Geological Survey, Reston, Virginia, 196 pp., https://doi.org/10.3133/70140094, 2015.

USGS: Mineral Commodity Summaries 2017, United States Geological Survey, Reston, Virginia, 202 pp., https://doi.org/10.3133/70140094, 2017.

Uzhydromet: Inventory of Anthropogenic Emissions Sources and Sinks of Greenhouse Gases in the Republic of Uzbekistan, 1990–2012: National Report, Centre of Hydrometeorological Service, Tashkent, available at: http://unfccc.int/national_reports/non-annex_i_natcom/items/10124.php (last access: 5 May 2017), 2016.

van Oss, H. G.: Cement, in: Minerals Yearbook (various years), edited by: USGS, United States Geological Survey, available at: https://minerals.usgs.gov/minerals/pubs/commodity/cement/index.html (last access: 12 January 2018), 1994–2012.

van Oss, H. G.: Cement, in: 2014 Minerals Yearbook, edited by: USGS, United States Geological Survey, available at: https://minerals.usgs.gov/minerals/pubs/commodity/cement/index.html (last access: 12 January 2018), 2017.

WBCSD: The Cement Sustainability Initiative: cement industry energy and CO_2 performance – "getting the numbers right", World Business Council for Sustainable Development, available at: http://www.wbcsdcement.org/ (last access: 30 April 2015), 2009.

WBCSD: Getting the Numbers Right Project: reporting CO_2, World Business Council for Sustainable Development, available at: http://www.wbcsdcement.org/GNR-2012/index.html (last access: 29 March 2017), 2012.

WBCSD: Getting the Numbers Right Project: reporting CO_2, World Business Council for Sustainable Development, available at: http://www.wbcsdcement.org/GNR-2014/index.html (last access: 29 March 2017), 2014.

WBCSD and IEA: Technology Roadmap: Low-Carbon Technology for the Indian Cement Industry, World Business Council for Sustainable Develop-

ment and International Energy Agency, available at: https://www.iea.org/publications/freepublications/publication/ technology-roadmap-low-carbon-for-the-indian-cement- industry- - -foldout.html (last access: 23 March 2017), 2013.

Xu, J.-H., Fleiter, T., Eichhammer, W., and Fan, Y.: Energy consumption and CO_2 emissions in China's cement industry: a perspective from LMDI decomposition analysis, Energ. Policy, 50, 821–832, https://doi.org/10.1016/j.enpol.2012.08.038, 2012.

Zhang, S., Worrell, E., and Crijns-Graus, W.: Evaluating co-benefits of energy efficiency and air pollution abatement in China's cement industry, Appl. Energ., 147, 192–213, https://doi.org/10.1016/j.apenergy.2015.02.081, 2015.