MONTREAL PROTOCOL

ON SUBSTANCES THAT DEPLETE

THE OZONE LAYER

UNEP

Technology and Economic Assessment Panel

TASK FORCE ON EMISSIONS DISCREPANCIES REPORT

October 2006

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Co-ordination:	**TEAP and its TFED Task Force**
Composition:	Lambert Kuijpers
Reproduction:	UNON Nairobi
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The opinions expressed are those of the Panel and its Task Forces and do not necessarily reflect the reviews of any sponsoring or supporting organisation.

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1 Introduction

1.1 Remit

Following a discussion on the TEAP Supplementary Report on at the Seventeenth Meeting of the Parties to the Montreal Protocol (Dakar, Senegal, 10-14 December 2005), the following Decision XVII/19 was adopted:

> *Decision XVII/19: Consideration of the Technology and Economic Assessment Panel and Intergovernmental Panel on Climate Change assessment report as it relates to actions to address ozone depletion*
>
> *Noting* with appreciation the special report of the Technology and Economic Assessment Panel and Intergovernmental Panel on Climate Change, "Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons" and the Technology and Economic Assessment Panel's supplementary report that sets out clearly the ozone depletion implications of the issues raised in the special report,
>
> *Noting* the supplementary report's conclusion that mitigation strategies on banks of ozone-depleting substances will have limited impact on ozone layer recovery,
>
> *Acknowledging* the need for Parties to have a full understanding of the policy implications for ozone layer protection of forecast emissions from banks of ozone-depleting substances in both global and regional terms,
>
> *Recalling* the report of the sixth meeting of Ozone Research Managers which reported that activities under the "mitigation scenario" presented in the special report provide an opportunity to protect the ozone layer further and to reduce greenhouse gases significantly,
>
> *Acknowledging* that the upcoming 2006 Scientific Assessment Report will cover in more detail some issues raised in the report of the Intergovernmental Panel on Climate Change and the Technology and Economic Assessment Panel, such as the discrepancy between atmospheric concentrations of ozone-depleting substances and emissions reported,
>
> 1. To request the Ozone Secretariat to organize an experts workshop in the margins of the twenty-sixth meeting of the Open-ended Working Group in 2006, to consider issues as described in paragraph 3 of the present decision, arising from the special report of the Intergovernmental Panel on Climate Change and the Technology and Economic Assessment Panel and the Technology and Economic Assessment Panel's supplementary report;
>
> 2. To request Parties to provide nominations for experts to participate in the workshop to the Ozone Secretariat by 30 March 2006, aiming for a balanced representation from regional groups;

3. To request that the TEAP present a summary of the reports at the workshop and that experts then produce a list of practical measures relating to ozone depletion that arise from the reports, indicating their associated ozone-depleting substances cost effectiveness, and taking into account full costs of such measures. The list should also contain information on other environmental benefits, including those relating to climate change that would result from these measures;

4. To request the Ozone Secretariat to produce a report of the workshop to the Parties by 1 September 2006 and report to the Eighteenth Meeting of the Parties;

5. To request the Ozone Secretariat to inform the Secretariat of the United Nations Framework Convention on Climate Change of the workshop and invite its representatives to attend as observers and report back to the United Nations Framework Convention on Climate Change;;

6. To request the Technology and Economic Assessment Panel to coordinate with the World Meteorological Organization and the Scientific Assessment Panel to clarify the source of the discrepancy between emissions determined from bottom-up methods and from atmospheric measurement, with a view to:

- *(a) Identifying the use patterns for the total production forecast for the period 2002-2015 in both non-Article 5 Parties and Article 5 Parties;*
- *(b) Making improved estimates of future emissions from banks including refrigeration, foams, and other sectors, given the accuracy of calculations of the size of banks and the emissions derived from them, as well as servicing practices, and issues relating to recovery and recycling and end-of-life;*

7. To request the Technology and Economic Assessment Panel to report back to the Parties at their Eighteenth Meeting on the activities relating to paragraph 6.

1.2 Task Force

Following the MOP-17, the TEAP responded to the Decision by making presentations at the Workshop, which was held back to back with the 26th OEWG, on 7 July 2006, and assisting the Ozone Secretariat in the conducting of the Workshop. The report of the Workshop can be found on the Ozone Secretariat’s website.

However, the request in paragraph 6 is a separate one, which has virtually no relation to the proceedings of the Workshop.

The TEAP therefore established a Task Force on Emissions Discrepancies, to be co-chaired by Paul Ashford, Lambert Kuijpers and Stephen A. Montzka, consisting of:

- ☐ Paul Ashford (UK, member TEAP, co-chair FTOC);
- ☐ Nick Campbell (UK, member MTOC);
- ☐ Denis Clodic (France, member RTOC);
- ☐ John S. Daniel (USA, CLA Science Assessment Panel);
- ☐ Lambert Kuijpers (The Netherlands, co-chair TEAP, co-chair RTOC);
- ☐ Pauline Midgley (Germany, University Stuttgart);
- ☐ Stephen A. Montzka (USA, Co-author Science Assessment Panel);
- ☐ Ian D. Rae (Australia, member TEAP. Co-chair CTOC);
- ☐ Guus Velders (The Netherlands, CLA SAP); and
- ☐ Dan Verdonik (USA, member TEAP, co-chair HTOC).

Originally it was envisaged to investigate discrepancies in emissions for various CFCs, HCFCs, CTC and halons. The time schedule for the completion of the report did not allow the Task Force to fully study the datasets for CTC and halons. The emissions analysed therefore are those of the chemicals CFC-11 and -12, HCFC-22, -141b and -142b.

Drafts were produced by the co-chairs and circulated amongst them via email. A final thorough review of the report was carried out by the TFED Task Force in September 2006. After this review, this report was considered and subsequently adopted by consensus of the UNEP Technology and Economic Assessment Panel (TEAP) as established under the Montreal Protocol; this took place during the beginning of October 2006.

1.3 The Structure of the Report

The structure of this Task Force Report is as given below.

Chapter 1, “Introduction”, presents the remit, the setting up of the Task Force and the process followed in preparing this report. It also describes the issue, as well as which chemicals are considered in this report.

Chapter 2, “Summary of published material” presents a summary of what was presented in the IPCC/TEAP Special Report on Ozone and Climate and in the TEAP Supplementary Report. It also deals briefly with the approach selected in the 2006 Ozone Assessment and refers to conclusions as presented in the Executive Summary of that report, published August 2006.

Chapter 3, “Production and consumption data of chemicals”, presents UNEP Article 7 data for production and consumption of five separate chemicals and presents a comparison between the production and the consumption values. It gives aggregated data of these chemicals for non-Article 5 and Article 5 countries reporting. It compares, wherever possible, the AFEAS reported production data with the data reported to UNEP on production under Article 7.

Chapter 4 gives general considerations on bottom-up methods, their potential and sources of uncertainty; this for both refrigeration (AC) and foams. It deals with release functions from banks and looks at emissive uses other than emissions from banks. Most of these considerations are of a qualitative nature.

Chapter 5 gives tabular data on the development of the banks and emissions for foams and refrigeration. Demand, banks and emissions are considered for the world-total, and for both the non-Article 5 and the Article 5 countries. This also provides insight on the percentage release from banks in these two different regions of the world, where banks (and emissions) may be completely different in composition. Chapter 5 also looks at emissive uses of the chemicals studied and compares estimates for these with the emissions from banks of foams and refrigeration. It considers uncertainties in these values and elaborates on the limitations of the method applied.

Chapter 6, "Global emissions derived from atmospheric measurements", describes in detail methods for deriving global emission magnitudes from atmospheric measurements. Uncertainties associated with measurement calibration, the halocarbon lifetime, calculation method, and other factors are considered along with atmospheric measurements from 2 to 3 independent groups to derive global emissions and their uncertainties.

Chapter 7, "Comparison of emissions derived from bottom-up methods and from measured atmospheric concentrations", makes comparisons of the data derived from bottom-up (Chapter 5) and top-down (Chapter 6) approaches, considering the new information available from UNEP at substance level on production, consumption, release functions, and revised uncertainties associated with emissions derived from atmospheric measurements. The comparisons also take into consideration the new estimates proposed on bottom-up uncertainties in Chapter 4.

Chapter 8 presents concluding remarks and summarises the issues that may require further study.

2 Summary of published material and material in preparation on discrepancies in emissions

2.1 SROC and TEAP Supplement Report

2.1.1 Special Report: Analysis of the potential reasons for discrepancies

Annex 11B in the IPCC/TEAP Special Report (IPCC TEAP, 2005) mentions a number of aspects, which are important when considering the discrepancies issue:

1. Emission functions for refrigeration equipment and foams have been assessed over several years. These vary significantly according to the application and good market analysis is required to ensure the use of appropriately weighted emission factors. The differences between consumption and forecast emissions using these functions are assigned to banks, which accrue and diminish with time. Verification of the physical existence of these banks has largely served to confirm the appropriateness of the emission functions adopted, although year-to-year emission projections can have significant error bars for banks that release slowly (e.g. foams), particularly where emission projections are largely based on end-of-life practices. These year-to-year errors tend to be offset with time, making the level of confidence greater over a multiyear period[1].

2. Observations of concentrations of long-lived species in the atmosphere can be used to estimate past emissions. If the lifetime of the chemical is long enough and the rate of mixing is sufficient to ensure a more or less homogeneous concentration in the whole lower troposphere, then past emissions can be derived by simple inverse modelling using the change in observed concentration and the lifetime of the species (details regarding this calculation and uncertainties associated with it appear in Chapter 6.)

3. Measurements of long-lived species are performed frequently and with high accuracy in several measurement networks. The uncertainty in derived emissions depends on the uncertainty in the trend in observed concentration and on the uncertainty in the lifetime. Both are relatively small for most species. Using different measurement networks may also yield different emissions and therefore information about the uncertainty. On this basis, the uncertainty in derived emissions is about 10% for CFC-11 and between 1% and 6% for other long-lived halocarbons (much of Chapter 6 concerns itself with refining our estimates of these uncertainties).

4. The determination of emissions via the bottom-up method has revealed substantial discrepancies with the emissions calculated from atmospheric measurements of the same chemicals. However, closer analysis of these discrepancies has found that even relatively small levels of consumption of fluorocarbons in rapidly emitting uses in developing countries, for example, can dominate emissions for specific chemicals (e.g. CFC-11) in specific years. This implies that there is a need to investigate consumption data, from countries as submitted to UNEP under the Montreal Protocol

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[1] For instance, it is difficult to assess with any accuracy the number of domestic refrigerators that will be decommissioned in a given year, but it is much easier to assess the number that will be decommissioned in a ten-year period based on the knowledge of the age profile of the global stock.

(following Article 7 on data reporting), in order to determine where such emissions might appear. However, the key weakness in the UNEP data set is that it makes no provision for the recording of use patterns. Nonetheless, the quantification of the gap between UNEP production/consumption data and the producer (AFEAS) data also remains valuable in identifying possible sources of discrepancy.

5. The companies surveyed by AFEAS include subsidiaries and joint ventures in all developed and several developing countries. Certain production in developing countries, for example in China, India and the Republic of Korea, is not included in the survey. The data collected by AFEAS for 2002 are thought (by comparison with the UNEP totals for production) to cover about 30-35% of global CFC production. Global coverage is much greater in the AFEAS survey for the HCFCs and HFCs. The AFEAS data currently cover 73% of all non-feedstock HCFC production, and are thought to represent at least 97% of global HFC production (AFEAS, 2004) (Chapter 3 in this report will present a more extensive analysis).

6. Estimates of atmospheric concentrations based on production and consumption statistics provided by manufacturers and national governments were, when coupled with historical emission factors, a good match with observations until recently. This was largely because of the dominance of rapid-release applications in developed countries. However, as these rapid-release applications have declined, the detailed assessment of delayed-release applications has become more important in developed countries. In addition, the gap between UNEP data and AFEAS data has increased, reflecting higher levels of activity in developing countries. As a result, the lack of use pattern data via the UNEP reporting structure is now a key impediment, particularly where usage might be occurring in rapid-release applications within Article 5 regions.

7. It could be possible that actual emissions are significantly larger than calculated via the bottom-up method for refrigeration and foams only because of additional contributions from rapid-release applications. In periods when other sources of emission are low (e.g. during the use-phase of foams), the sensitivity to rapid release applications is high.

8. In addition, the emission factors initially applied to HCFCs and HFCs were derived from those developed earlier for CFCs and HCFC-22. This may have been inappropriate in cases where there have been considerable changes in use-practices in the wake of the Montreal Protocol and, accordingly, emission factors remain subject to continual review. Revised emission factors (as described by McCulloch *et al.* (2001 and 2003)), have helped improve the situation and have been used in the most recent calculation of emissions (AFEAS, 2004). Nonetheless, there is a view that variation and uncertainties in emission factors per se are likely to be less significant overall than uncertainties in overall use pattern distributions between rapid-release applications and the delayed-release applications represented by refrigeration and foams.

9. Further study will be needed to make more precise estimates of future emissions from banks in refrigeration and foams, given the accuracy of calculations of the size of the banks and the emissions derived from them, as well as servicing practices, and issues relating to recovery and recycling and end-of-life.

2.1.2 The Supplementary Report: Discrepancies between emissions determined from bottom-up methods and from atmospheric measurements.

The TEAP Supplementary Report (TEAP, 2005) also mentions a number of aspects, which are important when considering the discrepancies issue:

1. The AFEAS data originate from the major producers of ODSs and their alternatives and has the advantage of being split by substance and sales pattern by sector. However, one drawback is that it is only declared by ‘hemisphere’ to avoid disclosure of confidential business information. An important observation on the AFEAS data-set is that the process for the allocation of sales to sectors has never been made fully transparent. For example, it is not clear as to what percentage of sales were to distributors and may have ended up in applications other than those anticipated.

2. UNEP’s data collection efforts on the other hand are reported directly by Parties and this has provided production, consumption, import and export data at country level. However, there has been no effort during the collection of this data series to assess sales patterns by sector. In earlier years, where discrepancies between AFEAS and UNEP data were relatively minor, this was of less importance to modellers. However, as the coverage of the AFEAS data-set has become less comprehensive, and the discrepancies between UNEP and AFEAS data-sets has become larger, the knowledge of sectoral end-use pattern has become less complete.

3. In the end, the sectoral modeller builds a model based only on the consumption, which can be positively assigned to the sector in question. This then has to be combined with outputs from modellers addressing other sectors to assemble a bottom-up, globally complete picture of consumption, which can be compared with the global UNEP data-set. It is still usual that the bottom-up approach falls short of the UNEP total, possibly because not all actual use sectors are covered in any bottom-up approach. However, it is typical to see greater than 80% of historic and current annual consumption covered by these methods.

4. The consumption patterns put together within bottom-up models probably represent the most complete sectoral analysis available. This baseline is essential for adequate emissions assessment since the lifecycle emission profiles vary so substantially. However, the lack of full sectoral coverage continues to make the assessments incomplete. In the (IPCC TEAP, 2005) report, the coverage was further limited by the scope of focusing on those sectors, which have selected substitutes containing HFCs and/or PFCs. These factors are important when considering the overall evaluation of consumption and emissions from a bottom-up perspective in that report.

5. It should be noted that the shortcomings pointed out under paragraphs 3 and 4 are related to the overall coverage of *combined* bottom-up methods and indeed the limitations of the scope of the (IPCC TEAP, 2005) report. Nothing therein particularly points to failures in bottom-up consumption data collection within a given sector. However, for the first time, in this report, the authors have had the opportunity to compare the bottom-up data by sector and chemical with the UNEP data **by chemical**. This has enabled the derivation of the ‘balance’ for each chemical which is as yet unassigned and likely to be emissive in character.

6. It can be seen that the consumption of ODS, which has taken place in sectors likely to develop banks has been well studied but continues to be an area where global understanding can be improved. However, before this dataset can be translated into a meaningful assessment of emissions, there is a need to apply appropriate emission factors to the data. Since emissions vary through the lifecycle of an application, there is also a need to keep a disciplined record of the time series of consumption rather than just the cumulative value of historic consumption at any given time. In other words, it is not just sufficient to know 'how much is in the bank'. It is also necessary to know 'when it entered the bank and when it is likely to leave'.

7. An additional complicating factor is that specific applications within a sector can have very different emissions profiles. This means that consumption needs to be known at sub-sectoral level in order for the appropriate emission factors to be applied. This fact brings with it two potential sources of further uncertainty. The first relates to the access to historical time-series of consumption at sub-sectoral (application) level. This further highlights the importance of genuinely bottom-up methods, which are generally better at characterising sub-sectoral definition. The second potential source is the statistical variation, which will always occur in practice around an average lifecycle characterisation. Most bottom-up models have point assumptions for matters such as the lifetime of a product or piece of equipment. Therefore, the retirement date of a piece of equipment is fixed by its year of manufacture. In reality, of course, some equipment will be retired earlier and some later.

2.2 Ozone Assessment 2006

A selection of paragraphs from the Executive Summary of the Ozone Assessment 2006 is given here (relevant to this report), which mention the following:

- The tropospheric abundance of hydrochlorofluorocarbons (HCFC-22, -141b and -142b) increased much less than projected in the previous (2002) Assessment. The implication is that the emissions have been lower than anticipated.

- Total organic tropospheric bromine from halons and methyl bromide peaked in about 1998 at 16.5 to 17 ppt and has since declined by 0.6-0.9 ppt (3-5%). This observed decrease was solely a result of the observed decline in methyl bromide. Bromine from halons continues to increase, but at slower rates in recent years (0.1 ppt Br/year in 2003-2004).

- Global emissions of CFC-11 (88 Gg/year, where 1 Gg=10^9 grams), CFC-12 (114 Gg/yr) and CFC-113 (6 Gg/yr) in 2003 were approximately 25%, 25% and 3% of their maximum values around 1986. Emissions of CFC-11, CFC-12 and CFC-113 have all continued to decrease since 2000.

- While emissions of HCFC-22 have remained nearly constant from 2000 to 2004, emissions of HCFC-141b and HCFC-142b decreased by approximately 15% over the same period.

- Long-term recovery of the ozone layer from the effects of ozone-depleting substances is expected to span much of the 21st century and is estimated to occur later than projected in the previous assessment (2002). An important milestone in the recovery process is the time when combined chlorine and bromine amounts (equivalent effective stratospheric chlorine, EESC) decline to pre-1980 values.

  - The date when equivalent effective stratospheric chlorine at mid-latitudes returns to pre-1980 levels is now calculated to be 2049, for the case of global compliance with the Montreal Protocol with no significant exceptions (Scenario A1). This date is about 5 years later than projected in the previous (2002) assessment. This projected later date primarily results from (i) an increase in CFC-11 and CFC-12 emissions due to the larger recent estimates of amounts currently contained in equipment and products (banks) and (ii) an increase in HCFC-22 emissions due to larger estimated future production, as reported in the 2005 Intergovernmental Panel on Climate Change/Technology and Economic Assessment Panel (IPCC/TEAP) Special Report on *Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons*.
  - The return to pre-1980 conditions of equivalent effective stratospheric chlorine for the Antarctic vortex is projected to occur around 2065, more than 15 years later than the return of mid-latitude equivalent effective stratospheric chlorine to pre-1980 levels. This projected later recovery is because, unlike in previous Assessments, we now recognise that the age of air is greater in the Antarctic lower stratosphere, which affects the amount of ozone-depleting gases available for ozone depletion. The equivalent effective stratospheric chlorine evaluation for the Antarctic vortex has not been presented in previous Ozone Assessments.

- Potential options for accelerating the recovery of the ozone layer have been evaluated. The table provided below shows hypothetical estimates of the *upper limits* of improvements that could be achieved if global anthropogenic *production* of ozone-depleting substances were to stop after 2006, if emissions were eliminated from existing banks at the end of 2006, or if global anthropogenic *emissions* of ozone-depleting substances were to stop after 2006. Some options show greater effectiveness for accelerating recovery of the ozone layer than in previous Assessments, for reasons noted below.

Table 2-1 *Percentage reductions in integrated equivalent effective stratospheric chlorine relative to the baseline (A1) scenario that can be achieved in the hypothetical cases.*

Compound or Compound Group	**Column A:** **All Emissions Eliminated from Production after 2006**	**Column B:** **All Emissions Eliminated from Existing Banks at End of 2006**	**Column C:** **All Emissions Eliminated after 2006**
Chlorofluorocarbons (CFCs)	0.3	11	11
Halons	0.5	14	14
Carbon tetrachloride (CCl_4)	3	(a)	3
Methyl chloroform (CH_3CCl_3)	0.2	(a)	0.2
Hydrochlorofluorocarbons (HCFCs)	12	4	16
Methyl bromide (CH_3Br) (anthropogenic)	5	(a)	5

(a) For these compounds, banks are uncertain and therefore emissions are equated to production in these calculations.

- The percentage cumulative (integrated) reductions in equivalent effective stratospheric chlorine for halons and CFCs, integrated from 2007 until the 1980 level is re-established (shown in Column B), are larger than previously reported. This is because recent bank estimates from the 2005 Intergovernmental Panel on Climate Change/Technology and Economic Assessment Panel (IPCC/TEAP) Special Report on *Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons* are significantly larger and likely more reliable than values presented in previous Assessments for CFC-11, CFC-12, and Halon-1211.
- The percentage reduction in integrated equivalent effective stratospheric chlorine for HCFCs shown in Column A is larger than previously reported. This is because of significantly larger estimates of future HCFC-22 production in Article 5 countries.
- The percentage reduction in integrated equivalent effective stratospheric chlorine for methyl bromide in Column A is larger than previously reported. This is because of the upward revision of the fraction of anthropogenic emissions relative to total methyl bromide emissions, as well as being due to the upward revision in the ozone-depletion effectiveness of bromine atoms compared with chlorine atoms mentioned earlier.
- In addition to the percentage reductions in integrated equivalent effective stratospheric chlorine, these scenarios can reduce the time for equivalent effective stratospheric chlorine to drop below 1980 values. A hypothetical elimination of all emissions of ozone-depleting substances after 2006 (Column C) would advance this time by about 15 years, from 2049 to 2034. A hypothetical elimination of all emissions from production of ozone-depleting substances after 2006 (Column A) would advance it by about 6 years, to 2043.

