



United Nations  
Environment  
Programme



Distr.  
GENERAL

UNEP/OzL.Pro/WG.1/23/3  
25 February 2003

ORIGINAL: ENGLISH

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OPEN-ENDED WORKING GROUP OF THE PARTIES TO  
THE MONTREAL PROTOCOL ON SUBSTANCES THAT  
DEplete THE OZONE LAYER

Twenty-third meeting  
7-11 July 2003

Synthesis of  
the 2002 Reports of the  
Scientific Assessment Panel (SAP)  
Environmental Effects Assessment Panel (EEAP)  
Technology and Economic Assessment Panel (TEAP)  
of the Montreal Protocol

**Synthesis Report**

The Synthesis of the assessment reports presented in this document has been prepared by the Co-chairs of the Assessment Panels on the basis of their reports: “Scientific Assessment of Ozone Depletion: 2002”, “Environmental Effects of Ozone Depletion: 2002 Assessment” and “2002 Assessment Report of the Technology and Economic Assessment Panel”, pursuant to Article 6 of the Montreal Protocol.

The full assessment reports can be viewed at: <http://www.unep.org/ozone> and <http://www.unep.ch/ozone>

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## I. SYNTHESIS SUMMARY AND FINDINGS

This report contains a synthesis of the findings of the Scientific, Environmental Effects, and Technology and Economic Assessment Panels in accordance with the Decision XI/17 of the Eleventh Meeting of the Parties to the Montreal Protocol in 1999. This report is the fifth one in a series that started in 1989 and continued in 1991, 1994 and 1998. Like the earlier ones, it forms the basis on which the Parties can assess the adequacy of control measures of the Protocol as provided in Article 6 of the Protocol and take appropriate decisions.

- **Synthesis Finding 1: The Montreal Protocol is working (SAP)**

1a. The Montreal Protocol is working, and the ozone-layer depletion from the Protocol's controlled substances is expected to begin to ameliorate within the next decade or so.

1b. The total combined effective abundances of anthropogenic chlorine-containing and bromine-containing ozone-depleting gases in the lower atmosphere (troposphere) peaked in the 1992-1994 time period and are continuing to decline. Furthermore, the stratospheric abundances of ozone-depleting gases are now at or near a peak. Thereafter, the level of stratospheric ozone should increase, all other influences assumed constant, but ozone variability will make detection of the onset of the long-term recovery difficult. Future ozone levels will also be influenced by other changes in atmospheric composition and by climate change. Based on assumed compliance with the amended and adjusted Protocol by all Parties, the Antarctic ozone "hole" is expected to disappear by the middle of this century—again, with all other influences assumed constant.

- **Synthesis Finding 2: The ozone layer will remain vulnerable (SAP)**

2a. The ozone layer will remain particularly vulnerable during the next decade or so, even with full compliance by all Parties with the Montreal Protocol control measures. Springtime Antarctic ozone depletion due to halogens has been large throughout the last decade, with the monthly total column ozone amounts in September and October about 40 to 55% below pre-ozone-hole values. Arctic ozone depletion is highly variable and difficult to predict, but a future Arctic polar ozone hole similar to that of the Antarctic appears unlikely. Estimates of the cumulative losses in the Arctic total column ozone amounts during the last four years range up to about 25%. In some recent cold Arctic winters during the last decade, maximum total column ozone losses due to halogens have reached 30%. Ozone losses due to halogens could be larger if a large volcanic eruption (with abundant stratospheric particles) or an unusually and persistently cold Arctic stratospheric winter were to occur. Relative to the pre-ozone-hole abundances of 1980, the 1997-2001 losses in total column (i.e., overhead) ozone amounts are:

- about 4% at northern mid-latitudes in winter/spring;
- about 2% at northern mid-latitudes in summer/fall; and
- about 6% at southern mid-latitudes on a year-round basis.

2b. Calculations based on relationships with total ozone and total irradiance suggest that UV irradiance has increased by 6-14% as compared to pre-ozone-hole values at more than 10 sites distributed over mid- and high latitudes of both hemispheres.

- **Synthesis Finding 3: Ozone depletion causes increased surface UV-B radiation, which has many effects on living organisms and materials (EEAP)**

3. New studies confirm and strengthen previous findings that UV-B radiation has serious adverse effects on the skin, eyes, and immune system. UV-B exposure causes skin cancer and plays a role in the formation of age-related cortical cataracts. Experimental work clearly shows that UV radiation reduces immune functions, but many questions remain as to the significance of these effects for human diseases. In several plants, UV radiation leads to decreased plant height and leaf area. Solar UV radiation also negatively affects many aquatic organisms. It exerts many influences in biogeochemical cycles. Some economically important natural and synthetic materials degrade by exposure to solar UV-B radiation.

- **Synthesis Finding 4: Interactions between ozone depletion and climate change have consequences for environmental effects (EEAP)**

4. Climate change can increase ozone depletion and worsen its consequences. For example, cooling of the stratosphere may keep the ozone layer at its depleted state for a longer period of time, which will lead to increases in those effects that depend on the UV doses accumulating over a long time, such as skin cancer and cataracts. On the other hand, ozone depletion can worsen climate change. For example, UV damage to phytoplankton and other aquatic organisms may reduce the oceans' sink for carbon dioxide from the atmosphere and so increase global warming. Higher temperatures influence many chemical and biological processes, even at unchanged UV levels, with outcomes as varied as accelerated UV-degradation of plastics and increased UV-induced skin cancer. Several characteristics of climate change, such as changed cloudiness, precipitation, ice cover and ocean temperatures, influence the transmission of UV radiation through the atmosphere, and therefore the doses received by organisms. Most of these changes are also likely to influence the time people will choose to spend outdoors, and thus the UV doses they receive.

- **Synthesis Finding 5: Failure to comply with the Montreal Protocol would delay or could even prevent recovery of the ozone layer (SAP)**

5. For example, continued constant production and subsequent emissions of all ozone-depleting substances at 1999 amounts would likely extend the recovery of the ozone layer well past the year 2100. Very short lived organic halogen containing substances have the potential to deplete stratospheric ozone, but quantitative estimation of their potentials is more challenging than for long-lived species like CFCs. The impact of very short-lived compounds can be significant if their emissions are large.

- **Synthesis Finding 6: Approaches to accelerating the recovery of the ozone layer are limited (SAP)**

6. Hypothetical estimates were made of the *upper limits* of ozone layer improvements that could be achieved relative to the current control measures (Beijing 1999). For example, a hypothetical elimination of all future anthropogenic production of *all* ozone-depleting substances in 2003 (with all other influences assumed constant) would advance the return of equivalent effective stratospheric chlorine loading to pre-1980 (pre-ozone-hole) values by about 4 years. A hypothetical elimination of additional emissions derived from all past and future industrial production of *all* ozone-depleting substances would advance the return of equivalent effective stratospheric chlorine loading to the pre-1980 values by about 10 years.

- **Synthesis Finding 7: Immediate phase-out of most uses is technically and economically feasible (TEAP)**

7. Phase-out of CFCs, halons, carbon tetrachloride and methyl chloroform by 2005