2.3 Other Sources

Important information relevant to the resolution of discrepancies is included in a paper that has been accepted but not yet published. The title of the paper is "Present and Future Sources and Emissions of Halocarbons: Towards New Constraints", by J. Daniel *et al.* (Daniel, 2006). A number of statements taken from this paper:

1. The bank at any particular time is equal to the difference between the total cumulative historical production and the total cumulative historical emission. Such a method, often referred to as one type of "top-down" approach, works well when global production and emissions estimates are accurate. However, the bank magnitudes calculated in this manner often represent small differences between two large numbers (cumulative production and emission) so that relatively small systematic reporting errors, or errors in atmospheric lifetimes, can lead to a large cumulative bank size error over a period of many years, which in turn can lead to large errors in future projections of emissions.

2. The bottom-up method is characterised by other, important uncertainties in, for example, knowledge of the amount of equipment or product in use, the rate of release of chemicals during use, end-of-life recovery, and even the lifetime of the equipment or product (IPCC TEAP, 2005). Notwithstanding these uncertainties, the availability of bottom-up estimates is useful as they provide additional, independent information with which the estimated sizes of the ODS banks from the top-down analyses can be evaluated.

3. If the CFC-11 lifetime were 10% larger, for example, the bank for the WMO case would increase by about 250 kt, and if the ratio of surface mixing ratio to the atmospheric average were assumed to be 1.10 in our box model, the 2002 bank would be about 140 kt larger due to the smaller annual emissions needed for consistency with atmospheric mixing ratio observations. Bank size increases for CFC-12 in 2002 resulting from a similar fractional change in the lifetime or in the surface mixing ratio factor are 190 kt and 200 kt, respectively. Increases to the bank sizes due to these uncertainties could explain some, but likely not all, of the discrepancy between the top-down and the bottom-up bank size estimates. The Special Report (IPCC TEAP, 2005) has also demonstrated that trend differences among the various observing networks can lead to emission differences. These emission uncertainties are likely to be smaller than those due to a 10% lifetime uncertainty, but they can still affect top-down bank estimates.

4. Errors in estimated production can also lead to inaccurate bank calculations. We mentioned earlier that the CFC ODP-weighted production from 1989 through 1999 according to AFEAS was about 2% smaller than that reported to UNEP. If all historic CFC-11 and -12 production were 2% underestimated through 1999, the cumulative effect would lead to underestimates of the CFC-11 and CFC-12 top-down banks of 190 kt and 260 kt, respectively. The importance of a seemingly small systematic error in production quantities illustrates the potential difficulties involved in estimating the bank size with the top-down method when the bank is relatively small compared to total historic production. Errors such as those discussed could also affect the bottom-up bank estimates in the Special Report (IPCC TEAP, 2005).

However, the importance of the bottom-up uncertainties and the implications of these uncertainties to bank estimates have not been assessed to date.

5. Knowledge of the future evolution of chlorine- and bromine-containing source gas mixing ratios is necessary to making accurate predictions of future stratospheric ozone. Over the past decades, the primary uses of ozone depleting substances (ODSs) have transitioned from rapidly emissive uses such as aerosol propellants to contained uses such as refrigeration and foams, in which release of the ODS represents a failure of the product, inadequate service practices, or release upon end of life. This has increased the importance of knowledge of the ODS bank sizes to an understanding of future source gas evolution. Recent bottom-up and top-down estimates have demonstrated that many questions remain regarding the sizes of the banks for several ODSs and that uncertainties currently remain large.

6. The larger sizes of the CFC banks in the IPCC/TEAP report compared to earlier estimates in Science Assessment Panel Reports (e.g., 2003) of the banks have the potential to lead to much larger importance of the CFC banks for future ozone destruction. If the banks are released immediately, a case chosen to provide an upper limit on the bank importance, the (IPCC TEAP, 2005) banks lead to a greater than 16% increase in a future integrated EESC compared to the banks used in the 2003 Science Assessment. Although this immediate release assumption is unrealistic, this result illustrates the potential importance of the bank sizes to future ozone depletion. The rate of release from the bank is very important, with a slower release counteracting, sometimes substantially, the larger bank sizes. Hence, accurate future estimates of ozone depletion and analyses of strategies proposed to reduce future ozone depletion require good knowledge of both the bank sizes and the future bank emission rates. Until the differences between top-down and bottom-up bank estimates are better reconciled, important uncertainty must be attached to an evaluation of the effectiveness of the capture and destruction of existing CFC-11 and -12 banks.

The large number of comments given above illustrate the need for further analysis of production and demand data, emissions functions, and the reconciliation of emissions calculated from a bottom-up method with the emissions derived from atmospheric measurements.

3 Production and consumption data of chemicals; analysis and uncertainties

3.1 Source of the data

Reported country-level production and consumption data for the chemicals CFC-11 and -12, HCFC-22, -141b and -142b have been obtained from UNEP's Ozone Secretariat, and can be published for the purpose of this report in aggregated form for both the non-Article 5 and the Article 5 countries. Both types of data are studied below and the relationship between them is analysed; thereafter a selection is made which data to use in this report for the study of the discrepancies in emissions.

3.1.1 Production data

In Table 3-1 the production data are given as submitted to UNEP (Article 7 reporting), where data gaps for certain years and countries have been filled in, by extrapolating or interpolating known data. This gives a more complete picture. It is of minor importance for the CFC chemicals considered, but is of more significance for the HCFCs where reporting in the period 1990-2002 was not very complete (HCFCs were not covered by the Montreal Protocol until 1992, when relevant decisions on HCFCs were taken in Copenhagen, at MOP-4).

The tabulated data may be interpreted in the following way. Until the year 1995, the majority of the quantities of CFC-11 and -12 had been produced in the non-Article 5 countries. The amounts produced in the developing countries are now larger than the amounts produced in the developed countries but did not exceed about 46,000 tons of CFC-11 and about 60,000 tons of CFC-12 at their peak in 1997. The global amounts produced decrease to about 20,000 tons of CFC-11 and about 40,000 tons of CFC-12 in the year 2004, when about 6-8% of this total was produced for (medical) essential uses.

In non-Article 5 countries, the global production of HCFC-22 reached a peak in 1995 (about 300,000 tons), which was about 90% of the total annual amount produced in that year. The production decreased thereafter in the non-Article 5 countries (to 140,000 tons in these countries in 2004) and increased rapidly in the Article 5 countries during the period 1998-2004. About two thirds of the total (370,000 tons) was produced in Article 5 countries as of 2004.

The production of HCFC-141b increased rapidly between 1991 and 1999 in the non-Article 5 countries, when it reached a peak, followed by a fast decrease (from more than 130,000 tons in 1999 to about 35,000 tons in 2004). Production of HCFC-141b started in the Article 5 countries in 1994-95, and exceeded the amount produced in the non-Article 5 countries by 2004 (55% of the total of about 78,000 tons).

Table 3-1 Production values as reported to UNEP under Article 7 by non-Article 5 and Article 5 countries for the period 1989-2004

		SubstName	MT 1986	MT 1989	MT 1990	MT 1991	MT 1992	MT 1993	MT 1994	MT 1995	MT 1996	MT 1997	MT 1998	MT 1999	MT 2000	MT 2001	MT 2002	MT 2003	MT 2004	Total 1989-2004	Total 1989-2003
Subtotal	nA5	CFC-11	373848	333128	242273	221751	193689	143938	60301	30341	16341	16161	12109	14457	14934	7346	7028	3241	2307	1319343	1317036
Subtotal	A5	CFC-11	18610	20872	21590	21840	24354	31432	39654	42252	39488	46312	42160	39529	29027	24819	24786	22124	19970	490209	470239
TOTAL		CFC-11	392458	354000	263863	243592	218043	175370	99955	72593	55828	62473	54269	53986	43961	32165	31814	25365	22277	1809552	1787275
Subtotal	nA5	CFC-12	442019	430440	294138	247115	227004	218787	142682	88307	31339	30352	32738	33152	35116	18256	18590	12904	7170	1868091	1860921
Subtotal	A5	CFC-12	39338	46902	46677	50305	45869	56228	69463	68298	58293	59610	55221	54273	48207	47258	40107	41745	40707	829162	788455
TOTAL		CFC-12	481357	477342	340815	297420	272873	275015	212145	156604	89633	89962	87959	87425	83323	65513	58696	54649	47877	2697253	2649376
Subtotal	nA5	HCFC-22	0	216168	209195	215108	173081	242409	220202	295690	236876	234532	257229	237046	225143	202219	182636	163804	141552	3452888	3311336
Subtotal	A5	HCFC-22	0	24894	21537	21132	22571	32918	42140	32516	36840	43899	32029	84536	116606	126498	140732	171443	229326	1179617	950291
TOTAL		HCFC-22	0	241062	230732	236240	195652	275327	262342	328206	273716	278431	289258	321582	341749	328717	323368	335247	370878	4632505	4261627
Subtotal	nA5	HCFC-141b	0	1007	5700	5000	16982	27827	84984	111319	104994	109120	126911	132667	128385	117531	123931	55465	35064	1186886	1151822
Subtotal	A5	HCFC-141b	0	0	0	0	0	0	470	1842	3299	5112	6850	11605	11975	13360	24697	35454	42618	157282	114664
TOTAL		HCFC-141b	0	1007	5700	5000	16982	27827	85454	113161	108293	114232	133761	144272	140360	130891	148628	90919	77682	1344168	1266486
Subtotal	nA5	HCFC-142b	0	16191	7645	11485	33306	19119	41417	44642	35276	41269	39741	39767	39697	33444	24489	27300	34196	488984	454788
Subtotal	A5	HCFC-142b	0	0	0	0	0	0	118	220	346	470	548	785	577	502	2387	4080	3854	13887	10033
TOTAL		HCFC-142b	0	16191	7645	11485	33306	19119	41535	44862	35622	41739	40289	40552	40274	33946	26876	31380	38050	502871	464821

The majority of HCFC-142b has been produced in the non-Article 5 countries at a level between 25,000 and 45,000 tons throughout the period 1994-2004. The Article 5 country production has increased more recently (2002-2004), but was still only at about 10% of the global total in 2004.

Since 1976, the chemical industry has voluntarily reported the production and sales of fluorocarbons through a survey compiled by an independent accountant. The main purpose of the survey is to provide the scientific community with data estimating the atmospheric release of CFCs and their alternatives. The production as reported by a number of companies is reported in annual surveys by the Alternative Fluorocarbon Environmental Acceptability Study (AFEAS). It is therefore also possible to look at the AFEAS reported production values. However, AFEAS does not report the production in the Russian Federation, and also does not report the majority of the developing country production (China, India, the Republic of Korea etc.). This implies that a study of the AFEAS data could be used to cross-check the order of magnitude of the (UNEP reported) production data by the non-Article 5 countries provided that the production activity in the Russian Federation is known from other sources (UNEP includes the Russian Federation in its non-Article 5 classification). However, because of increased production in Article 5 countries, a comparison of the AFEAS data with the total (UNEP reported) production data becomes meaningless as of the late 1990's for many chemicals. In fact, the "discrepancy" increases with every proceeding year for most of the CFCs and HCFCs produced.

Table 3-2 Comparison of production of CFC-11, -12 and HCFC-22 reported to UNEP (Article 7) and to AFEAS (ktons)

Year	**CFC-11**		**CFC-12**		**HCFC-22**	
	Total UNEP	AFEAS	Total UNEP	AFEAS	Total UNEP	AFEAS
1989	354.00	302.49	477.34	379.79	241.06	219.54
1990	263.86	232.92	340.82	230.95	230.73	213.71
1991	243.59	213.49	297.42	224.81	236.24	236.81
1992	218.04	186.43	272.87	216.21	195.65	245.72
1993	175.37	147.13	275.02	214.66	275.33	240.62
1994	99.96	60.23	212.15	133.60	262.34	239.44
1995	72.59	32.68	156.60	82.82	328.21	243.47
1996	55.82	22.12	89.63	48.86	273.72	267.52
1997	62.47	18.58	89.96	32.90	278.43	246.94
1998	54.27	14.60	87.96	33.27	289.26	271.98
1999	53.99	12.87	87.43	27.13	321.58	248.55
2000	43.96	9.90	83.32	24.56	341.75	239.20
2001	32.17	8.31	65.51	20.87	328.72	213.33
2002	31.81	6.80	58.70	20.18	323.37	193.96
2003	25.37	3.15	54.65	12.54	335.25	187.26
Total	1787.28	1271.69	2649.38	1703.15	4261.63	3508.04

The coverage of CFC-11 by AFEAS is higher than 80% compared to the UNEP data for the period 1989-1993, then decreases to around 50% for the years 1994-96, and reaches a low of 12% in the year 2003.
For the total period 1989-2003, AFEAS covers 71.0% of the UNEP production data. In fact, this is not enough for further comparisons with demand from the bottom-up calculations, and is the reason why AFEAS data have not been further evaluated for CFC-11 assessment in this study.

The coverage of CFC-12 by AFEAS is higher than 75% compared to the UNEP data for the period 1989-1993, then decreases to around 50% for the years 1994-96, remains in the order of 30% for the period 1997-2002 and reaches a low of 23% in the year 2003. For the total period 1989-2003, AFEAS covers 64.3% of the UNEP production data. In fact, this is not enough for further comparisons with demand from the bottom-up calculations, and is the reason why AFEAS data have not been further evaluated for CFC-12 assessment in this study.

The coverage of HCFC-22 by AFEAS is higher than 90% compared to the UNEP data for the period 1989-1998 (with an exception for the year 1995, and an unexplainable higher AFEAS value for the year 1992, most likely due to underreporting of production by an important producer country). It then decreases to around 70% for the years 1999-2001, and reaches a low of 56% in the year 2003. For the total period 1989-2003, AFEAS covers 82.3% of the UNEP production data. In fact, this is still reasonable for a comparison with the demand from the bottom-up calculations. However, for the purposes of consistency with the treatment of chemicals CFC-11 and -12, AFEAS data have not been further evaluated for HCFC-22 assessment within this study.

The coverage of HCFC-141b (although not presented in Table 3-2) by AFEAS is good, and covers almost all production until the year 2001. Indeed, during the period 1995-1997 AFEAS data was greater than UNEP data. The percentage of the UNEP production reported by AFEAS amounts to 78% for the year 2002, and 82% for the year 2003. However, again, for consistency, the UNEP data has been the preferred basis for further analysis.

Since almost all HCFC-142b is being produced by developed country producers that report to AFEAS, the AFEAS coverage compared to UNEP is excellent (1989-2003: UNEP 464.82 ktons, AFEAS 469.75 ktons). This implies that the UNEP and AFEAS data are consistent, and either one of them could be used in this report. Nonetheless, for consistency reasons, the UNEP production data have been taken for further comparisons.

3.1.2 AFEAS use sectors

Despite the preference for UNEP production data, it is useful to look at the end-use categories that AFEAS utilises for the different chemicals for the period 1989-2003. This information has been useful historically for bottom-up methods when analysing the demand and comparing it, with UNEP production and consumption data (see chapter 5).

In the tables below, the percentage use in certain end-use categories is given (for refrigeration and AC, foams, and aerosols and all other uses) as well as the total sales (production figure) as presented by AFEAS (see website www.afeas.org). The total AFEAS figure is also expressed as a percentage of the UNEP reported production for the years 1989-2003.

Table 3-3 CFC-11 sales by end-use category (AFEAS, percentage of the total), total sales (AFEAS) and comparison with UNEP reported production data (%)

Year	Refrigeration and Air Conditioning	All Foams	Aerosol and all other uses	Total sales (tons)	Total sales vs UNEP (%)
1989	8.9	71.3	19.8	302,489	85.5
1990	8.7	78.7	12.6	232,916	88.3
1991	9.4	82.3	8.4	213,486	87.6
1992	9.5	83.4	7.1	186,434	85.5
1993	11.5	80.2	8.4	147,131	83.9
1994	20.7	70.9	8.4	60,232	60.3
1995	28.3	57.6	14.1	32,683	45.1
1996	31.3	42.5	26.2	22,123	39.6
1997	33.4	48.8	17.8	18,577	29.7
1998	25.9	57.6	16.5	14,600	26.9
1999	6.6	69.7	23.8	12,871	23.8
2000	4.0	71.4	24.7	9,900	22.5
2001	3.6	71.6	24.8	8,311	25.8
2002	6.0	68.6	25.3	6,795	21.4
2003	6.1	56.0	37.9	3,145	12.4
TOTAL	11.2	75.9	12.9	1,271,693	71.1

Table 3-4 CFC-12 sales by end-use category (AFEAS, percentage of the total), total sales (AFEAS) and comparison with UNEP reported production data (%)

Year	Refrigeration and Air Conditioning	All Foams	Aerosol and all other uses	Total sales (tons)	Total sales vs UNEP (%)
1989	64.5	13.1	22.4	379,788	79.6
1990	70.0	11.9	18.1	230,950	67.8
1991	77.8	8.9	13.2	224,805	75.6
1992	82.1	6.6	11.3	216,207	79.2
1993	88.1	3.9	8.1	214,664	78.1
1994	89.1	2.9	8.1	133,600	63.1
1995	85.9	2.1	12.1	82,822	52.9
1996	84.3	3.5	12.2	48,856	54.5
1997	75.7	4.4	19.9	32,900	36.6
1998	80.8	3.6	15.6	33,269	37.8
1999	77.8	3.5	18.7	27,132	30.9
2000	77.7	3.6	18.8	24,564	29.5
2001	77.8	4.1	18.1	20,873	31.9
2002	84.3	0.0	15.7	20,181	34.4
2003	81.1	0.0	18.9	12,536	22.9
TOTAL	77.2	7.8	15.1	1,703,147	64.3

Table 3-5 HCFC-22 sales by end-use category (AFEAS, percentage of the total), total sales (AFEAS) and comparison with UNEP reported production data (%)

Year	Refrigeration and Air Conditioning	Closed cell foams	Aerosol and all other uses	Total sales (tons)	Total sales vs UNEP (%)
1989	88.4	0.1	11.4	219,537	91.1
1990	84.6	0.9	14.5	213,714	92.6
1991	85.3	3.3	11.5	236,812	101.1
1992	84.1	3.5	12.3	245,715	125.6
1993	84.9	5.6	9.5	240,619	87.4
1994	86.7	3.0	10.4	239,444	91.3
1995	83.5	5.1	11.4	243,468	74.2
1996	86.1	3.0	10.9	267,523	97.7
1997	87.5	1.5	11.0	246,937	88.7
1998	88.4	4.0	7.6	271,980	94.1
1999	87.1	3.5	9.4	248,552	77.3
2000	85.6	3.3	11.2	239,197	70.1
2001	87.2	1.7	11.1	213,328	64.9
2002	67.9	3.7	28.4	193,955	60.1
2003	86.0	6.4	7.6	187,262	55.9
TOTAL	85.1	3.2	11.7	3,508,043	82.3

Table 3-6 HCFC-141b sales by end-use category (AFEAS, fractions of the total), total sales (AFEAS) and comparison with UNEP reported production data (fraction)

Year	Refrigeration and Air Conditioning	Closed cell foams	Aerosol and all other uses	Total sales (tons)	Total sales vs UNEP (%)
1990	3.0	83.8	13.1	99	
1991	0.1	81.5	18.4	1,507	
1992	0.4	79.6	20.1	13,254	82.9
1993	1.0	80.1	18.8	43,291	155.6
1994	0.7	82.8	16.5	81,231	95.1
1995	0.8	83.4	15.8	113,154	101.1
1996	11.4	77.3	11.2	121,085	111.8
1997	0.5	89.2	10.4	122,356	107.1
1998	0.4	88.0	11.6	129,037	96.5
1999	0.0	90.3	9.7	130,415	90.4
2000	0.0	92.0	8.1	132,476	94.4
2001	0.0	89.7	10.3	121,757	93.1
2002	0.0	90.4	9.6	116,673	78.5
2003	3.4	87.5	9.1	74,596	82.1
TOTAL	1.6	86.9	11.4	1,200,931	95.1

Table 3-7 HCFC-142b sales by end-use category (AFEAS, percentage of the total), total sales (AFEAS) and comparison with UNEP reported production data (%)

Year	Refrigeration and Air Conditioning	Closed cell foams	Aerosol and all other uses	Total sales (tons)	Total sales vs UNEP (%)
1989	0.1	92.4	7.5	10,288	63.5
1990	0.1	87.4	12.6	18,757	245.4
1991	0.3	87.6	12.1	27,154	236.4
1992	0.1	82.5	17.4	30,691	92.2
1993	0.0	92.5	7.5	33,682	176.2
1994	0.1	94.6	5.3	38,361	92.4
1995	1.1	89.5	9.5	38,711	86.3
1996	1.7	89.3	9.1	37,736	105.9
1997	1.6	95.4	3.1	40,197	96.3
1998	1.6	95.3	3.1	38,771	96.2
1999	2.3	95.0	2.7	40,165	99.1
2000	3.8	93.1	3.2	40,517	100.6
2001	1.3	90.8	7.8	33,616	99.1
2002	4.0	92.8	5.8	21,417	79.7
2003	3.5	91.1	5.5	19,685	62.7
TOTAL	1.4	91.6	7.1	469,748	

3.1.3 Consumption data

In Table 3-8 the consumption data for the chemicals considered are given. They follow the same pattern (year-by-year trends) as the production data. As can be expected, the values for the developed countries are much lower (owing to exports to the developing countries) and the values for the developing countries are much higher (owing to imports).

The Task Force has investigated whether the adjustment of consumption data (by filling in the gaps for the years for which no country reports were received by UNEP) would have a significant influence. This has been done for HCFC-22 where more gaps in data reporting occur than for other ODSs (e.g. CFC-11 and -12). A comparison of both cases (no adjustments versus adjustments) yields differences of less than 1% per year after 1993 (when more or less full reporting of HCFCs occurred for all countries). For this reason no extra consumption data have been filled in the gaps (as was done for production data, see above).

When comparing production and consumption data, it seems useful to look at the differences (production minus consumption). In principle the difference should be positive for the developed countries (due to exports), negative for the developing countries (due to imports), and the total difference should be more or less zero. Results are presented in Table 3-9.

Table 3-8 Consumption data as reported to UNEP under Article 7 by both non-Article 5 and Article 5 countries (and totals) for the period 1989-2004

			MT	MT	MT	MT	MT	MT	MT	MT	MT	MT	MT	MT	MT	MT	MT	MT	MT	Total 1989-2004	Total 1989-2003
		SubstName	1986	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004		
Subtotal	nA5	CFC-11	341688	292893	205687	175543	152665	109187	47715	16800	6925	1696	3629	7108	6621	1906	1449	666	756	1031244	1030489
Subtotal	A5	CFC-11	51520	56153	41154	47261	65344	64681	67631	73549	64371	69069	62628	57269	48240	41664	37610	30172	21833	848630	826796
TOTAL		CFC-11	393208	349046	246840	222805	218009	173867	115346	90349	71297	70764	66257	64377	54861	43571	39059	30837	22589	1879874	1857285
Subtotal	nA5	CFC-12	410126	396925	259308	197941	179268	180016	115825	63691	15886	19093	17909	17453	22677	5258	1506	2406	1951	1497114	1495164
Subtotal	A5	CFC-12	80817	83304	58666	64973	79183	90499	100077	105281	81344	76535	72249	61011	62683	57033	48955	41679	39729	1123201	1083472
TOTAL		CFC-12	490944	480229	317975	262914	258451	270515	215901	168972	97230	95629	90158	78464	85360	62291	50461	44085	41679	2620315	2578636
Subtotal	nA5	HCFC-22	0	193712	147587	177444	146964	214404	187742	251468	199255	186289	214423	204250	176967	177483	147034	159025	148969	2933016	2784047
Subtotal	A5	HCFC-22	0	41601	14090	19180	37004	55707	67756	63096	71683	82074	67769	122821	154618	151148	150729	161457	204347	1465078	1260731
TOTAL		HCFC-22	0	235313	161677	196624	183968	270111	255498	314565	270938	268363	282192	327070	331585	328631	297762	320482	353316	4398094	4044778
Subtotal	nA5	HCFC-141b	0	1296	897	526	16755	24443	67438	105275	98564	100805	119532	119459	113783	103392	117762	44046	13956	1047928	1033972
Subtotal	A5	HCFC-141b	0	0	0	82	188	992	4783	5705	7968	13874	16880	25955	38149	34343	43247	56199	70142	318507	248365
TOTAL		HCFC-141b	0	1296	897	608	16943	25435	72221	110979	106531	114679	136413	145414	151932	137735	161008	100245	84098	1366435	1282336
Subtotal	nA5	HCFC-142b	0	17005	12449	18969.4	35510	21933	44259	48838	35417	40259	40973	43226	34435	32415	19798	21917	19147	486550	467404
Subtotal	A5	HCFC-142b	0	38	28	11	11	143	223	257	863	1015	1399	1344	1638	1676	1598	5909	5811	21962	16151
TOTAL		HCFC-142b	0	17043	12477	18981	35521	22076	44482	49095	36279	41274	42372	44571	36072	34091	21396	27826	24958	508513	483555

Table 3-9 Differences between production and consumption (as Prod. – Cons.) for each year and each chemical considered for non-Article 5 and Article 5 countries and differences between the global totals for production and consumption (refer to the UNEP data in Tables 3-1 and 3-8)

		SubstName	MT 1986	MT 1989	MT 1990	MT 1991	MT 1992	MT 1993	MT 1994	MT 1995	MT 1996	MT 1997	MT 1998	MT 1999	MT 2000	MT 2001	MT 2002	MT 2003	MT 2004	Total 1989-2004	Total 1989-2003
Subtotal	nA5	CFC-11	32160	40235	36586	46208	41024	34751	12586	13541	9415	14465	8479	7349	8314	5439	5578	2575	1551	288099	286548
Subtotal	A5	CFC-11	-32910	-35281	-19564	-25421	-40990	-33248	-27977	-31297	-24884	-22757	-20467	-17740	-19213	-16845	-12824	-8048	-1863	-358421	-356557
TOTAL		CFC-11	-750	4954	17022	20787	34	1502	-15391	-17755	-15469	-8292	-11988	-10391	-10900	-11406	-7245	-5473	-312	-70322	-70010
Fraction of production in year			0.00	0.01	0.06	0.09	0.00	0.01	-0.15	-0.24	-0.28	-0.13	-0.22	-0.19	-0.25	-0.35	-0.23	-0.22	-0.01		
Subtotal	nA5	CFC-12	31893	33515	34830	49174	47736	38771	26858	24616	15453	11259	14829	15699	12439	12997	17083	10498	5219	370976	365757
Subtotal	A5	CFC-12	-41479	-36402	-11989	-14668	-33314	-34271	-30614	-36984	-23050	-16925	-17028	-6738	-14476	-9776	-8848	66	978	-294039	-295017
TOTAL		CFC-12	-9587	-2887	22841	34506	14422	4500	-3756	-12368	-7597	-5667	-2199	8961	-2037	3222	8235	10564	6198	76937	70740
Fraction of production in year			-0.02	-0.01	0.07	0.12	0.05	0.02	-0.02	-0.08	-0.08	-0.06	-0.02	0.10	-0.02	0.05	0.14	0.19	0.13		
Subtotal	nA5	HCFC-22	0	22456	61608	37663	26117	28005	32460	44222	37621	48243	42806	32796	48176	24735	35602	4779	-7417	519872	527289
Subtotal	A5	HCFC-22	0	-16706	7447	1952	-14434	-22788	-25616	-30580	-34843	-38175	-35739	-38284	-38012	-24650	-9997	9986	24979	-285461	-310440
TOTAL		HCFC-22	0	5749	69055	39615	11684	5216	6844	13642	2778	10068	7066	-5488	10164	85	25605	14765	17562	234411	216849
Fraction of production in year				0.02	0.30	0.17	0.06	0.02	0.03	0.04	0.01	0.04	0.02	-0.02	0.03	0.00	0.08	0.04	0.05		
Subtotal	nA5	HCFC-141b	0	-289	4803	4474	227	3384	17545	6044	6430	8315	7379	13208	14602	14139	6169	11419	21108	138958	117851
Subtotal	A5	HCFC-141b	0	0	0	-82	-188	-992	-4313	-3863	-4669	-8762	-10030	-14350	-26174	-20983	-18550	-20745	-27524	-161225	-133701
TOTAL		HCFC-141b		-289	4803	4392	39	2392	13232	2182	1762	-447	-2652	-1142	-11572	-6844	-12380	-9326	-6416	-22266	-15850
Fraction of production in year				-0.29	0.84	0.88	0.00	0.09	0.15	0.02	0.02	0.00	-0.02	-0.01	-0.08	-0.05	-0.08	-0.10	-0.08		
Subtotal	nA5	HCFC-142b	0	-814	-4804	-7484	-2204	-2814	-2841	-4196	-141	1010	-1232	-3460	5262	1029	4691	5382	15049	2434	-12615
Subtotal	A5	HCFC-142b	0	-38	-28	-11	-11	-143	-105	-37	-517	-545	-851	-559	-1061	-1174	789	-1829	-1957	-8075	-6118
TOTAL		HCFC-142b	0	-852	-4832	-7496	-2215	-2957	-2947	-4233	-657	465	-2083	-4019	4202	-145	5480	3553	13092	-5642	-18734
Fraction of production in year				-0.05	-0.63	-0.65	-0.07	-0.15	-0.07	-0.09	-0.02	0.01	-0.05	-0.10	0.10	0.00	0.20	0.11	0.34		

In the case of CFC-11, large negative values result for the difference in the developing countries, which can be traced back to the annual totals (most of them being negative). Although it is difficult to draw firm conclusions, the negative difference can be either caused by:

- Over-reporting of consumption

or

- Under-reporting of production.

Since supply chain communication is usually better in non-Article 5 countries, it is less likely that there is over-reporting of consumption there than in Article 5 countries, where there are potential risks of double-counting because of the often difficult distinction between MLF projects and non-funded activities. Under-reporting of production could occur in both the Article 5 and the non-Article 5 countries, but is generally less explainable. Bearing in mind the clear reporting procedures adopted among members of AFEAS, it is more likely that, if under-reporting of production would occur, this would be from countries (producers), which do not report to AFEAS.

The total difference between consumption and production over the period 1989-2004 amounts to about 70,000 tons of CFC-11, which is equal to 1-2 years of production during the period 1996-2004 (the fact that negative values occur during 1995-2004 seems to confirm the earlier conclusion that this may be due to reporting problems in Article 5 countries.

In the case of CFC-12 the same type of differences can be observed, however, differences are much smaller. Negative values for the total are only found between 1994 and 2000, which is different from the CFC-11 case. The total difference over the years 1989-2004 is about 80,000 tons (larger production), which is equal to the amount produced globally in one year during the late nineties.

In the case of HCFC-22, non-Article 5 production is larger than non-Article 5 consumption for every year over the period from 1989 to 2003. Only in 2004 does the trend reverse. For the Article 5 countries, annual consumption is normally larger, but production is larger than consumption as of the year 2003 (with increasing production values over the period 2000-2004). Global production is larger than consumption for every year in the period 1989-2004, with annual values varying from 85 tons (2001) to about 25,000 tons (2002) (not taking into account the years 1989-1992 when there has most likely been under-reporting ahead of the ratification of the Copenhagen Amendment). The cumulative difference over the period amounts to about 230,000 tons, being somewhat less than the production of one year of HCFC-22 in the nineties. This implies that there are more uses for HCFC-22 than are being reported through the consumption data unless the material is being stockpiled.

In the case of HCFC-141b, global consumption values are larger than production values as of 1997. This is also the year when production reported by AFEAS started to become lower than the global production (as reported to UNEP). The negative values may be due to under-reporting of production or over-reporting of consumption by Article 5 countries. The cumulative difference amounts to about –22,000 tons, being about 20% of one year's global production in the late nineties.

In the case of HCFC-142b, differences between production and consumption vary over the period 1989-2004 (more negative than positive values). Values during 2002-2004 show a positive trend. AFEAS reported production covers almost the entire global production until 2002, when differences between AFEAS and UNEP figures become larger. It is likely that there is some over-reporting of consumption here, but evidence is still lacking.

The above raises the question: "Should production or consumption values be used to compare the demand function for refrigeration, AC and foams in the bottom-up method?" There are no compelling arguments to select any one of them based on the different production versus consumption characteristics for CFC-11, CFC-12, HCFC-22, -141b and -142b. However, with total cumulative consumption generally higher than total cumulative production, it was felt that basing calculations on the higher dataset would represent a 'worst case' for annual emissions.

On this basis, it was decided to take for a comparison the consumption values for all the chemicals considered. However, in the subsequent discussion on the results it should always be taken into account that the annual production for CFC-12 and HCFC-22 was about 5-10% larger than consumption (the cumulative value being about one year's production during 1989-2004) and that emissions of these chemicals might be under-estimated by bottom-up methods as a result.

4 General considerations on bottom-up methods

4.1 Potential of bottom-up methods and sources of uncertainty

A bottom-up method is best described as one which re-assesses consumption patterns by using data from a number of different sources and derives emissions estimates by the application of sets of emission functions that are specific to each end-use. This approach often requires a more detailed assessment of end-uses than that identified in section 3.1.2 (AFEAS use classifications). However, this combination of heightened end-use analysis and dedicated emission functions allows the modeller to describe the release of material from the installed base and is particularly important where release is not immediate - primarily in refrigeration and closed-cell foam applications.

The purpose of such an approach is three-fold:

(1) To identify the emissions which have already taken place from previous consumption by end-use.

(2) To forecast the future emissions which will occur from consumption that has already taken place

(3) To predict the future growth of consumption and related emissions that will add to the emissions identified under (1) and (2).

Each of these aspects carries a level of uncertainty. For (1), the uncertainty can be limited because there is an opportunity to cross-check bottom-up estimates of historic emission with observed atmospheric concentrations. Nevertheless, since the bottom-up emissions estimate will have included an assessment of overall consumption, detailed end-use analysis and related emission function, it is always possible that inaccuracies in one parameter (e.g. annual consumption by end-use) will have been inadvertently offset by inaccuracies in another parameter (e.g. emission function from that end-use). It is therefore important that, wherever possible, independent information is obtained on historic end-use consumption and on emission functions from each application (or sub-application).

For example, one way of checking the end-use estimates arising from the AFEAS analysis (Section 3.1.2) is to gain information on the historic sales of specific types of refrigeration equipment or foams. With knowledge of the amount of refrigerant or blowing agent contained in each piece of equipment or product, it is possible to calculate the overall consumption represented by these sales. Data collection on equipment and/or product sales therefore becomes an integral part of bottom-up modelling, although there is a need to also understand the breadth and distribution of refrigerant or blowing agent choices in order to make this assessment chemical-specific. Adopting this type of approach can expose short-comings in the broader data collection processes operated by AFEAS and UNEP and, in some cases, can identify specific areas of unintentional under-reporting.

For refrigeration and air conditioning uses, there is an additional source of consumption related to the servicing of existing equipment and, in some markets this can be a substantial, and even dominant, factor. Parameters such as the frequency of servicing, the amount of re-use and recycling practised and emission losses during servicing all become additional factors in the assessment. In markets and/or technologies where there is little or no new equipment being introduced (e.g. in technologies that are being phased-out) it is reasonable to assume that total consumption is related to servicing and that the servicing demand is driven by emissions that have already occurred from equipment. This is sometimes referred to as the "mass balance" method.

Uncertainties in (2) will depend significantly on the quality of data obtained and derived from the analysis of (1). When projecting future emissions from equipment and products already in existence, it would be normal to assume that emission functions will remain constant into the future. Of course, there are always exceptions and it may be necessary to make adjustments. An example would be where practices have been improved to avoid releases during the servicing of existing refrigeration equipment.

For (3), there are even greater sources of uncertainty. Determining future emissions from future consumption requires an assessment of each of the following:

- the sales of new equipment and products into the future
- the trends in both refrigerant/blowing agent selection
- the trends in design, servicing practice and/or end-of-life management which could modify the assumed emission functions

Despite these concerns, bottom-up modelling is perhaps at its most powerful for assessments of future consumption and emission, since it takes its assessment right back to the technological and economic drivers which ultimately dictate emission. Nevertheless, future projections of emissions need to be handled with caution and a full understanding of the uncertainties is important.

4.2 Scope of bottom-up evaluations considered in this report and related uncertainties

For the purposes of this report, the Task Force has focused specifically on the validity of emissions projections falling under category (1) – i.e. historic emissions up to the present. This is the aspect with the lowest level of uncertainty, as reflected in section 7 of this report.

It should be noted that the Montreal Protocol is not the only global agreement interested in such assessments. The supporting materials to the Kyoto Protocol (notably the *Inter-Governmental Panel on Climate Change Guidance on National Greenhouse Gas Inventories*) contain substantial bottom-up methodology for assessing emissions from sectors employing ODS Substitutes. This includes both refrigeration and foam applications. The bottom-up methods outlined in this section are described in detail within the IPCC publication, where they are referred to explicitly as Tier 2 methods. For those seeking further information on the methodologies applied for each end-use sector, application and sub-application, this is an essential reference.

In order to put some figures to the anticipated uncertainties arising from (1), current leading practitioners, including the respective Lead Authors of the Special Report (IPCC, TEAP 2005) have assessed the composite annual uncertainties as follows based on unknowns surrounding consumption, product/equipment manufacturing practices, servicing, lifecycle and end-of-life practices:

For foams:

Average annual uncertainties for period 1990-2003

(+/-)	**CFC-11**	**CFC-12**	**HCFC-141b**	**HCFC-142b**	**HCFC-22**
Consumption	15%	20%	5%	10%	20%
Emissions	25%	20%	15%	15%	20%

For refrigeration, the average annual uncertainties for all application options are taken as follows:

Average annual uncertainties for period 1990-2003

(+/-)	**CFC-11**	**CFC-12**	**HCFC-141b**	**HCFC-142b**	**HCFC-22**
Consumption	17%	17%	N/A	17%	17%
Emissions	25%	25%	N/A	25%	25%

These individual uncertainties are clearly not always additive and a root mean square sum technique is used in section 7 to derive overall uncertainties arising from bottom-up analyses.

4.3 Handling uncertainties outside of the foam and refrigeration sectors

Apart from the specific uncertainties arising from the bottom-up methods themselves, there is a need to consider the impact of uncertainties in the overall UNEP consumption data. For the purposes of this report, it is assumed that all consumption not allocated to either foam or refrigeration is attributed to rapid-release, emissive applications. For consistency across the range of chemicals considered, it is assumed that emissions take place in the year after consumption. An uncertainty of +/-16% is adopted across the board for overall UNEP consumption data.

This approach can lead to some surprising results. For instance, where consumption figures for foam and refrigeration exceed that declared within the UNEP data as a whole, the result is a 'negative' consumption for short-term emissive uses. In turn, this is passed through to the emissions calculation as a 'negative' emission. Clearly, there are not 'negative' emissions in practice. However, the existence of a 'negative' value for a specific year indicates that the UNEP data must be under-reporting or, alternatively, the bottom-up assessments for foam and/or refrigeration are over-reporting. These prospects are discussed in detail against the analyses themselves in section 7.

In conclusion, the formula for overall bottom-up annual emissions estimation can be summarised as follows:

$$E_y = FE_y + RE_y + (UC_{y-1} - (FC_{y-1} + RC_{y-1}))$$

where E_y = *Estimated emissions for year 'y'*
FE_y = *Estimated foam emissions for year 'y'*
RE_y = *Estimated refrigerant emissions for year 'y'*
UC_{y-1} = *Declared UNEP consumption for year 'y-1'*
FC_{y-1} = *Assessed consumption in the foam sector for year 'y-1'*
RC_{y-1} = *Assessed consumption in the refrigerant sector for year 'y-1'*

5 Specific considerations on banks and emissions

5.1 The scenarios in the IPCC TEAP Special Report; 2002 data and subsequent corrections

In the Special Report (IPCC TEAP, 2005) a Business as Usual and a Mitigation (MIT) scenario were developed for the projections of the demand, banks and emissions of CFCs, HCFCs, HFCs and some PFCs (where these are used as replacements for ozone-depleting substances). In the MIT scenario different annual market growth percentages are assumed for different regions in the world, equal to the ones used in the BAU scenario. These projections assume that all existing measures will remain in place, including the Montreal Protocol (phase-out) and relevant national regulations. The Mitigation case assumes improved application of all existing measures and improvement in best-practice emission reduction techniques. As a consequence under this scenario, changes to the usual practices and emission rates are already factored into the projections over the period 2002-2015.

Both scenarios, however, are anchored by demand, banks and emissions assessments for the year 2002. Accordingly, in the analysis of discrepancies between emissions from bottom-up methods and from atmospheric measurements, it does not make sense to look at the period 2002-2015. In a first instance, the analysis of the period 1989-2003 (2004) is important, as a result of which certain banks and cumulative emissions are calculated in the bottom-up method for the year 2003 (2004).

In the case of an analysis of consumption and resulting atmospheric concentrations of ozone depleting chemicals for 2003, not only is the period 1989-2003 (2004) important, but also that between 1970 (or earlier) and 1989.

The following is considered in this chapter:
1. a comparison of the demand values with the consumption values reported to UNEP;
2. the derivation of the values for banks and emissions;
3. further considerations on banks and emissions if there are differences between the demand values and the consumption values reported to UNEP.

In the Special Report and the Supplement Report the demand for the different chemicals is given for refrigeration and air conditioning. The 2002 demand is rather low for CFC-11 (about 5,800 tons) and very high for CFC-12 (about 130,000 tons). This was a result of an analysis (assessment) of the US refrigerant market for mobile air conditioning, where it was concluded that emissions were rather low. However, the authors of the 2004 US EPA and ADEME reports have again analysed the assumptions regarding mobile air conditioning with practices in 2005-2006 and concluded --on the basis of practical information—that recovery efficiencies, lifetimes, retrofits and average charge were different than those assumed in 2004. These new assumptions lead to a substantial decrease in the CFC-12 demand assumed.

Recently, corrections were also made to the commercial refrigeration sector, in particular the supermarket and hypermarket sectors in China. Taking into account the latest data obtained for 2003, the growth rate of 8%, as had been assumed earlier, proved to be too high. The corrections led to a decrease of the CFC use in commercial equipment. As a result, the current 2002 CFC-12 demand assessment amounts to 69,200 tons.

Compared to the data in the IPCC TEAP Special Report and in the Supplement on chiller air conditioning, a further study was made of the global ratio of CFC-11 and CFC-12 based chillers. It turned out that the number of CFC-11 chillers (particularly in developing countries) was much larger than previously assumed. Corrections to the demand, banks and emissions had to be made. This led to a reduction in the CFC-12 demand for this sector (see also above) and an increase in the CFC-11 demand (13,300 tons for the year 2002).

5.2 Comparison of demand and UNEP consumption values for refrigeration, AC and foams

In the first instance, this section gives demand data for refrigeration/AC and foams, separately for non-Article 5 and Article 5 countries. For comparison with the demand, it also gives again the UNEP consumption data for the same country groups. In a second instance it gives banks and emissions data, and tries to estimate total emissions on the basis of the comparison of the demand data with the UNEP consumption data.

5.2.1 Demand data

In the tables below demand data for CFC-11, CFC-12, HCFC-22, -141b and -142 b are given, as well as the UNEP consumption data for the years 1990-2003 (2004) (in metric tons).

Table 5-1 Demand data for CFC-11 and comparison with UNEP consumption data

CFC-11	**Refr/AC**	**Foams**	**Refr/AC**	**Foams**	**Subtotal**	**Subtotal**	**Bottom-up**		**UNEP**	**UNEP**	**UNEP**
Year	**Non-A5**	**Non-A5**	**A5**	**A5**	**Non-A5**	**A5**	**Total**		**Non-A5**	**A5**	**Total**
1,990	16,358	109396	5,714	28,264	125,754	33,978	159,731		205687	41154	246840
1,991	17,100	100000	5,930	29,573	117,100	35,503	152,603		175543	47261	222805
1,992	15492	81468	5795	31755	96,960	37,550	134,510		152665	65344	218009
1,993	15614	56107	5425	33958	71,721	39,383	111,104		109187	64681	173867
1,994	15192	37277	5284	36271	52,469	41,554	94,023		47715	67631	115346
1,995	12188	19059	4987	33132	31,247	38,119	69,366		16800	73549	90349
1,996	12105	1711	5132	32216	13,816	37,349	51,164		6925	64371	71297
1,997	11833	475	4791	29510	12,308	34,301	46,609		1696	69069	70764
1,998	11506	364	4603	25298	11,870	29,901	41,771		3629	62628	66257
1,999	11134	248	4276	21112	11,382	25,388	36,769		7108	57269	64377
2,000	10838	126	4096	16807	10,964	20,903	31,867		6621	48240	54861
2,001	10141	0	3946	12857	10,141	16,804	26,945		1906	41664	43571
2,002	9494	0	3823	10745	9,494	14,567	24,061		1449	37610	39059
2,003	8838	0	3712	8344	8,838	12,056	20,894		666	30172	30837
2,004		0		5486					756	21833	22589

Table 5-2 Demand data for CFC-12 and comparison with UNEP consumption data

CFC-12	**Refr/AC**	**Foams**	**Refr/AC**	**Foams**	**Subtotal**	**Subtotal**	**Bottom-up**		**UNEP**	**UNEP**	**UNEP**
Year	**Non-A5**	**Non-A5**	**A5**	**A5**	**Non-A5**	**A5**	**Total**		**Non-A5**	**A5**	**Total**
1,990	81885	30557	44569	1110	112,441	45,679	158,121		259308	58666	317975
1,991	81735	26943	47998	1161	108,677	49,159	157,836		197941	64973	262914
1,992	81794	19695	49719	1209	101,489	50,928	152,417		179268	79183	258451
1,993	74149	12388	51029	1255	86,537	52,284	138,821		180016	90499	270515
1,994	63669	7484	52393	1298	71,153	53,691	124,844		115825	100077	215901
1,995	51215	2357	54106	1339	53,573	55,444	109,017		63691	105281	168972
1,996	46627	78	57520	1376	46,705	58,896	105,601		15886	81344	97230
1,997	39475	0	59585	1306	39,475	60,891	100,366		19093	76535	95629
1,998	33185	0	59604	1164	33,185	60,769	93,954		17909	72249	90158
1,999	26471	0	60578	1016	26,471	61,595	88,065		17453	61011	78464
2,000	19971	0	61325	855	19,971	62,180	82,150		22677	62683	85360
2,001	13795	0	61189	649	13,795	61,838	75,633		5258	57033	62291
2,002	9451	0	59749	550	9,451	60,299	69,750		1506	48955	50461
2,003	6534	0	58813	413	6,534	59,226	65,760		2406	41679	44085
2,004		0		249					1951	39729	41679

Table 5-3 Demand data for HCFC-22 and comparison with UNEP consumption data

HCFC-22	**Refr/AC**	**Foams**	**Refr/AC**	**Foams**	**Subtotal**	**Subtotal**	**Bottom-up**		**UNEP**	**UNEP**	**UNEP**
Year	**Non-A5**	**Non-A5**	**A5**	**A5**	**Non-A5**	**A5**	**Total**		**Non-A5**	**A5**	**Total**
1990	85854	472	50823	0	86,327	50,823	137,150		147587	14090	161677
1991	91809	1459	56181	0	93,268	56,181	149,449		177444	19180	196624
1992	105897	3537	58963	0	109,435	58,963	168,398		146964	37004	183968
1993	103452	5520	58972	0	108,972	58,972	167,944		214404	55707	270111
1994	120325	7803	65624	0	128,127	65,624	193,752		187742	67756	255498
1995	127957	10057	71487	0	138,014	71,487	209,501		251468	63096	314565
1996	139527	11273	79542	0	150,800	79,542	230,342		199255	71683	270938
1997	136721	11373	85225	0	148,094	85,225	233,319		186289	82074	268363
1998	146731	11376	87382	79	158,107	87,461	245,568		214423	67769	282192
1999	152374	11268	96888	169	163,642	97,057	260,699		204250	122821	327070
2000	154348	11102	112003	181	165,450	112,183	277,633		176967	154618	331585
2001	151047	10059	120824	184	161,106	121,008	282,114		177483	151148	328631
2002	157188	6366	134661	197	163,555	134,858	298,412		147034	150729	297762
2003	156466	5934	146594	214	162,400	146,809	309,209		159025	161457	320482
2004		6124		231					148969	204347	353316

Table 5-4 Demand data for HCFC-141b and comparison with UNEP consumption data

HCFC-141b	Foams	Foams	Bottom-up	UNEP	UNEP	UNEP
Year	**Non-A5**	**A5**	**Total**	**Non-A5**	**A5**	**Total**
1,990	0	0	0	897	0	897
1,991	6579	0	6579	526	82	608
1,992	20522	0	20522	16755	188	16943
1,993	40107	0	40107	24443	992	25435
1,994	59102	0	59102	67438	4783	72221
1,995	76163	1155	77319	105275	5705	110980
1,996	92832	2754	95586	98564	7968	106532
1,997	94444	4803	99247	100805	13874	114679
1,998	95841	7845	103687	119532	16880	136412
1,999	97017	10948	107964	119459	25955	145414
2,000	95653	14219	109872	113783	38149	151932
2,001	93448	17307	110754	103392	34343	137735
2,002	76191	20451	96642	117762	43247	161009
2,003	24426	24487	48913	44048	56199	100247
2,004	10949	28483	39432	13956	70142	84098

Table 5-5 Demand data for HCFC-142b and comparison with UNEP consumption data (there is also some use of HCFC-142b in refrigeration but demand data cannot be assessed with reasonable accuracy)

HCFC-142b	Foams	Foams	Bottom-up	UNEP	UNEP	UNEP
Year	**Non-A5**	**A5**	**Total**	**Non-A5**	**A5**	**Total**
1,990	4252	0	4252	12449	28	12477
1,991	7989	0	7989	18969	11	18980
1,992	14102	0	14102	35510	11	35521
1,993	20161	0	20161	21933	143	22076
1,994	24104	0	24105	44259	223	44482
1,995	28078	0	28078	48838	257	49095
1,996	30232	0	30232	35417	863	36280
1,997	31174	29	31203	40259	1015	41274
1,998	32076	138	32215	40973	1399	42372
1,999	32798	261	33059	43226	1344	44570
2,000	32889	306	33196	34435	1638	36073
2,001	30588	345	30933	32415	1676	34091
2,002	24242	371	24613	19798	1598	21396
2,003	23919	405	24324	21917	5909	27826
2,004	24769	437	25207	19147	5811	24958

The following observations may be made:

- The UNEP consumption figures for CFC-11 are considerably larger than the total determined via the bottom-up methods for refrigeration/AC and foams. Total (global) differences are in the order of 70-90,000 tons (per year) before 1995 (most likely due to many short-term uses in developed countries, which have been phased out in the period 1993-1995), and amounts between 10,000 and 30,000 tons after the year 1995. The methodology adopted for this report adds these allocated amounts for refrigeration and foams to their respective banks for that specific year and to consider the difference as the amount of chemical with short-term uses, which will be emitted one year later (so the bank of these materials in year *'y'* is assumed to be completely emitted in year *'y+1'*).

- The UNEP consumption figures for CFC-12 are considerably larger than the ones derived from the bottom-up methods until 1995 (most likely also due to short-term uses in the developed countries, which were phased out in the period 1993-1995). After 1995 the amounts calculated by the bottom-up methods are systematically larger than the UNEP consumption figures. The values from the bottom-up methods are 5-20,000 tons higher than the UNEP consumption figures, with a consistently increasing trend after 1995. This can only be due to the amounts determined for refrigeration, which show a much smaller decrease over the period 2000-2003 than the trend of the decrease in the UNEP consumption figures.

- The UNEP consumption figures for HCFC-22 are larger for virtually all years considered, varying from more or less zero to about 60,000 tons (and even larger values for the years around 1993, where there has most likely been under-reporting of consumption to UNEP, when a large number of countries had not ratified the Copenhagen Amendment). The question is whether one should use the consumption figures from UNEP for these years (1990-1994) to determine the extra short-term banks and emissions, or whether a study of UNEP and AFEAS numbers would result in somewhat better estimates. This will automatically follow from a comparison of the emissions with the emissions determined from atmospheric measurements. The difference between the UNEP consumption values and the values determined with the bottom-up methods are becoming small after the year 2001, which seems to become a systematic trend. It should be remembered that the UNEP production figures for HCFC-22 are systematically larger for all years considered.

- The trend in the UNEP consumption figures when compared with the amounts determined for closed cell foams via the bottom-up method is interesting. After initial random differences (probably due to reporting problems, compare HCFC-141b for UNEP and AFEAS in the relevant Table 3-2), the difference becomes considerable after a 1993, and has maximum values in 2000 (about 42,000 tons; compared to a consumption value of about 150,000 tons) and 2002 (about 60,000 tons, compared to a consumption value of about 160,000 tons). The methodology adopted for this report is to add the differences to the banks in the same year and to extra short-term emissions in the year thereafter.

In the case of HCFC-142b, differences between UNEP consumption and the values reported for closed cell foam from bottom-up methods are relatively small as of the year 2000. Differences are much larger for the period 1990-2000 with e.g. values of 20,000 tons for the years 1992 and 1994 (compared to a total consumption of 35-45,000 tons), which value is also more or less the maximum value that occurs.

5.2.2 Banks data

In the tables below the banks are given for the different chemicals considered, for refrigeration and closed cell foams for the developed and the developing countries, and the global total, for the period 1990-2004 (in metric tons). To the global total, the difference between UNEP consumption and the demand is then added.

Table 5-6 Banks for CFC-11 for the period 1990-2003

CFC-11	Refr/AC	Foams	Refr/AC	Foams	Subtotal	Subtotal	Bottom-up		Short term	TOTAL
Year	Non-A5	Non-A5	A5	A5	Non-A5	A5	Total		estimate	(incl short)
1990	108,817	1,432,764	34,194	180443	1,541,581	214,637	1,756,218		87,109	1,843,327
1991	111,200	1,514,905	34,905	204237	1,626,105	239,142	1,865,247		70,202	1,935,449
1992	111,583	1,579,291	35,251	229882	1,690,875	265,133	1,956,007		83,499	2,039,506
1993	111,635	1,619,779	35,074	257430	1,731,414	292,504	2,023,918		62,763	2,086,681
1994	110,931	1,642,403	34,632	287004	1,753,334	321,636	2,074,970		21,323	2,096,293
1995	107,304	1,647,824	33,840	313468	1,755,128	347,308	2,102,435		20,983	2,123,418
1996	102,920	1,636,939	32,857	338942	1,739,860	371,799	2,111,659		20,132	2,131,791
1997	96,974	1,624,654	30,888	361771	1,721,628	392,659	2,114,288		24,155	2,138,443
1998	90,709	1,611,966	28,728	380521	1,702,675	409,249	2,111,924		24,486	2,136,410
1999	84,167	1,598,871	26,357	395235	1,683,039	421,591	2,104,630		27,607	2,132,237
2000	78,301	1,585,314	24,358	405814	1,663,615	430,172	2,093,787		22,993	2,116,780
2001	74,001	1,571,409	23,289	412541	1,645,410	435,830	2,081,240		16,626	2,097,866
2002	70,170	1,557,524	22,481	417267	1,627,695	439,749	2,067,443		14,998	2,082,441
2003	66,322	1,543,588	21,696	419796	1,609,910	441,492	2,051,402		9,944	2,061,346
2004										

Table 5-7 Banks for CFC-12 for the period 1990-2003

CFC-12	Refr/AC	Foams	Refr/AC	Foams	Subtotal	Subtotal	Bottom-up		Short term	TOTAL
Year	Non-A5	Non-A5	A5	A5	Non-A5	A5	Total		estimate	(incl short)
1990	365,204	193,591	199,840	3,288	558,795	203,127	761,923		159854	921,777
1991	375,160	208,855	206,120	3,592	584,015	209,712	793,727		105078	898,804
1992	383,157	219,072	212,782	3,905	602,229	216,687	818,916		106034	924,950
1993	383,239	224,471	219,694	4,227	607,710	223,921	831,630		131694	963,325
1994	372,710	226,827	226,600	4,555	599,536	231,155	830,692		91058	921,750
1995	345,054	226,030	233,730	4,891	571,084	238,620	809,704		59955	869,659
1996	313,086	224,248	241,868	5,231	537,334	247,098	784,432		0	784,432
1997	274,519	222,437	250,018	5,545	496,957	255,563	752,520		0	752,520
1998	234,526	220,640	256,020	5,819	455,165	261,839	717,004		0	717,004
1999	194,897	218,853	261,354	6,049	413,750	267,403	681,154		0	681,154
2000	152,603	217,078	267,129	6,229	369,681	273,358	643,039		0	643,039
2001	116,485	215,312	270,945	6,356	331,797	277,301	609,098		0	609,098
2002	89,099	213,555	273,521	6,461	302,654	279,982	582,636		0	582,636
2003	72,025	211,812	274,536	6,512	283,837	281,048	564,885		0	564,885
2004										

Table 5-8 Banks for HCFC-22 for the period 1990-2003

HCFC-22	Refr/AC	Foams	Refr/AC	Foams	Subtotal	Subtotal	Bottom-up		Short term	TOTAL
Year	Non-A5	Non-A5	A5	A5	Non-A5	A5	Total		estimate	(incl short)
1990	505,781	519	242,306	0	506,300	242,306	748,606		24,527	773,134
1991	534,728	1,599	256,420	0	536,327	256,420	792,747		47,175	839,922
1992	568,087	3,879	270,366	0	571,965	270,366	842,331		15,570	857,901
1993	596,825	7,384	282,422	0	604,209	282,422	886,630		102,167	988,797
1994	636,003	12,282	297,991	0	648,285	297,991	946,277		61,746	1,008,023
1995	680,555	18,891	316,571	1	699,447	316,571	1,016,018		105,063	1,121,081
1996	729,579	26,421	338,745	1	756,000	338,746	1,094,746		40,596	1,135,342
1997	771,618	34,178	361,590	2	805,796	361,593	1,167,389		35,044	1,202,433
1998	815,043	42,156	382,302	79	857,199	382,382	1,239,580		36,625	1,276,205
1999	862,592	50,273	408,381	243	912,865	408,623	1,321,488		66,371	1,387,860
2000	904,762	58,473	442,016	417	963,236	442,433	1,405,669		53,951	1,459,620
2001	939,632	65,893	476,311	595	1,005,525	476,905	1,482,431		46,517	1,528,948
2002	972,697	70,566	513,557	784	1,043,263	514,342	1,557,604		0	1,557,604
2003	1,000,522	74,922	546,944	784	1,075,444	547,728	1,623,172		11,273	1,634,445
2004										

Table 5-9 Banks for HCFC-141b for the period 1990-2003

HCFC-141b	Foams	Foams	Bottom-up		Short term	TOTAL
Year	Non-A5	A5	Total		estimate	(incl short)
1990	-	-	-		0	0
1991	6,134	-	6,134		0	6,134
1992	25,094	-	25,094		0	25,094
1993	61,867	-	61,867		0	61,867
1994	115,912	-	115,912		13119	129,030
1995	185,199	444	185,643		33661	219,304
1996	269,289	2,607	271,895		10946	282,841
1997	354,269	6,540	360,809		15432	376,241
1998	439,966	13,132	453,099		32725	485,824
1999	526,163	22,418	548,581		37450	586,031
2000	610,534	34,541	645,075		42060	687,135
2001	692,298	49,303	741,601		26981	768,582
2002	757,504	66,759	824,263		64367	888,629
2003	774,455	87,772	862,227		51334	913,561
2004						

Table 5-10 Banks for HCFC-142b for the period 1990-2003

HCFC-142b Year	Foams Non-A5	Foams A5	Bottom-up Total		Short term estimate	TOTAL (incl short)
1990	4,674	-	4,674		8225	12,899
1991	10,580	-	10,580		10991	21,571
1992	20,876	0	20,876		21419	42,295
1993	35,476	0	35,476		1915	37,392
1994	52,758	0	52,758		20377	73,135
1995	72,778	0	72,778		21017	93,796
1996	94,170	0	94,170		6048	100,218
1997	116,069	22	116,090		10071	126,161
1998	138,453	141	138,595		10157	148,752
1999	161,262	371	161,634		11511	173,144
2000	184,026	636	184,662		2877	187,539
2001	204,963	929	205,892		3158	209,050
2002	221,066	1,242	222,308		0	222,308
2003	236,860	1,581	238,441		3502	241,943
2004						

The following observations can be made:

- The dominant bank in terms of size is the one for CFC-11. This is driven primarily by the long-lived foam banks, which have accrued over more than 20 years of continued use.

- Banks of ODSs which are primarily used as refrigerants (e.g. CFC-12) can be significant but tend to have a greater ‘turnover’ because of higher loss rates than from foams.

- The growth of the HCFC-22 bank is particularly rapid and has been driven by widespread use in both non-Article 5 and Article 5 regions.

5.2.3 Emissions data

In the tables below the emissions are given for the different ODSs considered in this report and cover bottom-up assessments of refrigeration and closed cell foams based on current emission functions. Data is included for both the developed and the developing countries, together with the global total, for the period 1990-2004 (in metric tons). To the global total, the difference between UNEP consumption and the bottom-up demand is then added for the year after that specific difference has been concluded.

Table 5-11 Emissions for CFC-11 for the period 1990-2003, bottom-up (refrigeration/AC and closed cell foams) plus estimate for short-term emissions, and total emissions

CFC-11	Refr/AC	Foams	Refr/AC	Foams	Subtotal	Subtotal	Bottom-up		Short term	TOTAL
Year	Non-A5	Non-A5	A5	A5	Non-A5	A5	Total		estimate	(incl short)
1990	15,943	17631	5,610	5412	33,574	11,022	44,596			
1991	16,029	17859	5,720	5779	33,888	11,499	45,387		87109	132,496
1992	15,811	17082	5,770	6110	32,893	11,880	44,774		70202	114,975
1993	15,618	15619	5,737	6410	31,237	12,146	43,383		83499	126,882
1994	15,325	14653	5,682	6697	29,978	12,379	42,356		62763	105,119
1995	14,690	13638	5,578	6668	28,328	12,245	40,573		21323	61,896
1996	14,321	12596	5,565	6742	26,917	12,307	39,224		20983	60,207
1997	13,837	12759	5,499	6681	26,596	12,180	38,776		20132	58,909
1998	13,132	13053	5,321	6548	26,184	11,869	38,053		24155	62,208
1999	12,299	13342	5,051	6397	25,641	11,448	37,089		24486	61,575
2000	11,275	13684	4,688	6228	24,959	10,916	35,875		27607	63,483
2001	10,224	13905	4,402	6131	24,129	10,533	34,662		22993	57,655
2002	9,487	13884	4,200	6018	23,371	10,218	33,590		16626	50,216
2003	8,861	13937	4,078	5814	22,798	9,893	32,690		14998	47,689
2004		13747		5728					9944	

Table 5-12 Emissions for CFC-12 for the period 1990-2003, bottom-up (refrigeration/AC and closed cell foams) plus estimate for short-term emissions, and total emissions

CFC-12	Refr/AC	Foams	Refr/AC	Foams	Subtotal	Subtotal	Bottom-up		Short term	TOTAL
Year	Non-A5	Non-A5	A5	A5	Non-A5	A5	Total		estimate	(incl short)
1990	114,994	12376	41,020	816	127,370	41,835	169,206			169,206
1991	118,318	11679	42,153	856	129,997	43,009	173,006		159854	332,860
1992	120,400	9478	43,492	896	129,877	44,388	174,265		105078	279,343
1993	121,472	6990	44,688	933	128,462	45,622	174,083		106034	280,117
1994	120,206	5128	46,138	969	125,333	47,108	172,441		131694	304,135
1995	114,730	3154	47,656	1004	117,884	48,659	166,544		91058	257,602
1996	113,690	1861	49,578	1036	115,550	50,614	166,165		59955	226,120
1997	107,097	1810	51,230	992	108,907	52,222	161,129		0	161,129
1998	95,132	1798	52,293	891	96,929	53,184	150,113		0	150,113
1999	81,431	1786	53,371	786	83,217	54,157	137,374		0	137,374
2000	67,373	1775	53,664	675	69,148	54,340	123,488		0	123,488
2001	50,916	1766	53,179	522	52,682	53,701	106,383		0	106,383
2002	33,240	1757	53,510	445	34,997	53,954	88,952		0	88,952
2003	20,424	1743	53,838	362	22,166	54,199	76,366		0	76,366
2004		1728		269					0	

Table 5-13 Emissions for HCFC-22 for the period 1990-2003, bottom-up (refrigeration/AC and closed cell foams) plus estimate for short-term emissions, and total emissions

HCFC-22 Year	Refr/AC Non-A5	Foams Non-A5	Refr/AC A5	Foams A5	Subtotal Non-A5	Subtotal A5	Bottom-up Total		Short term estimate	TOTAL (incl short)
1990	59,640	122	99,821	0	59,762	99,821	159,583			159,583
1991	62,654	379	105,248	0	63,033	105,248	168,281		24527	192,808
1992	65,864	1,258	110,468	0	67,122	110,468	177,590		47175	224,765
1993	68,313	2,015	114,878	0	70,328	114,878	185,206		15570	200,776
1994	72,360	2,904	121,730	0	75,264	121,730	196,994		102167	299,160
1995	76,907	3,448	129,699	0	80,356	129,698	210,054		61746	271,800
1996	82,528	3,744	139,686	0	86,272	139,686	225,957		105063	331,020
1997	87,332	3,616	149,170	0	90,947	149,170	240,117		40596	280,713
1998	92,578	3,398	158,259	2	95,976	158,261	254,237		35044	289,281
1999	97,884	3,151	168,718	6	101,035	168,724	269,759		36625	306,384
2000	102,620	2,902	181,214	6	105,522	181,220	286,741		66371	353,113
2001	106,808	2,640	190,181	6	109,448	190,187	299,635		53951	353,586
2002	110,353	1,693	201,391	8	112,046	201,398	313,444		46517	359,962
2003	112,945	1,578	211,470	10	114,523	211,479	326,003		0	326,003
2004		1613		12					11273	

Table 5-14 Emissions for HCFC-141b for the period 1991-2004, bottom-up (closed cell foams) plus estimate for short-term emissions, and total emissions

HCFC-141b Year	Foams Non-A5	Foams A5	Bottom-up Total		Short term estimate	TOTAL (incl short)
1990	-	-	-			-
1991	445	8	453		0	453
1992	1,562	40	1,602		0	1,602
1993	3,334	101	3,435		0	3,435
1994	5,057	195	5,253		0	5,253
1995	6,876	367	7,243		13119	20,362
1996	8,742	592	9,334		33661	42,995
1997	9,463	870	10,333		10946	21,279
1998	10,144	1,253	11,397		15432	26,829
1999	10,820	1,662	12,482		32725	45,207
2000	11,282	2,096	13,378		37450	50,828
2001	11,684	2,544	14,228		42060	56,288
2002	10,985	2,996	13,981		26981	40,961
2003	7,475	3,473	10,948		64367	75,315
2004	5982	4023	10,005		51334	61,339
2005					44666	

Table 5-15 Emissions for HCFC-142b for the period 1991-2004, bottom-up (a small part of the emissions originate from refrigeration/AC, almost all is released from closed cell foams) plus estimate for short-term emissions, and total emissions

HCFC-142b Year	Foams Non-A5	Foams A5	Bottom-up Total		Short term estimate	TOTAL (incl short)
1990	1,098	-	1,098			1,098
1991	2,083	-	2,083		8225	10,308
1992	3,806	-	3,806		10991	14,797
1993	5,560	-	5,560		21419	26,980
1994	6,823	-	6,823		1915	8,739
1995	8,057	-	8,057		20377	28,434
1996	8,840	-	8,840		21017	29,858
1997	9,275	7	9,283		6048	15,331
1998	9,692	19	9,710		10071	19,781
1999	9,989	31	10,020		10157	20,178
2000	10,126	41	10,168		11511	21,678
2001	9,651	52	9,703		2877	12,580
2002	8,139	58	8,197		3158	11,355
2003	8,125	66	8,191		0	8,191
2004	8402	74	8,476		3502	11,978
2005					0	

The following observations may be made:

- The emissions of CFC-11 from closed cell foams are larger in the developed countries than in the developing countries reflecting larger banks from long-standing historic use.

- Emissions of CFC-11 are likely to reduce further in developing countries over the next five years as foam production is phased out;

- Although foam banks are much greater than refrigeration banks, emissions of CFC-11 are of the same order or magnitude from both refrigeration/AC and closed cell foams primarily because chillers tend to have greater leakage rates;

- The bottom-up total emissions of CFC-11 decrease from about 45,000 tons in 1991 to about 32,000 tons in 2003. Short-term emissions are very large in the early 1990s (caused by use of CFC-11 as a propellant, a solvent or in flexible foams in the developed countries). The estimates for short-term emissions are between 15,000 and 26,000 tons for the period 2000-2003.

- After 1994-1995, the emissions of CFC-12 from closed cell foams are negligible compared to the emissions from refrigeration/AC in developed countries, and for the entire 1990-2003 period in the developing countries.

- The bottom-up total emissions of CFC-12 decrease from about 170,000 tons in the early nineties to about 80,000 tons in 2003. Short-term emissions are very large in the early 1990s (use of CFC-12 as propellant in the developed countries). The estimates for the short-term direct emissions are negative for the period 2000-2003 (due to larger demand than consumption reported to UNEP), but can be considered as zeros in the calculation of emissions here.

- The emissions of HCFC-22 from closed cell foams are relatively small in the developed countries compared to the emissions from refrigeration/AC. In fact, virtually all global HCFC-22 (>98% for all the years in the period 1990-2003) emissions originate from refrigeration/AC;

- The bottom-up total emissions of HCFC-22 increase from about 160,000 tons in 1990 to about 325,000 tons in 2003. Short-term emissions are estimated to have been somewhat smaller in the early nineties than around the turn of the century. The estimates for short-term emissions are between 15,000 and 100,000 tons for the period 1991-2003, which implies that the bottom-up emissions are between 10 and 40% lower than the total, dependent on the specific year. Further study is required to determine the nature of the sources for these short-term direct emissions.

- The emissions of HCFC-141b from closed cell foams are much larger in the developed countries than in the developing countries due to larger banks. This will change in the future, since HCFC-141b has been virtually phased out in foam manufacture in the developed countries (current exceptions being Canada and Australia) and the manufactured volume of foams is increasing in the developing countries;

- Emissions of HCFC-141b will be of the same order of magnitude in both the developed and the developing countries in 2004-2005, as production losses generally exceed losses from banks on an annual basis;

- The bottom-up total emissions of HCFC-141b increase from about zero in 1990 to about 14,000 tons in 2001, after which they decrease again. The rate of decrease may become smaller due to remaining production in the developing countries after 2004-2005.

- Short-term emissions are estimated to have been large after 1994 (and this could be caused by the use of HCFC-141b as a solvent, refrigeration equipment flushing agent and as a technical aerosol propellant, primarily in developing countries). The estimates for short-term emissions are between 10,000 and 60,000 tons per year for the years in the period 1995-2004, which implies that the bottom-up emissions only cover the total HCFC-141b emissions by about 60-85%, dependent on the specific year.

- The emissions of HCFC-142b from closed cell foams are almost all originating in the developed countries. However, this may change in time if markets for extruded polystyrene foam continue to develop in China.

- No banks or emissions for HCFC-142b are cited in the refrigeration sector, although it should be noted that there is some HCFC-142b use in specific refrigerant blends (e.g. R-409A and R-409B)

- Total global emissions of HCFC-142b increase from 1,000 to 10,000 tons over the period 1990-2000, after which they decrease again;

- Short-term emissions of HCFC-142b are estimated to have been relatively large, in particular until 2000, after which year they are much smaller. The estimates for short-term emissions are between 1,000 and 20,000 tons for the period 1991-2000, which implies that the bottom-up emissions cover the total HCFC-142b emissions by about 40-70%, dependent on the specific year. It needs further study where precisely the sources are for these short-term HCFC-142b emissions.

6 Global Emissions Derived from Atmospheric Measurements

6.1 Introduction

Changes in the global atmospheric burden of a trace gas (dG/dt) arise from an imbalance between emissions to the atmosphere and losses (the amount of gas irreversibly removed from the atmosphere):

$$dG/dt = \text{Emission} - \text{Loss} \tag{1}$$

where emission and loss are considered over a finite time period, for example, 1 year. A simple rearrangement of this equation provides the fundamental relation that allows annual emissions of a trace gas to be derived from atmospheric data:

$$\text{Emission} = dG/dt + \text{Loss} \tag{2}$$

Emissions can be derived from atmospheric observations because observations provide a direct estimate of dG/dt, the change in global atmospheric burden of a trace gas. Furthermore, because loss processes can generally be considered 1st order (i.e., they are proportional to the trace gas burden), atmospheric measurements also provide an important component to accurately estimating halocarbon losses: a measure of the atmospheric burden of a trace gas. The second critical component to estimating loss concerns the rate at which a trace gas becomes irreversibly removed from the atmosphere, either by photochemical oxidation, photolytic destruction, hydrolysis, or other processes. These rates can be derived from laboratory measurements and an understanding of global oxidant levels or global radiation fields. This information is propagated to the entire atmosphere with the aid of models to provide reasonably accurate estimates of global lifetimes and loss rates of longer-lived trace gases. These rates can also be derived independently from model calculations with trace gas observations in the stratosphere (Volk et al., 1997).

Emission magnitudes derived from atmospheric observations have uncertainties related both to the atmospheric measurements and to the estimates of loss. These uncertainties arise primarily because of instrumental analysis errors, errors associated with estimating global means from a small number of sampling sites, and errors associated with loss estimates. Because the main focus of this report is to explore the differences between emissions derived from “bottom-up’ analyses and those derived from atmospheric measurements, the focus of Chapter 6 is to explore the magnitude of uncertainties on emissions derived from atmospheric measurements that arise from these potential sources of error.

An understanding of the dependence of emission estimates on these uncertainties can be provided by considering a multiplicative scaling factor δ related to uncertainties in the observations:

$$\text{Emission} = d(G*\delta)/dt + (G*\delta)*k \qquad (3)$$

Here, loss is expressed as a pseudo, 1st order rate constant, k, and the inverse of k is the halocarbon atmospheric lifetime. If the errors represented by δ scale consistently across all regions of the globe, then:

$$\text{Emission} = \delta(dG/dt + G*k) \qquad (4)$$

and it is apparent that errors in emissions derived from observations are directly proportional to observational uncertainties. Although the magnitude of representation errors, i.e., those associated with estimating global halocarbon mixing ratios from a small number of sampling sites, may not scale consistently across the global atmosphere, in this analysis it has been assumed that these errors can be approximated in this way. From Equation 4, it also is apparent that uncertainties in emissions have a more complex relationship to uncertainties in loss rate constant k, and that these uncertainties scale by the atmospheric burden of the halocarbon.

6.2 Atmospheric measurements

Two to three independent laboratories or groups have regularly measured CFC and HCFC abundances at multiple sites across the globe over the past two or three decades (Table 6-1).

Table 6-1 Atmospheric sampling networks

Group	*Techinque/Sample Frequency*	*# of Sites Used_to Derive Global Means*
AGAGE[*]	in situ GC-ECD/multiple day^{-1}	4 sites/CFCs; since 1978
	in situ GC-MS/multiple day^{-1}	2 sites/HCFCs; since 1994 or 1998[**]
NOAA/ ESRL[*]	in situ GC-ECD/multiple day^{-1}	5 sites/CFC-11, CFC-12; since 1978
	Flask samples by GC-MS/2-5 mo^{-1}	8 sites/HCFCs; since 1992
UCI[*]	Flask samples by ECD, 4 yr^{-1}	40-45 pacific sites/CFCs; since 1988

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[*] AGAGE is the Advanced Global Atmospheric Gas Experiment (Prinn *et al.*, 2000); NOAA/ESRL is the National Atmospheric and Oceanic Administration/Earth System Research Laboratory (Elkins *et al.*, 1993); UCI represents the efforts of Professors S. Rowland and D. Blake at the University of California at Irvine (Blake, 2005). GC-ECD = gas chromatography with electron capture detection, GC-MS = gas chromatography with mass spectrometry detection.

[**] AGAGE GCMS data began in 1994 at Mace Head and 1998 at Cape Grim.

Different calibration techniques, instrumentation, and sampling strategies are used by these groups to derive global surface mixing ratios based upon measurements at selected ground-based stations. As a result, these different groups provide independent estimates of the global atmospheric burden and burden rate of change for halocarbons, and, therefore, global halocarbon emissions (Figure 6-1). The different methodologies employed by these groups allow an assessment of the magnitude of errors in global emissions derived from atmospheric data that are associated with instrumental analysis and estimating global means from a small number of different sampling sites. Other groups make regular measurements of halocarbon surface mixing ratios at sites in only the Northern or Southern Hemisphere and these results provide additional constraints on uncertainties associated with instrumentation and calibration errors.

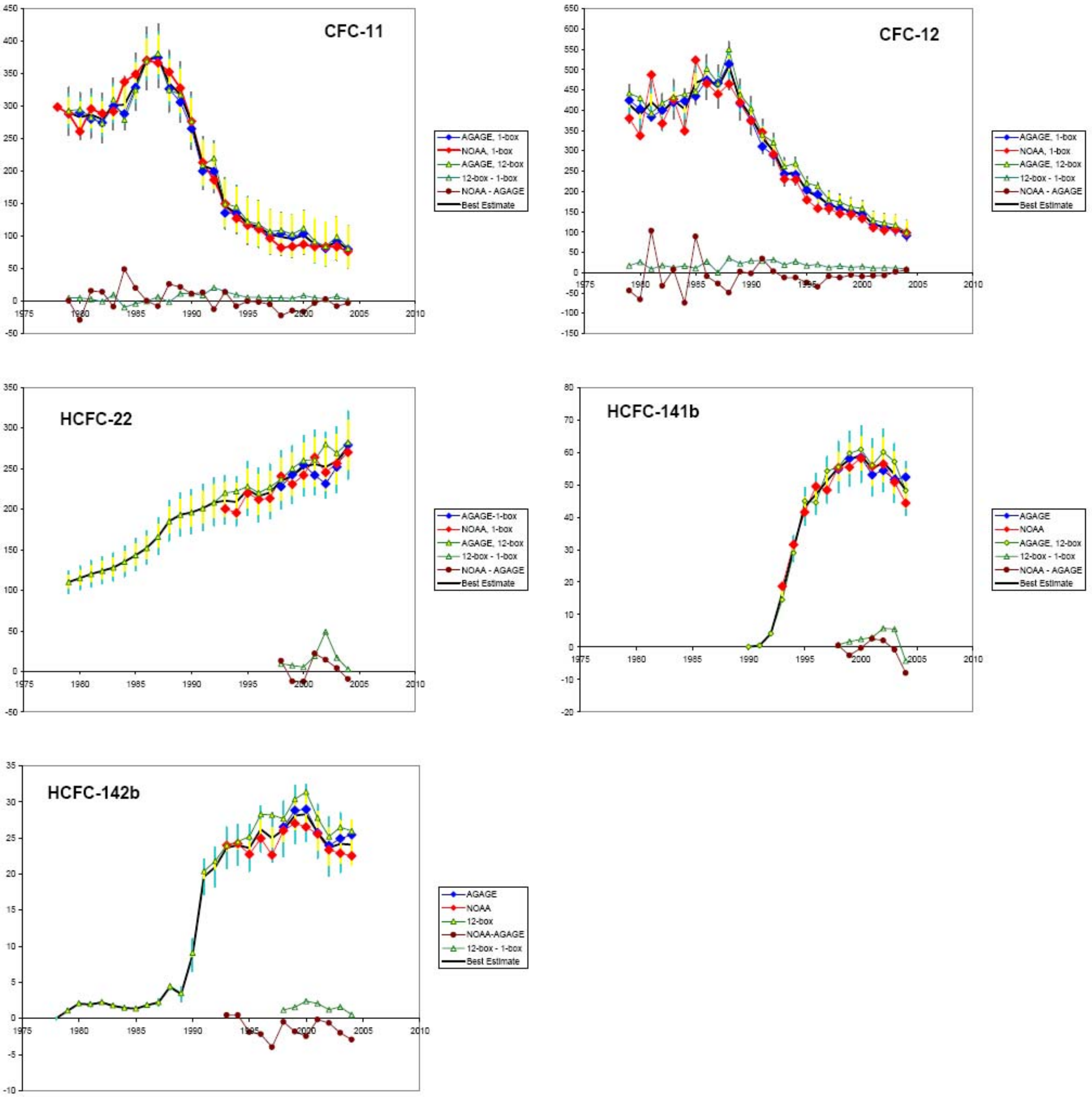


__Figure 6-1 Global annual emissions (in kt/yr or 10^9 g/yr)__ inferred from atmospheric observations independently determined by different groups (NOAA—red diamonds, 1-box model; AGAGE—blue diamonds, 1-box model; UCI—green diamonds, 1-box model; AGAGE—green/yellow diamonds, 12-box model). Best estimate emissions are plotted as a mean of AGAGE (1-box), AGAGE (12-box), and NOAA (1-box) after corrections based upon calibration differences were accounted for. Best estimate and AGAGE (12-box) emissions for HCFCs in the years before 1993 are derived from a 12-box analysis of archived samples collected only at Cape Grim, Tasmania (no additional representation error has been added during this period). Uncertainties are plotted on the best estimate results from multiple influences: Yellow = lifetime uncertainty only; blue = combined uncertainty of analysis, representation, and lifetime errors; gray = combined uncertainty but with representation errors doubled (CFCs only).

6.3 Uncertainty arising from instrumental analysis, calibration accuracy, and measurement precision

The determination of global emission rates and changes in emissions over time from atmospheric measurements requires an instrumental analysis system that is accurate, precise, and consistently calibrated over long periods. Errors in inferred emissions are directly proportional to inaccuracies associated with instrumental and calibration accuracy errors. The accuracy of a measurement is difficult to ascertain exactly; in practice, a rough gauge of accuracy can be obtained by considering the consistency among results from independent laboratories that employ different measurement and standardisation techniques. A number of laboratories make regular ambient air measurements at some identical locations. Data from these common sampling locations provide important constraints on measurement errors arising from instrumental analysis and calibration.

Table 6-2 Halocarbon mixing ratios reported by different networks

Table 6-2a Individual sampling event comparisons at a common site

Lab (site)	*Date range*	*Ratio of results between labs, expressed as: [(lab X / AGAGE – 1)*100] (1.s.d), # of discrete comparisons*
HCFC-22		
NOAA(MH)	‘99-’02	0.5(0.7), 18
NOAA(CG)	’98-’02	-0.3(0.8), 136
UEA(CG)	‘98-’01	0.0 (1.3), 19
SIO(CG)	‘98-’01	-0.1(0.8), 43
HCFC-141b		
NOAA(MH)	‘98-’02	-0.1(1.5), 24
NOAA(CG)	’98-’02	-0.7(1.0), 119
UEA(CG)	‘98-’01	3.7(1.6), 22
NIES(CG)	‘00-’01	-2.0(2.6), 42
HCFC-142b		
NOAA(MH)	‘98-’02	-4.7(1.5), 23
NOAA(CG)	’98-’02	-4.8(1.5), 139
UEA(CG)	‘98-’01	-1.1(3.4),20
NIES(CG)	‘00-’01	-5.1(2.9), 44

Adapted from O’Doherty *et al.* (2004). Sampling sites include Cape Grim, Tasmania (CG) and Mace Head, Ireland (MH). Institutions involved in the comparison included UEA = University of East Anglia; SIO = Scripps Institute of Oceanography; NIES = National Institute for Environmental Studies. Results from flask samples were compared to an AGAGE in situ measurement if the samples were collected within 3 hrs of one another.

Table 6-2b A comparison of annual means at individual sites and annual means estimated for the globe at Earths' surface made by different groups

Chemical	*Group*	*Site-to-site annual means, comparisons to AGAGE$^{\#}$ (1s.d.), (n)*	*Global annual means, comparisons to AGAGE$^{\#}$ (1s.d.), (n)*
CFC-11			
	NOAA	**+1.9**(0.08)%, 15 (Samoa)	**+1.4**(0.6)%, 15
	UCI	*n.a.*	**+0.2**(0.2)%, 15
CFC-12			
	NOAA	**−1.4**(0.5)%, 18 (Samoa)	**−1.3**(0.4)%, 15
	UCI	*n.a.*	**−1.3**(0.2)%, 15
HCFC-22			
	NOAA	**−0.2**(0.5)%, 7 (C. Grim)	**−1.3**(1.0)%, 13
	NOAA	**+0.1**(1.2)%, 3 (M. Head)	
HCFC-141b			
	NOAA	**−1.3**(0.7)%, 7 (C. Grim)	**+0.2**(2.9)%, 13
	NOAA	**−2.1**(1.6)%, 3 (M. Head)	
HCFC-142b			
	NOAA	**−3.3**(0.7)%, 7 (C. Grim)	**−5.4**(1.1)%, 13
	NOAA	**−2.1**(1.6)%, 3 (M. Head)	

n.a. = not available.

- Data and calibration comparisons are taken from Elkins *et al.* (1993), Montzka *et al.* (1999), Prinn *et al.* (2000), O'Doherty *et al.* (2004), Blake (2005), and updates to these studies.
- Differences are expressed relative to the AGAGE result, for example, as [(UCI – AGAGE)/AGAGE]*100.
- from over 3 years of monthly means differences measured from samples collected at Mace Head (2001.5-2004), and 6 years of monthly mean differences measured at Cape Grim (1998-2004). Results are reported as the mean difference with 1 standard deviation on that mean difference given in parentheses; n is the number of years included in the comparison.

Comparisons for HCFCs have been performed in the past based upon flask samples and samples collected and analysed by an instrument on site provided the 2 samplings were within a time window of +/-3 hrs (Table 6-2a). Comparisons of this type among 4 independent laboratories show mean differences whose range is <1% for HCFC-22, <6% for HCFC-141b, and <5% for HCFC-142b (O'Doherty *et al.*, 2004).

Furthermore, data from these common sites can allow an assessment of different sampling schemes for estimating annual mean mixing ratios at any individual site. Annual means are derived for HCFCs by AGAGE based upon air samples collected multiple times per day, while these annual means are derived by NOAA based upon only a few flask samplings per month (Table 6-2b). For the HCFCs, the differences in annual means estimated at individual sites are fairly consistent with the sample-to-sample differences between NOAA and AGAGE appearing in Table 6-2a, which suggests that the discrepancies in monthly or annual means at individual sites arise primarily from calibration differences. It appears that the different methodologies used by AGAGE and NOAA to derive annual means at these common surface sites do not substantially influence these estimates.

With regard to CFC measurement consistency, comparisons between AGAGE and NOAA are possible at Samoa, where both groups estimate monthly and annual means from instruments collecting and analysing multiple samples per day. A comparison of results for CFC-11 and CFC-12 from these two independent groups at Samoa indicates that annual mean mixing ratios reported by these different groups for these trace gases at the same station are not more than 2% different (Table 6-2b).

When the differences between annual means estimated at common sites by NOAA and AGAGE are considered together with calibration differences among all laboratories (Tables 6-2a and 6-2b), the magnitude of potential systematic errors in calculated emissions arising from errors in measurement calibration, instrument operation, or sampling schemes are estimated to be <2% for CFCs and HCFC-22, and up to 6% for HCFC-141b and HCFC-142b.

Calibration scale consistency over multiple years is another essential component to the accurate derivation of global emissions from atmospheric data. Even small errors in the propagation of a calibration scale can lead to quite large errors in inferred emissions. For example, an erroneous step change of 1% in a single year during 1978 – 2005 for the global mixing ratio of CFC-11 would lead to a 40 – 60 Gg error (10 – 70% error) in inferred emission. While such an error could arise from improper propagation of calibration standards, other influences could produce step changes in mixing ratios and inferred emissions, such as imprecise measurements or year-to-year variations in atmospheric transport that influence a global mean mixing ratio estimate derived from a small number of sampling stations. Such influences would likely lead to imprecise estimates of annual emission rates (or noisy estimates) rather than systematic errors; this noise can be minimised by averaging mixing ratio changes and inferred emissions over multiple years. Errors related to poor calibration consistency or imprecise measurements may be identified by inconsistencies in annual emissions inferred from observations by independent laboratories. Variations in transport that affect atmospheric mixing ratio gradients unusually in one year compared to another also will be expressed as enhanced variability in derived annual emissions, provided the changes in transport are not systematic. These influences may explain the fairly large differences in annual emissions inferred by NOAA and AGAGE for CFC–12 in the early to mid-1980s and by UCI in the late 1980s to early 1990s (Figure 6-1). Discrepancies among annual emissions estimates derived by different groups have become smaller in recent years, most likely because of improvements in instrumentation and calibration techniques over time, and because of reduced tropospheric variability in mixing ratios of these gases as emissions have declined.

Table 6-3 Top-down halocarbon emissions derived from NOAA, AGAGE, and UCI sampling networks and an error estimate from the influences of uncertainties in instrumental analysis and calibration, surface and vertical representation errors, and lifetime (see Table 6-4)

	CFC-11			CFC-12			HCFC-22			HCFC-141b			HCFC-142b		
YEAR	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low
1979	291	319	268	415	442	389	110	124	97	0	0	0	1	1	1
1980	283	311	260	389	416	365	115	130	101	0	0	0	2	2	2
1981	287	317	263	421	451	393	120	136	105	0	0	0	2	2	2
1982	280	311	255	394	422	368	124	141	108	0	0	0	2	2	2
1983	302	334	275	425	456	398	128	146	111	0	0	0	2	2	2
1984	302	337	275	403	432	376	135	154	117	0	0	0	1	2	1
1985	335	371	306	468	502	436	143	163	124	0	0	0	1	2	1
1986	371	409	340	479	514	448	152	173	132	0	0	0	2	2	2
1987	375	415	343	457	490	426	166	189	145	0	0	0	2	2	2
1988	336	376	304	508	545	475	185	210	161	0	0	0	4	5	4
1989	318	360	286	424	459	394	193	220	168	0	0	0	3	4	3
1990	274	315	242	384	418	355	196	224	170	0	0	0	9	10	8
1991	208	249	177	331	365	303	201	230	174	1	1	0	20	22	17
1992	203	243	172	300	333	273	208	238	180	4	5	4	21	23	19
1993	145	187	114	244	275	220	210	241	182	17	19	15	24	26	21
1994	136	176	107	246	277	221	209	240	180	30	34	26	24	27	21
1995	119	159	90	201	230	177	224	258	192	43	49	38	24	26	21
1996	114	153	85	187	217	164	216	250	185	47	53	41	26	29	23
1997	102	141	74	168	198	144	220	255	188	51	59	44	25	28	22
1998	99	135	72	158	188	135	235	272	201	55	63	48	26	30	23
1999	96	132	68	151	181	128	241	278	207	58	66	50	28	32	24
2000	101	138	74	144	174	121	252	291	216	59	68	51	28	32	24
2001	88	126	60	119	149	96	255	297	218	55	64	47	26	30	22
2002	83	121	55	112	142	90	252	295	213	57	67	48	24	28	20
2003	92	129	64	109	140	86	259	301	221	53	63	45	24	28	20
2004	79	116	52	96	127	73	277	320	237	48	57	41	24	28	20

*Emissions are a weighted average of those derived by the following networks and calculation methods: NOAA (1-box), AGAGE (1-box), and AGAGE (12-box). The weightings were derived considering Table 6-2 and were as follows: for CFC-11: AGAGE+0.9%, NOAA-0.9%; for CFC-12: AGAGE-0.7%, NOAA+0.7%; for HCFC-22 and HCFC-141b: no adjustments; for HCFC-142b: AGAGE+3.9%, NOAA+0.9%. The high and low estimates reflect the propagation of uncertainties listed in Table 6-4.

6.4 Uncertainty in estimating global mean halocarbon burdens and changes from a small number of surface sampling sites (representation error)

The derivation of global halocarbon emissions from atmospheric observations requires that the observations provide a measure of the global halocarbon burden and time-dependent changes in this global burden. Because air-monitoring stations are limited in number and limited to surface or near-surface locations, data from these stations must be extrapolated to provide estimates of global mean burdens and changes.

6.4.1 Surface representation errors

Errors in estimates of global mean halocarbon burdens are introduced by extrapolating observations at a limited number of sites to the entire globe. These errors are enhanced particularly when large mixing ratio gradients exist at Earth's surface but are not adequately characterised by the sampling network. Tropospheric gradients and representation errors at Earth's surface can be substantial for gases with large emissions or lifetimes that are comparable to atmospheric mixing times (on the order of ≤0.5 yr). These errors also are dependent upon site location—samples from sites far removed from emissions will provide results that are less directly influenced by these emissions and that are representative of the largest atmospheric region possible, not just the local environment.

Surface gradients in mixing ratios of long-lived CFCs and HCFCs develop at Earth's surface primarily from the spatial heterogeneity of emissions. As a result, some sampling networks have more sampling sites in the Northern Hemisphere, where most of the halocarbons are released, in order to capture gradients in the remote atmosphere arising from these emissions. Furthermore, because atmospheric mixing rates in the troposphere are more rapid across longitudes than latitude, broad-scale gradients arising from emissions are expected across latitudes. Accordingly, more accurate global surface means are expected from a network of sampling sites situated over a wide range of latitudes rather than longitudes. Finally, global surface means are typically derived with weighting factors to account for the mass of air that is characterised by data from any individual site.

Gradients in mixing ratios of CFCs at the surface owing to loss processes are quite small because loss is exclusively in the stratosphere (Nevison *et al.*, 2004). For HCFCs, surface gradients can be enhanced owing to tropospheric loss via OH oxidation, though this influence is not substantial for HCFCs with long lifetimes. For example, intrahemispheric surface mixing ratio gradients observed for CH_3CCl_3 (lifetime ~5 yr) in the absence of significant emissions are on the order 3-4% (Montzka *et al.*, 2000). The lifetimes of the HCFCs considered here are ≥10 yr, however, and would suggest an influence of losses on surface gradients to be substantially less than observed for CH_3CCl_3.

Based upon these considerations, smaller surface representation errors are expected for CFCs in recent years compared to the 1980s, but potentially larger surface representation errors are possible for HCFCs recently. A qualitative estimate of surface representation error can be obtained from differences in global means derived by different networks and data from largely independent sampling locations after differences in calibration are considered (Table 6-2b).

Differences in annual global surface means derived by the AGAGE and NOAA networks are 1.4(0.6)% for CFC-11 and –1.3(0.4)% for CFC-12, or nearly identical to the differences in annual means measured by these two groups for these gases at Samoa only. These considerations suggest that uncertainties in estimates of global surface means arising from surface representation errors for CFCs owing to sampling the atmosphere at only 4 to 5 stations is <1%.

For HCFCs, differences in global means derived by the different sampling networks are comparable to those expected based upon instrumental and calibration scale differences. There is a suggestion that global means derived for HCFC-22 and HCFC-142b are 1 to 3% larger than expected from common site comparisons, though these differences are comparable to the magnitude of variability in these differences from year-to-year (Table 6-2). The results imply that the representation of global surface means for HCFCs may be on the order of a few percent.

The magnitude of these representation errors are supported by previous modeling work, which suggested that sampling error associated with estimating global mean surface mixing ratios of CFC-11 from the ALE/GAGE/AGAGE sites in the 1980s was less than 2% (Prather *et al*., 1987).

6.4.2 Vertical representation errors

Surface-based observations of long-lived trace gases at remote locations are able to fairly accurately characterise halocarbon burdens throughout much of the troposphere because vertical mixing in the troposphere is relatively rapid. Substantial vertical gradients are possible in the troposphere, but these areas are typically restricted to regions strongly influenced by emissions. By situating sampling stations well away from local sources these influences are minimised.

Strong mixing ratio gradients persist for CFCs and HCFCs vertically within the stratosphere, however, that are not well characterised by surface-based sampling. These gradients arise because the stratosphere is not well mixed and because CFCs and HCFCs undergo strong photolytic loss in the upper stratosphere. As a result, halocarbon mixing ratios decrease substantially in the upper stratosphere. Furthermore, additional mixing ratio gradients can develop between the troposphere and stratosphere because it can take up to 6 years for tropospheric changes to become transported to some regions of the stratosphere.

Owing to the expense and impracticality of making highly accurate and precise measurements throughout the entire atmosphere, vertical mixing ratio gradients of halocarbons are not as well characterised as those across Earth's surface. Measurements from satellite, aircraft and balloon platforms have provided much information about vertical halocarbon gradients (Volk et al. 1997; Walmsley et al., 1998; Engel et al., 1998; Schauffler et al., 2003; Rinsland et al., 2005). These observations have added substantially to our understanding of halocarbon atmospheric distributions and have allowed for realistic estimates of transport rates and loss rates of halocarbons in the stratosphere. These parameters are incorporated into models of varying complexity so that global mean burdens can be derived from surface observations. In 1-box models, the influence of a vertical gradient is accounted for with a vertical scaling factor that is applied to the measured surface mixing ratio that relates the mean global mixing ratio to that measured at the surface. In many past Scientific Assessment reports, this scaling factor was estimated to be a constant 1.07 (e.g., Chapter 1 in WMO, 2003, see also Daniel et al., 2006), or similar to that estimated directly from atmospheric observations in 1994 (1.06 for CFC-12 and 1.08 for CFC-11; Volk et al., 1997). During periods of fairly constant emissions or constant atmospheric growth, the errors induced by a constant scaling factor are minimised. When emissions and mixing ratios gradients change substantially, however, this approach can lead to larger uncertainties. In some recent work, a time-dependence to this vertical scaling has been included in 1-box model calculations (e.g., Velders et al., 2005). In that report the time dependence of the vertical scaling factor was derived from a 12-box model calculation.

Conversely, the magnitude of vertical representation errors can be investigated with multidimensional models in which halocarbon distributions are calculated throughout the entire atmosphere based upon specified rates of emission, transport and loss (Fraser et al., 1999; Cunnold et al., 1997; Huang and Prinn, 2002). It is a fairly straightforward process to invert this calculation to provide estimates of emissions from a specified time series of surface mixing ratio observations. This type of approach should provide a more realistic simulation of time-dependent changes in halocarbon atmospheric distributions and loss rates than those derived from a 1-box calculation. Emissions derived with the AGAGE 12-box model using this approach are, on average, 5 Gg/yr higher for CFC-11 and 18 Gg/yr higher for CFC-12 than calculated with the simple 1-box model using a consistent atmospheric distribution over time and the steady state lifetime (Figure 6-1, brown circles). Though these differences are generally small compared to the overall uncertainties in the derived emissions, they suggest a systematic difference that could substantially affect bank magnitude estimates that are derived from atmospheric measurements and halocarbon production figures.

Based upon the differences in emissions derived from the 12-box and 1-box model calculation, and considering that the magnitude of this influence is limited because the mass of the stratosphere is only 15-20% of the mass of the troposphere, an uncertainty of 5% for CFCs and 10% for HCFCs is applied to emissions estimates owing to vertical representation errors in the present analysis (Table 6-4).

Table 6-4 Propagation of errors on estimates of global halocarbon emissions (%)

	Analysis & calibration	Representation (surface)	Rep (vertical)	lifetime* (year)
CFC-11	2	1	5	27
CFC-12	1.5	1	5	26
HCFC-22	1	2	10	17
HCFC-141b	6	2	10	24
HCFC-142b	5	2	10	20

Note: these uncertainties are incorporated into the results given in Table 6-3. Figure 6-1 also includes error bars where representation errors for CFC-11 and CFC-12 have been doubled for all years.

* The uncertainties quoted here on lifetime are based upon multiple model estimates of the lifetime and the results of Volk et al. (1997)—the uncertainties on derived emissions that stem from lifetime uncertainties are time-dependent and different from the percentage given here because they scale with the global mixing ratio.

6.4 Uncertainty arising from trace gas lifetimes

As mentioned in the introduction to Chapter 6, accurate estimates of emissions can be derived from observed atmospheric mixing ratio changes only when halocarbon losses are accurately estimated. Both CFCs and HCFCs are slowly removed from the atmosphere through photolytic and photochemical processes. Laboratory studies provide estimates of reaction rate constants and the efficiency of light absorption by halocarbons that leads to photodecomposition. Loss rates can then be inferred from an understanding of the global distribution of atmospheric oxidants (such as the hydroxyl radical), the atmospheric flux of ultraviolet and near ultraviolet light, and the atmospheric distribution of the chemical of interest. Atmospheric loss rates also have been derived directly from atmospheric observations (Volk et al., 1997).

For CFCs, atmospheric loss is dominated by photolytic reactions in the stratosphere, where the atmospheric flux of high-energy solar radiation is the greatest. Estimates of lifetime are made with multidimensional atmospheric models that incorporate the laboratory estimates of photodecomposition as a function of radiation wavelength, the flux of light in the atmosphere as function of location and season, air mixing rates, and the distribution of the trace gas. Considering the interaction of these processes and the distribution of the trace gas, a loss frequency or atmospheric lifetime (the inverse of the loss frequency) can be calculated with an appropriate model. Such a lifetime is most generally calculated at steady state, when the distribution of the halocarbon is unchanging with time, and emissions, sinks, and atmospheric transport are in long-term balance.

Estimates of lifetime have also been derived from atmospheric observations (Volk et al., 1997). These estimates are particularly useful because they are entirely independent of lifetimes calculated in models. These estimates rely on the correlations between different trace gases in the lowermost stratosphere to yield stratospheric loss rates. Because CFCs are destroyed exclusively in the stratosphere, this method yields estimates of global atmospheric lifetimes of these gases. Stratospheric observations of SF_6 provide a record of mean elapsed time an air parcel has remained in the stratosphere. Reconciling expected mixing ratios of halocarbons based on concurrently measured SF_6 with observed halocarbon mixing ratios allows an estimate of halocarbon loss rates in the stratosphere. Corrections are applied to derive steady-state lifetimes A second benefit of the Volk et al. (1997) study was that it derived relative stratospheric loss rates, or lifetimes, with fairly small uncertainties. This observational-based study suggests, for example, that the stratospheric (and, therefore, global) lifetimes of CFC-12 and CFC-11 are different by about a factor of 1.9 (±0.2).

Table 6-5 Lifetimes (year) for halocarbons derived from multiple models (from Kurylo et al. 1998, Table 1-4) and independently from stratospheric observations (Volk et al., 1997).

Chemical	*10 model mean (s.d.)*	*Observed Volk A*	*Observed Volk B*	*Best estimate (s.d.)*
CFC-11	51(10)	41(12)	na	45 (35-57)
CFC-12	106(17)	77(26)	87(17)	100 (79-125)
HCFC-22	na	na	na	12.0 (±17%)
HCFC-142b	na	na	na	17.9 (±24%)
HCFC-141b	na	na	na	9.3 (±20%)

* Volk estimates are steady-state lifetimes derived from observed atmospheric gradients in the lower stratosphere (Volk et al. (1997, Table 5) and are corrected with two different methods: 'A' includes a correction based on stratospheric age of air, and 'B' includes a correction based upon the observed correlation to CFC-11 in stratospheric air and an assumed lifetime of 45(7) yr.

* For the CFCs, the best estimates are from WMO (2003); the stated uncertainty on these best estimates are obtained by taking the root mean square sum of the variances from the model-based estimates (Kurylo *et al.*, 1998) and the variances given by Volk et al. (1997).

Because of the differences in models and their treatment of atmospheric processes, a range of steady-state lifetimes can be calculated for the CFCs (Table 6-5). The mean of these results suggests a steady-state lifetime for CFC-11 of 45 (35-57) years, and for CFC-12 of 100 (79-125) years. The uncertainties quoted on the CFC lifetimes are derived from the range of model calculated lifetimes plus an additional uncertainty from the (Volk *et al.*, 1997) estimates. The observationally derived estimates of steady-state lifetimes are 41 ± 12 yr for CFC-11 and 77 ± 26 yr for CFC-12 (Volk *et al.*, 1997). The results from these two independent approaches suggest comparable lifetimes for the CFCs (Table 6-5). For HCFCs, loss is predominantly from tropospheric oxidation by the hydroxyl radical, though photolysis in the stratosphere plays a significant role. Lifetime uncertainty ranges are obtained by combining the uncertainty in the global hydroxyl radical burden of 14% given by Prinn et al. (2001) with the uncertainties in the reaction rates between the HCFCs and the hydroxyl radical from Sander et al. (2005). The uncertainty in the hydroxyl radical burden is derived from a budget analysis of methyl chloroform observations and emissions derived from industrial production figures. This analysis gives overall lifetime uncertainties of ±17% for HCFC-22, ±20% for HCFC-141b, and ±24% for HCFC-142b.

In order to facilitate model inter-comparisons, halocarbon lifetimes are generally calculated for steady-state conditions. Under non-steady state conditions, actual halocarbon lifetimes will be different than those at steady-state. Lifetimes depend upon halocarbon distributions because loss rates vary in different regions of the global atmosphere. When the atmospheric distribution of a halocarbon changes such that a higher percentage is present in a region with enhanced loss rates (the stratosphere for CFCs or the tropical troposphere for HCFCs), the atmospheric lifetime will be reduced. As emissions have declined and the fraction of the global burden of CFC-11 present in the stratosphere has increased, the lifetime of this gas has decreased. The AGAGE 12-box model calculation suggests that the lifetime of CFC-11 decreased by over 10% from 1980 to 2000. These influences are implicitly included in multi-dimensional model calculations and emissions derived from these models include these considerations. Simple, 1-box model calculations generally have not incorporated such time dependencies and these influences can potentially lead to significant differences in derived emissions. An assessment of the magnitude of this influence can be derived for CFCs by comparing emissions from a more complex model (e.g., a 12-box model) to that from a 1-box model in which the lifetime is fixed over all years. Despite the shortcomings of the 1-box model calculation, annual differences in calculated emissions between the 1-box and 12-box approach are generally <10 Gg/yr for CFC-11 and 10-30 Gg/yr for CFC-12. Emissions derived from the 12-box model are biased slightly higher than the 1-box calculation, however; the cumulative sum of emissions derived from the 12-box model approach from 1979-2004 is 140 Gg larger for CFC-11 and 470 Gg larger for CFC-12 than inferred with a simple 1-box model.

6.6 Emissions derived from atmospheric measurements.

The ‘top-down’ emissions derived from atmospheric observations suggest that emissions of CFCs in 2004 were only about 20% as large as they were in the late 1980s, when peak emissions occurred. Over this period emissions of HCFCs, however, have increased substantially. Independent sampling networks and calculation approaches have yielded fairly consistent ‘top-down’ emissions estimates for CFCs and HCFCs over the past 10 to 25 years (Figure 6-1). The differences among the networks are small compared to the changes implied in global emission rates over the past 10 to 25 years. The consistency among the networks implies well-maintained calibration scales and a network of sampling stations that are similarly capturing the global atmospheric changes in halocarbon mixing ratios over time.

Because relatively small emission differences are calculated with 1-box and 12-box models, for example, the additional processes and effects accounted for in the 12-box model have a fairly small influence on the derived emissions for these long-lived gases.

The uncertainties in emissions derived from atmospheric observations and this ‘top-down’ approach since 1990 are typically around ±(10 to 30)% . Most of this uncertainty arises from the relatively large uncertainty in halocarbon lifetimes (yellow error bars in Figure 6-1). Because this uncertainty scales with the halocarbon mixing ratio, they are largest in recent years. Uncertainties in top-down emissions from calibration differences and representation errors are smaller than those related to lifetime (compare yellow with blue error bars in Figure 6-1). Even if representation errors were doubled (gray bars, Figure 6-1) the uncertainty in derived emissions increases only slightly.

Most of the uncertainties discussed here do not impart random errors on calculated emissions. Potential errors in lifetime or calibration would result in emissions over the observational record that would be systematically different, within the error bars indicated, from the best estimate emissions in Table 6-4.

7 Comparison of emissions derived from bottom-up methods and from measured atmospheric concentrations

This chapter takes the outputs from the bottom-up modelling and atmospheric monitoring communities and makes comparisons of the data which reflect the level of confidence (degree of uncertainty) inherent in each of the approaches. In order to place the focus on chemicals where discussion is most needed, there is a short overview of the general results and specific findings followed by more in-depth discussion on anomalies and likely sources of continued discrepancy.

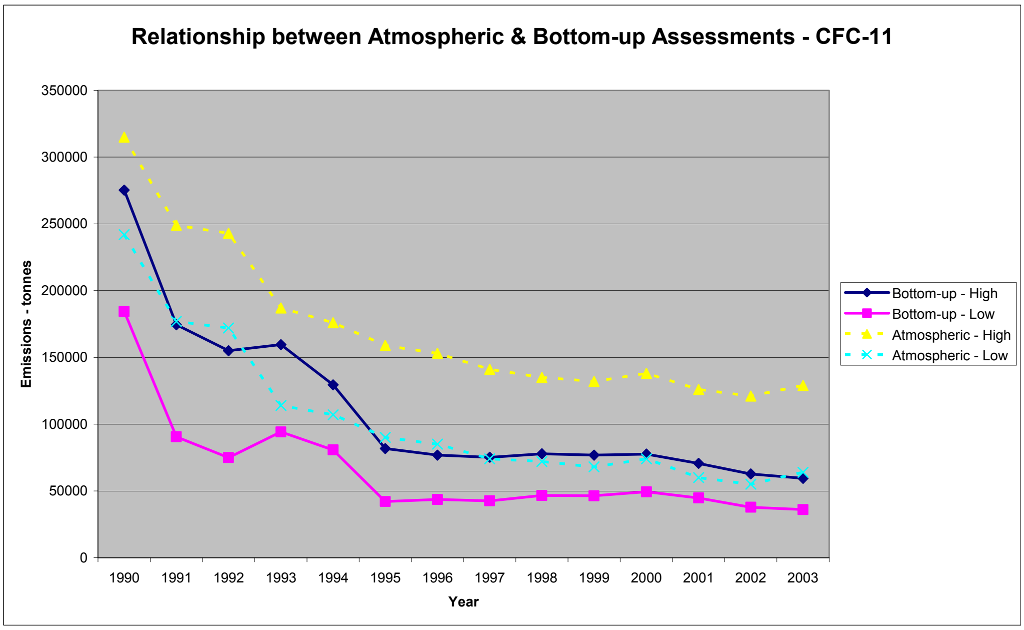
7.1 General observations on emissions data

With emission uncertainty ranges for both bottom-up modelled data and atmospheric monitoring data using the same methods of determining uncertainty ranges (root mean square sum methodology), it is generally gratifying to note that there are few occasions, (with the notable exception of CFC-11) where there is no ‘overlap’ between the annual emissions data derived from each source. Where such lack of overlap does exist, there are generally concerns over the quality of UNEP consumption data, which are often the most irregular of the inputs. This matter is discussed at greater length in the subsequent sections of this chapter.

7.2 Graphical comparisons and immediate observations

7.2.1 CFC-11 comparisons

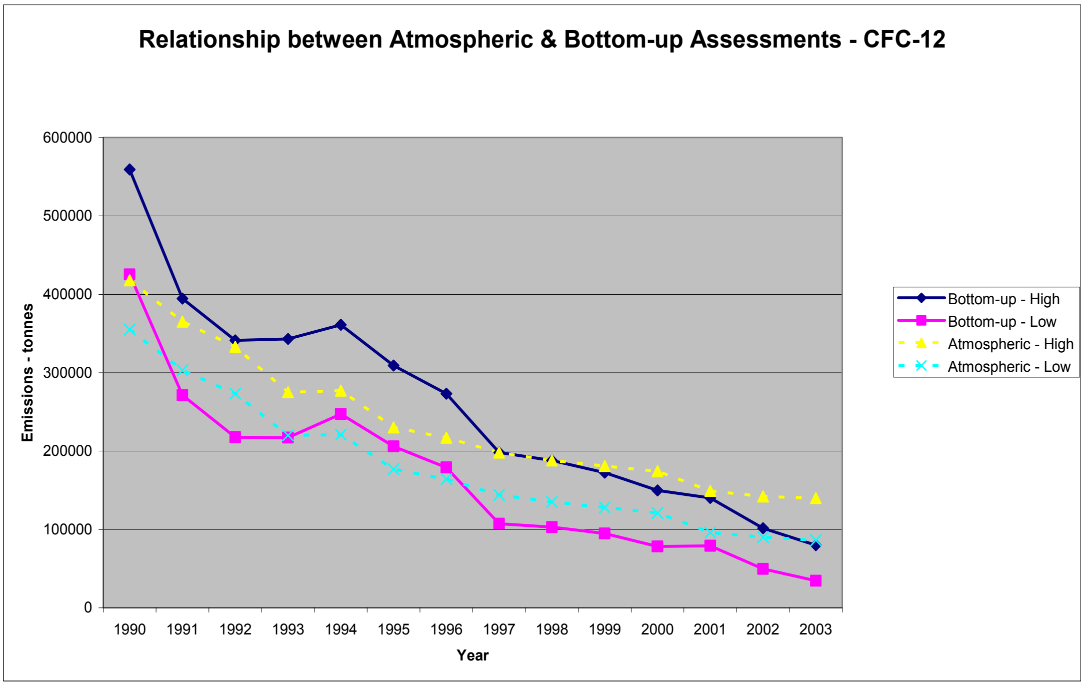
The following graph provides the comparison for CFC-11 bottom-up and atmospheric sources.



It can be seen that the general pattern is one where emissions derived from atmospheric measurements (top-down) are higher than derived from bottom-up methodologies. This difference persists despite the inclusion in this analysis of 10,000-25,000 tons of additional CFC-11 from short-term release applications annually in the period 1994-2003. As the use of CFC-11 has declined, the uncertainty in predicted bottom-up emissions has reduced, as expected. The uncertainty in the top-down method, however, has remained high owing to uncertainties in the atmospheric lifetime of CFC-11, which scale with its atmospheric abundance. Though the 1-sigma uncertainty bounds of the two approaches overlap in most years, the difference from 1990 through 2003 in the mean estimates of the different methodologies sums to 628 (-98 to 1490) Gg of CFC-11. This amounts to approximately 40% of the cumulative CFC-11 emissions over this same period. Nonetheless, this graph represents the most significant discrepancy issue for an individual chemical within this report and is the subject of greater analysis in section 7.3.

7.2.2 CFC-12 comparisons

The following graph provides the comparison for CFC-12 bottom-up and atmospheric sources.



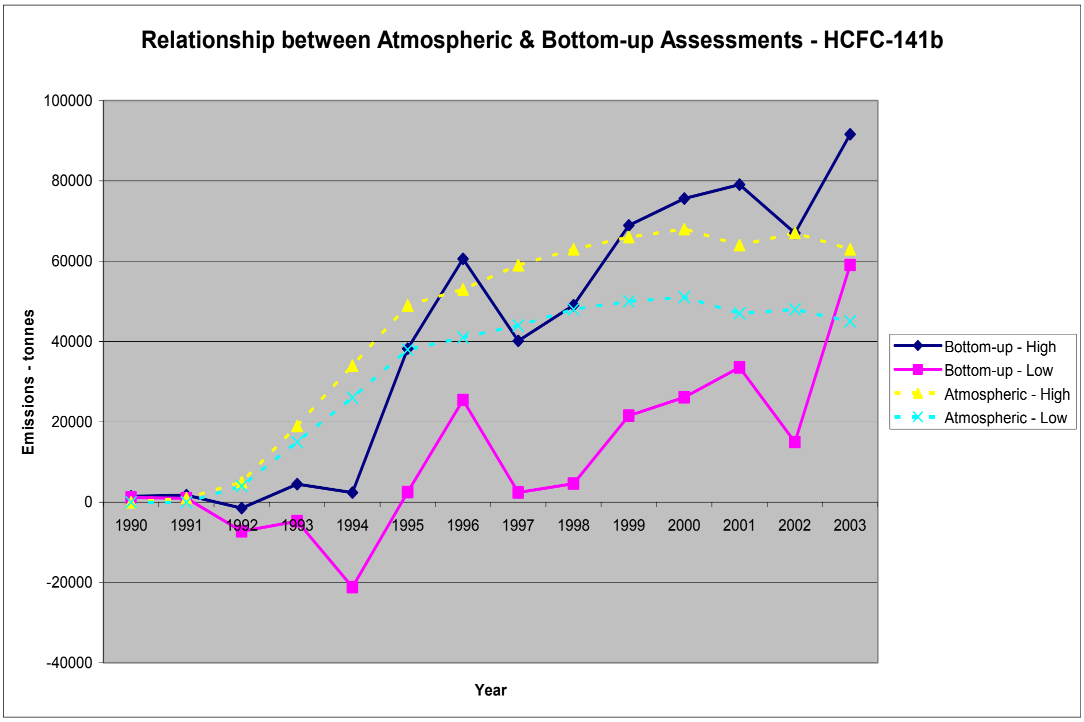
As can be seen, the relative shape and slope of emission decline is consistent between bottom-up and atmospherically derived estimates. The difference between cumulative emissions derived from top-down and bottom-up methodologies from 1990-2003 is only 100,000 Gg, or <4%. The years in which there is no overlap whatsoever are 1990 and 2003, with 2002 also being marginal. There is perhaps a hint that the atmospheric and bottom-up data sets are diverging in the post-2000 period, when uses in various sectors are known to have declined substantially in developed countries. Possible explanations for this trend would be:

- Under-reporting of CFC-12 consumption in developing countries via the UNEP dataset;
- Under-estimation of CFC-12 leakage during servicing operations;
- Under-estimate of on-going losses from other installed products.

In the current analysis, the under-reporting of UNEP consumption seems most likely based on the comparisons with bottom-up estimates. Throughout the period from 1996, there has been a consistent shortfall between the two. The data for 2004 and 2005 could provide further guidance on the most relevant interpretation, once available.

7.2.3 HCFC-141b comparisons

The following graph provides the comparison for HCFC-141b bottom-up and atmospheric sources.



This graph is unique within the set produced for this report, in that it illustrates the potential for an annual ‘negative’ emission as previously described in section 4.3 (there is also a minor example in the HCFC-142b graph – see 7.2.5). Where such events occur, it is most appropriate to look first at the UNEP consumption dataset to assess the cause. However, in doing so, it is important to recall that the emission ‘shortfall’ in 1994 reflects a consumption ‘shortfall’ in 1993. Inspection of the 1992-

1994 UNEP consumption dataset shows a growth curve which is significantly slower than that understood from the bottom-up foam consumption data. A similar observation can be made about the 1997 and 1998 emissions arising, in part, from 1996 and 1997 UNEP dataset consumption.

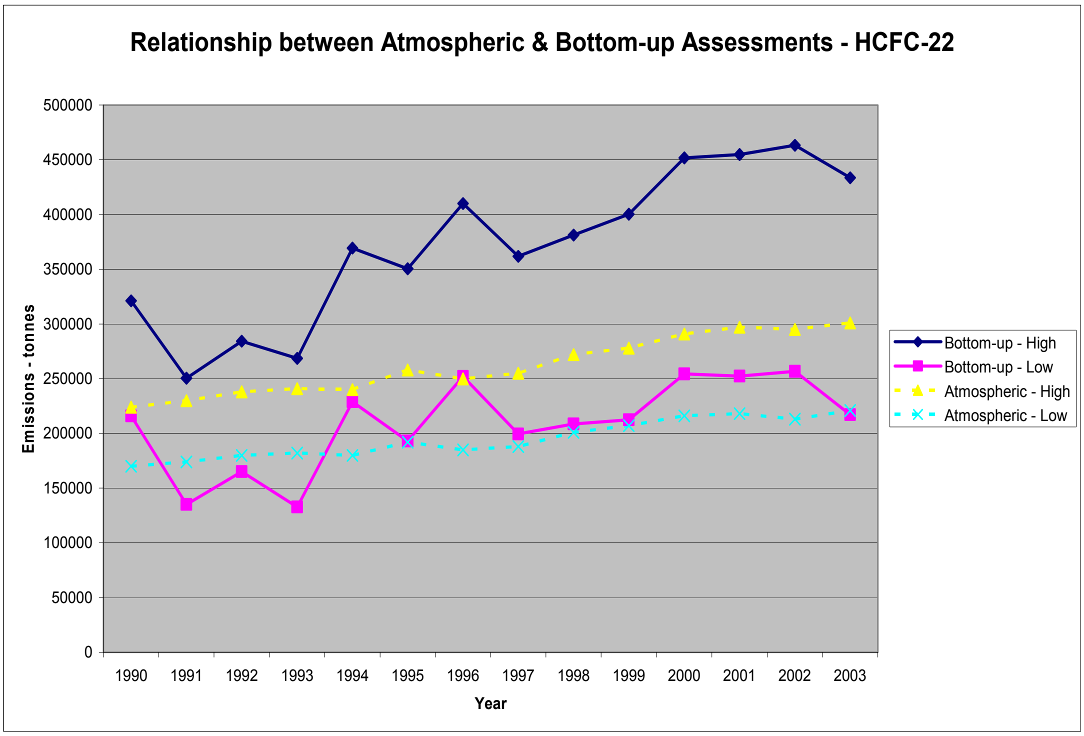
Further investigation of the history of UNEP reporting reveals that reporting Parties took some time to identify sources of production and consumption in their own countries, resulting in systematic under-reporting in the early years. In addition, there were issues over the ratification of the Copenhagen Amendment. This situation improved from 1995 onwards, although even in 1996 and 1997 the growth curve was still a little erratic.

The better alignment of emissions in the period from 1999-2002 could suggest that the earlier consumption estimates of the bottom-up foam models may have been realistic, particularly since the atmospheric measurements are slightly on the higher side of the bottom-up estimates in latter years. The bottom-up emissions figure for 2003 represents a substantial spike in UNEP reported consumption in 2002 and further data will be required for 2004 and 2005 before any conclusions can be drawn about its significance.

As a concluding observation, it should be noted that the size of uncertainty in the bottom-up assessment is being driven largely by the uncertainties in the UNEP dataset rather than in the foam bottom-up data, which is well studied through a number of sources (e.g. the Multilateral Fund Project statistics). The sensitivity is magnified by the fact that unaccounted for consumption is assumed to be emissive. Further work on the identification of non-foam HCFC-141b usage would therefore be valuable.

7.2.4 HCFC-22 comparisons

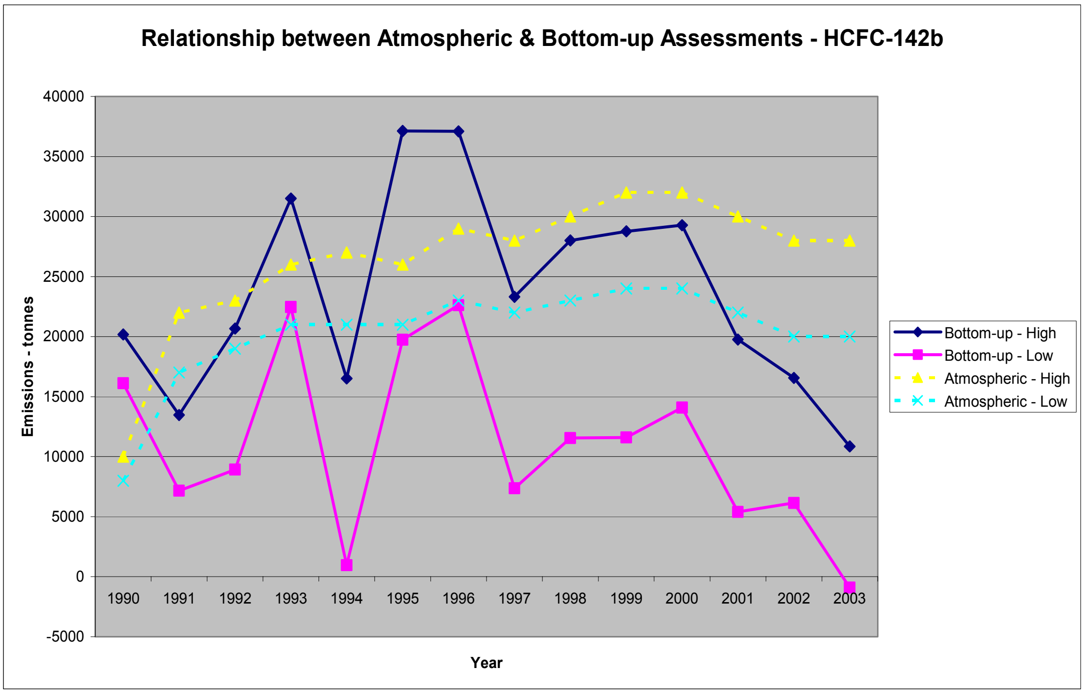
The following graph provides the comparison for HCFC-22 bottom-up and atmospheric sources.



In contrast to the latter years of the CFC-12 emissions comparison (also dominated by refrigeration emission sources), the HCFC-22 comparison shows a general tendency to over-estimate emissions in bottom-up assessments. However, it is clear that this observation is made in a framework where the general level of agreement between bottom-up and atmospherically derived emissions is good. Possible reasons for the difference between CFC-12 and HCFC-22 comparisons could relate to the period in the lifecycle involved, although it must be noted that many HCFC-22 uses are already many years old. It may just be that the consumption figures used to drive the bottom-up estimates are too high, particularly in the emissive applications derived from the UNEP consumption dataset.

7.2.5 HCFC-142b comparisons

The following graph provides the comparison for HCFC-142b bottom-up and atmospheric sources.



The first obvious factor to note in observing this graph is the erratic nature of the bottom-up emissions assessment. This primarily arises from substantial fluctuations in the UNEP consumption dataset itself. Since the mean ranges of emission over multiple years (e.g. 1991-1997) could be argued to be broadly consistent, it would be possible to conclude that the issue was just a matter of phasing. However, throughout the period, it is self-evident that the bottom-up emissions are struggling to keep pace with atmospheric observations. This could possibly be as a result of an incomplete UNEP reporting set.

There is also some evidence (Wu et al., 2004), that emissions during fluorocarbon manufacture could have been as high as 2200 tons per year between 1989 and 1993, decreasing to around an additional 600 tons per year in 2001. This level of emission may seem high but reflects that fact that much of the production of HCFC-142b is as feedstock of PVDF. Emissions from this source (and, by inference, any similar emissions from, as yet, unreported production) are not currently included within the UNEP consumption dataset used as the basis for the graph above.

Nonetheless, there is clearly a more significant downward trend in the post-1997 period where the emission assessment by bottom-up methods is lower than that derived from atmospheric measurement. Since there is believed to be little use of HCFC-142b in the refrigeration sector, this must result from under-estimated emissions from foams. Estimation of emissions of HCFC-142b from foams is complicated by difficulties in dividing reported consumption between closed cell (slow release) foams and more emissive packaging foam applications (polyethylene foam and XPS sheet). This relies on the quality of bottom-up reporting, particularly where the use of HCFC-142b in packaging applications is being phased-out (e.g. in

Japan). Although it is difficult from the data available to postulate a discrepancy in this period of more than 1,000 tons per year from this source, it is possible that there are additional foam sheet applications outside of the current reporting framework.

Taking due consideration of the similar, if more minor, trends for CFC-12 in latter years, there is also some circumstantial evidence to suggest that emission estimates for foams containing CFC-12 and/or HCFC-142b may have been under-stated and that some extruded insulation foam products may have been more emissive in their use phase than has been assumed in the various bottom-up models. This could arguably be further substantiated by observations made in Japan during the recent JTCCM project when aged CFC-12 containing foams were removed from buildings and found to contain less blowing agent than envisaged (JTCCM, 2003, 2004). However, this could be due to low thicknesses used and specific local technology choices (see next paragraph). A series of studies (most notably (Vo & Paquet, 2004)) has subsequently demonstrated that the diffusion coefficients for typical historical and current North American and European insulation products would only substantiate relatively low losses in XPS board foams.

In summary, three possible explanations remain ‘on the table’. Firstly, the amount of HCFC-142b consumed in latter years may have been under-estimated in the UNEP consumption dataset, particularly as it relates to accelerating production in China of both HCFC-142b itself and foam made with HCFC-142b during the reporting period. Secondly, the amount of HCFC-142b used in packaging foam may have been under-estimated in proportion to the insulation foam consumption. Thirdly, it is possible that XPS technologies have varied in their emission characteristics both geographically and in history. In the work that surrounded the (Vo & Paquet, 2004) paper, there was circumstantial evidence to suggest that XPS foams made in Japan in the pre-1990 period were of a different formulation to those made elsewhere. The situation is yet further complicated by the fact that diffusion rates are inversely proportional to the square of the thickness of foams and that, since thicknesses of foams have increased in latter years, the weighted average of emissions from the bank of materials in use could have decreased significantly with time.

Work is on-going to make the bottom-up models used to predict emissions more versatile in depicting these regional and time-related variations in emission rates. However, since there are still a number of other factors which remain to be validated (e.g. the UNEP dataset itself), it is clear that this will be an issue which will need reassessing over the next few years – particularly when further data is available for 2004 and 2005.

7.3 Further evaluation of the CFC-11 discrepancy

There are a number of potential sources for a discrepancy of the type observed in graph shown in section 7.2.1. These can most simply be summarised as follows:

- Under-estimate of on-going emissions from closed cell foams in use and already in the waste stream

- Under-reporting of on-going CFC-11 consumption and use, particularly in emissive applications (e.g. flexible foams, refrigeration equipment flushing etc.)

- Potential under-estimate of the lifetime of CFC-11, leading to an over-estimate of new emissions to replace apparently decomposed CFC-11.

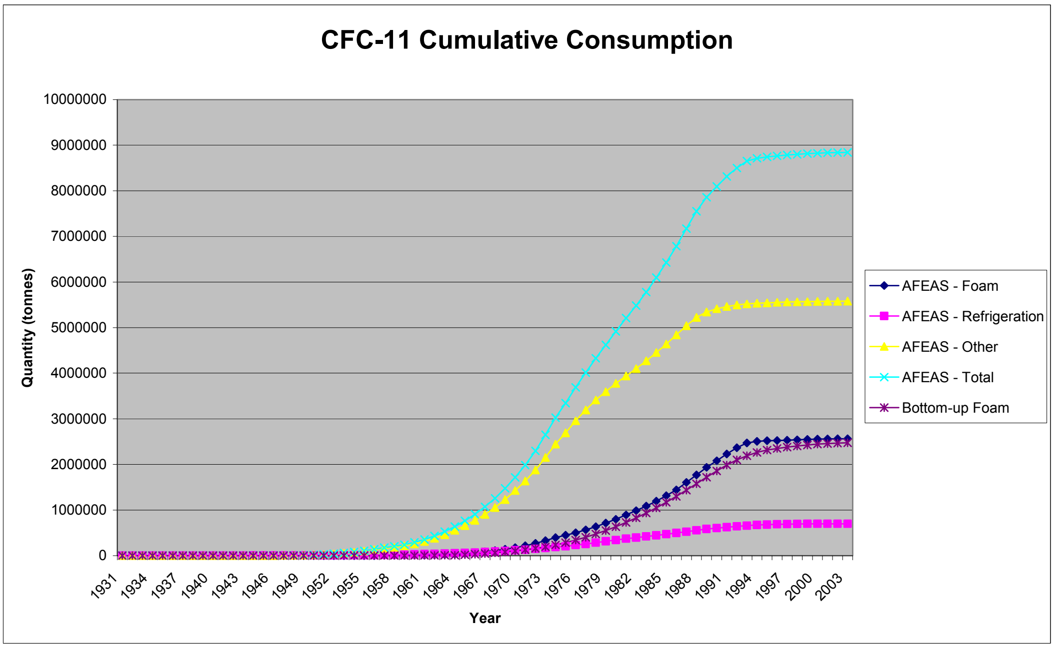
Each of these options is considered in turn in the following sub-sections.

7.3.1 Potential under-estimation of CFC-11 emissions from closed cell foams

Although there is some evidence to suggest that emissions from thermoplastic foams might be higher than previously modelled (affecting CFC-12 and HCFC-142b emissions), no such evidence is available in support of higher emission rates for CFC-11 blown foams in application. The same JTCCM programme in Japan (JTCCM, 2003, 2004) yielded expected levels of retained CFC-11 based on the age of samples taken from buildings. Similarly, for appliances, sampling of aged refrigerators by the manufacturing industry has substantiated the low losses assumed in the bottom-up models for that sector. This is also reflected in the practical recovery levels achieved within commercial refrigerator recycling plants. Most recently, an extended blowing agent recovery trial carried out on steel-faced panels recovered from a building of known age showed high levels of retention and recovery (Kingspan, 2006).

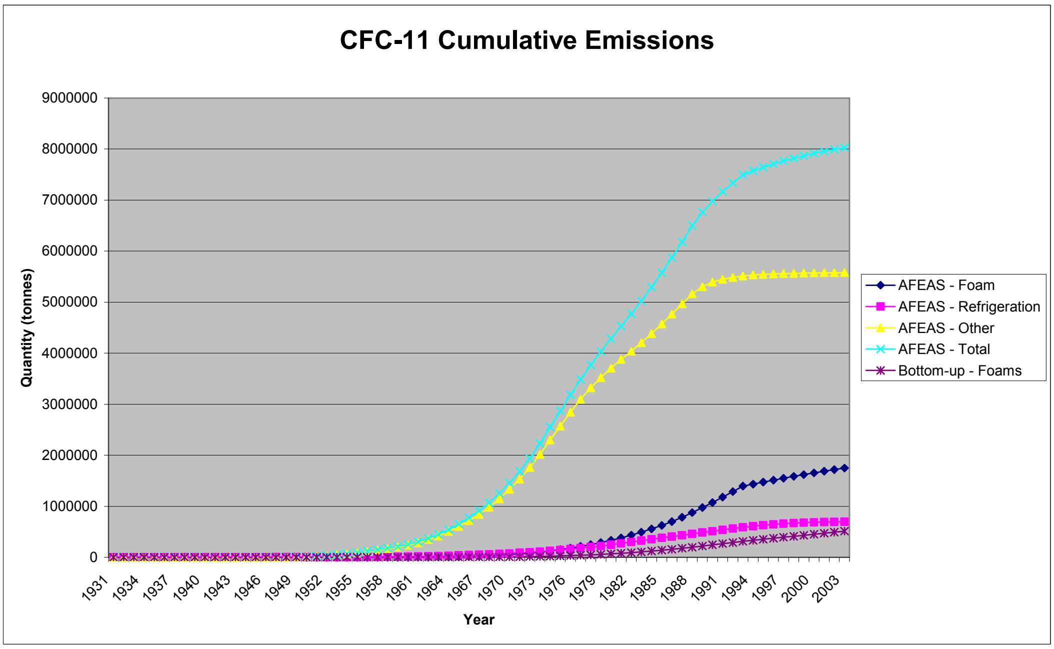
Additionally, the HCFC-141b data, while more erratic than for the more established blowing agents such as CFC-11, indicates that the overall predicted emission levels are sustained, particularly as the usage pattern matures. This is important, since the portfolio of foam uses served by HCFC-141b is very similar to that previously by CFC-11.

One other means by which an under-estimation of emissions could arise is through an overall under-estimation of cumulative consumption. At one point, there was concern that some bottom-up models (e.g. the Armines/Caleb/Marbury Project carried out for US EPA/ADEME) has under-estimated consumption against that originally assumed by AFEAS. However, comparison of the data in the following graph shows this to be only a marginal factor at worst.



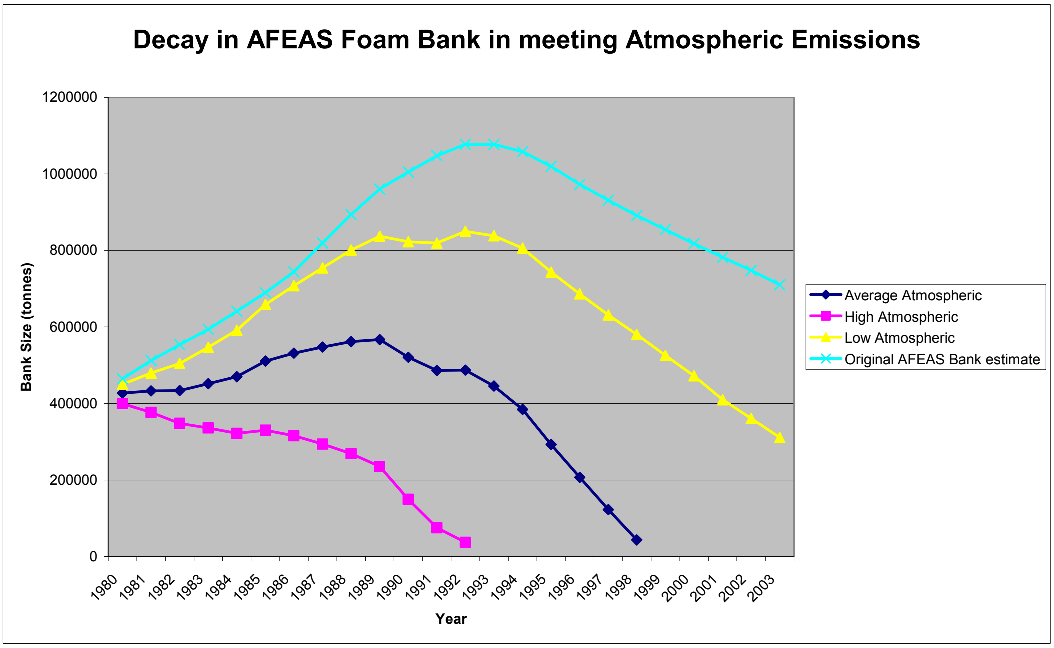
The graph is also quite revealing in illustrating the amount of short-term release applications (aerosols, solvents and others) practised historically using CFC-11 (over 5 million tonnes in total).

The parallel graph for cumulative emissions, on the other hand, shows a major discrepancy between current bottom-up emissions estimates (e.g. Armines/Caleb/Marbury) and those previously predicted by AFEAS.



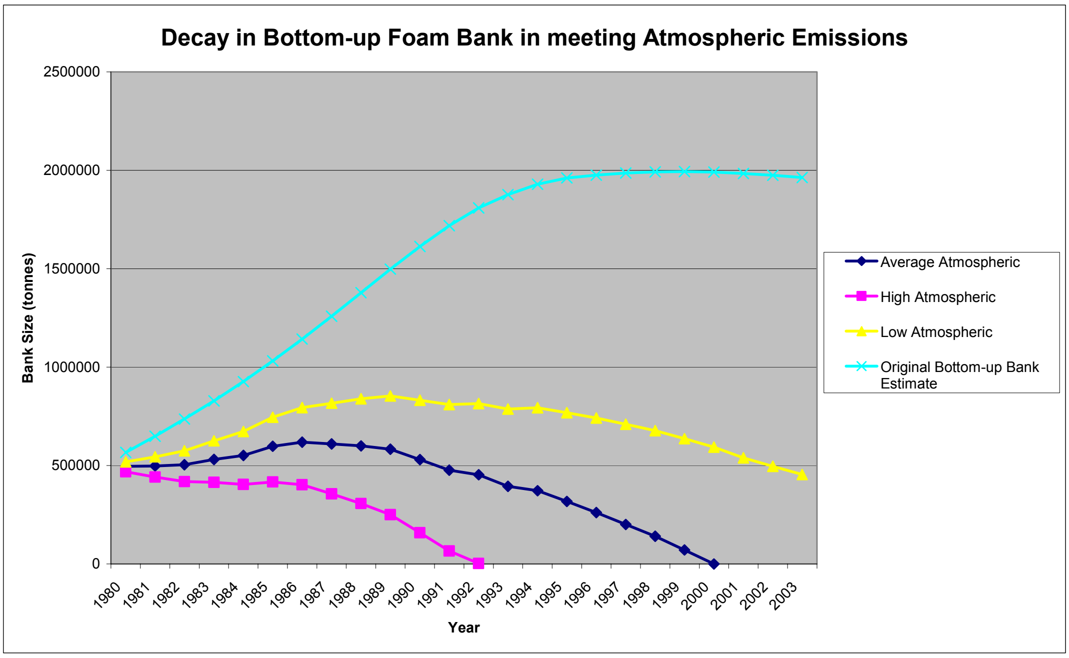
This reflects the fact that the AFEAS emissions model for closed cell foams was originally based around the assumptions in Gamlen et al (1986) of 10% first year loss and 4.5% per year thereafter. More recently, the AFEAS emission estimates were brought into line with the bottom-up modelled dataset for the period post-1993 (2003 AFEAS data, 2004). However, this remains rather an arbitrary adjustment and leads to inconsistency with emission predictions for earlier years, which remain unchanged.

Most commentators would concur that the Gamlen model is a substantial over-estimate of emissions, leading to smaller predicted bank sizes even as early as 1980 (~400,000 tonnes versus Caleb's assessment in Armines/Caleb/Marbury of ~500,000 tonnes). However, more importantly, even if the original AFEAS approach based on Gamlen were correct, it would still not be sufficient to support the higher emissions derived from atmospheric measurements. The following graph illustrates how the bank predicted by AFEAS (Gamlen) would need to be further depleted to meet the demands of the emissions levels derived from atmospheric observations.

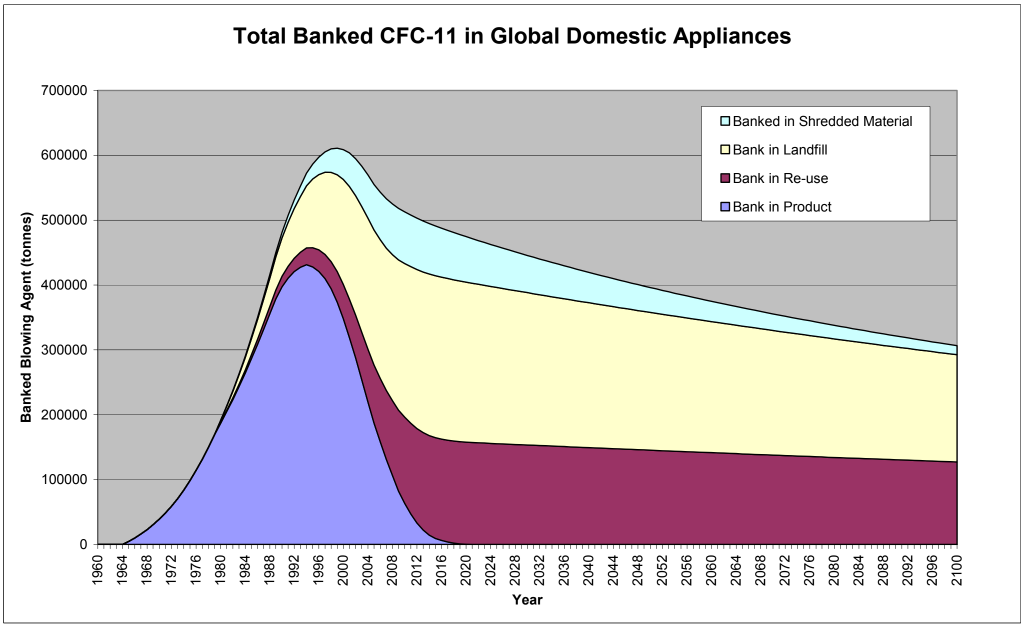


Effectively, the bank would be completely exhausted by 1993 to meet the high level emissions level estimates and by 1998 to meet the mean emission level estimates. The low level estimates could, in theory, be accommodated leaving a bank as at 2003 of ~300,000 tonnes.

A parallel analysis for banks derived from Armines/Caleb/Marbury data shows similar conclusions, since more of the bank would need to be emitted to make up the difference between the baseline estimate and the emissions derived from atmospheric measurements.



In passing, it should be noted that the bottom-up bank assessment (Armines/Caleb/Marbury) shown in the previous graph includes banks which are already in the waste stream (e.g. landfill). This is strictly correct, because such banks still represent CFC-11 consumed but not emitted. Of course, this does not imply that all banks are still recoverable. The graph below illustrates the situation for CFC-11 in appliances and forward predictions of bank development ('Banks in re-use' are blowing agents in refrigerators that have passed into secondary use or have extended lifetimes):



In summary, it would be inappropriate to state categorically that there is no under-estimate of emissions from closed cell foams. For example, there is a distinct possibility that first year (process) losses could have greater in the early years of a specific technology – a prospect not generally covered in current models. However, it is equally clear that the differences between bottom-up assessments and emissions derived from atmospheric measurements are too great to be explained solely on the basis of any potential inaccuracies in emission algorithms from closed cell foams Indeed, evidence suggests that closed cell foam emissions might only be a small part of the explanation.

7.3.2 Potential under-estimation of CFC-11 consumption, particularly in emissive uses

The quality of the UNEP consumption dataset continues to be an important part of the analysis. The historic dominance of emissive applications in CFC-11 use patterns makes data gathering on remaining emissive uses particularly sensitive. Even in the period 1990-2003, emissive applications still represented over 33% of total consumption. However, to explain the consistent under-reporting of emissions as shown in section 7.2.1, it is necessary to postulate systematic under-reporting throughout the period. Recent evidence has come to light indicating that the flushing of refrigeration equipment using CFC-11 (and more recently HCFC-141b) was much more common-place than previously thought. However, it is still unclear whether this consumption would already be accounted for within the UNEP dataset. Additional concerns remain on the residual use of CFC-11 in flexible foams in developing countries.

7.3.3 Potential under-estimate of the lifetime of CFC-11

The discussion in chapter 6 describes how the dominant source of uncertainty in the derivation of global emissions from measured atmospheric changes stems from halocarbon lifetimes. The discrepancy between emissions estimated from top-down and bottom-up methods would be reduced if the actual lifetime of CFC-11 were longer than 45 year (see Table 6.5). With a 1- box model calculation, one can estimate that a lifetime of 65 (52-88) year would be required to minimise the differences in the best estimate top-down emissions with the best estimate emissions from the bottom-up analysis (the range given here of 52-88 year corresponds to the different lifetimes required to minimise the differences between top-down emissions and the high and low estimates of emissions from the bottom-up analysis). Although there is some overlap in the uncertainty ranges on these lifetimes (35-57 and 52-88 year), the difference is substantial enough to suggest that it is unlikely that an error in the CFC-11 atmospheric lifetime can account for the entire discrepancy in emissions derived from different methods. The probability that the true lifetime of CFC-11 is as long as 65 years is quite low, especially considering that the best estimate lifetime is derived from modelling and observation-based methods that are independent. A lifetime longer than 65 year was calculated in only 1 of the 10 models in Kurylo *et al*. (1998), and the lifetime estimated from interpretation of stratospheric observations was 41(±12) year.

Annex Example of the determination of (high/low) bottom-up CFC-11 emissions

CFC-11	***1998***	***1999***	***2000***	***2001***	***2002***	***2003***	***Uncertainty***
UNEP Consumption	*66257*	*64377*	*54861*	*43571*	*39059*	*30837*	***16%***
High	76527	74355	63364	50325	45113	35617	
Low	55987	54399	46358	36817	33005	26057	
Refrig. Demand	*16109*	*15410*	*14934*	*14087*	*13317*	*12550*	***17%***
High	18848	18030	17473	16482	15581	14684	
Low	13370	12790	12395	11692	11053	10417	
Closed Cell Foam Demand	*25662*	*21359*	*16934*	*12857*	*10745*	*8344*	***15%***
High	29511	24563	19474	14786	12357	9596	
Low	21813	18155	14394	10928	9133	7092	
Derived Emissive Uses							
High	35790	38411	32224	24048	21659	15325	
Low	13182	16805	13762	9206	8335	4561	
Average	*24486*	*27608*	*22993*	*16627*	*14997*	*9943*	
Uncertainty	***46.17%***	***39.13%***	***40.15%***	***44.63%***	***44.42%***	***54.13%***	
Refrig. Emissions	*18453*	*17350*	*15963*	*14626*	*13687*	*12939*	***25%***
High	23066	21688	19954	18283	17109	16174	
Low	13840	13013	11972	10970	10265	9704	
Closed Cell Foam Emissions	*19601*	*19739*	*19912*	*20037*	*19902*	*19751*	***25%***
High	24501	24674	24890	25046	24878	24689	
Low	14701	14804	14934	15028	14927	14813	
Total Derived Emissions							
High		**76837**	**77634**	**70648**	**62670**	**59390**	
Low		**46313**	**49332**	**44664**	**37762**	**35984**	
Average		***61575***	***63483***	***57656***	***50216***	***47687***	
Uncertainty (+/-)		***24.79%***	***22.29%***	***22.53%***	***24.80%***	***24.54%***	
Derived from Atmosphere							
High	140647	142422	136973	141507	124295	118037	
Low	73796	75850	70828	75596	59068	53402	
Assessment	*102303*	*104244*	*99027*	*103710*	*86847*	*80917*	

8 Concluding remarks

8.1 General Comments

This assessment of the available data on emissions derived from bottom-up models and atmospheric measurements has indicated better than expected correlation for most chemicals reviewed. However, the following specific observations should be highlighted:

- No single data source from UNEP, AFEAS or any of the bottom-up methods adopted can be considered as providing a uniquely accurate snapshot of the total situation. Accordingly, on-going development in the quality of each source will remain important.
- There is considerable variability in consumption and resulting emissions estimated year-to-year in the early phases of introduction of a new chemical while reporting practices become established
- There is particular sensitivity to the completeness and accuracy of the UNEP consumption dataset because differences between the dataset and bottom-up analysis are assumed to be representative of emissive applications.
- There is still work to be done with HCFC-142b in establishing its emission sources and particularly rates of loss from thermoplastic foams. This may include the continuing development of more versatile bottom-up models.

8.2 Conclusions regarding CFC-11

The discrepancies between emissions derived from bottom-up methods and those derived from atmospheric measurements are largest for CFC-11. Whether this is a systematic discrepancy remains a matter for further study. However, the following observations have emerged from this study:

- There is no concrete evidence to suggest that CFC-11 emissions from closed cell foams are being under-estimated at present, although there is potential that first-year losses could have been higher than forecast in the earlier years of specific technologies.
- The currently estimated bank of CFC-11 in foams would not, in itself, be sufficient to make-up the cumulative difference between bottom-up and atmospherically derived estimates over the period of use in foams.
- The discrepancy between bottom-up and top-down emissions estimates for CFC-11 suggests the potential for additional emissive uses for CFC-11 that are, as yet, unaccounted for within the UNEP dataset.

- The global atmospheric lifetime of CFC-11 and other gases have substantial uncertainties that directly affect emission estimates from the top-down approach. A lifetime of 65 (52-88) year would be required to minimise the discrepancy between CFC-11 emissions derived from top-down and bottom-up methodologies. Because this lifetime is larger than the best estimate, CFC-11 lifetime of 45 (35-57) year, which is derived from modelling and observation-based methods, it is unlikely that the entire emissions discrepancy results from an error in the CFC-11 lifetime.

8.3 Significance for current bank sizes and future emissions projections

One of the objectives of Decision XVII/19 was that further study of discrepancies between emissions derived from bottom-up and those derived from atmospheric measurements could allow for improved estimates of present-day bank magnitudes and, ultimately, future emissions of ozone depleting substances. As a result of the analysis conducted as part of this report the following conclusions can now be drawn:

- It remains true that atmospheric projections of future halocarbon emissions and atmospheric mixing ratios depend upon the size and character of present day banks and the rates of emissions from these banks as well as emissions resulting directly from future production and use.

- In comparison with the situation described in Annex 11B of the Special Report on Ozone and Climate, it has been possible to reconcile the various methods used to derive emissions from bottom-up modelling and from atmospheric measurement for most ODS. The only possible exception is CFC-11. This reconciliation has been partly due to a reassessment of the impact of atmospheric lifetimes and mixing ratios on the one hand and uncertainties in consumption patterns and emission functions on the other.

- This provides further evidence that there is no fundamental error in either approach but that appropriate caution is necessary in relying on either dataset independently of the other.

- In the case of CFC-11, it may be necessary to carry out further analysis of the use patterns represented in the UNEP consumption dataset before drawing further conclusions on the size of present-day banks and likely future emissions.

9 Glossary

AFEAS	Alternative Fluorocarbon Environmental Acceptability Study
CFC	Chlorofluorocarbon
EESC	Equivalent Effective Stratospheric Chlorine
HCFC	Hydrochlorofluorocarbon
IPCC	Intergovernmental Panel on Climate Change
ODS	Ozone Depleting Substance
OEWG	Open-Ended Working Group
PVDF	PolyVinylidine DiFluoride
SROC	Special Report on Ozone and Climate (IPCC TEAP, 2005)
TEAP	Technology and Economic Assessment Panel
TFED	Task Force on Emissions Discrepancies
WMO	World Meteorological Organization
XPS	Extruded Polystyrene

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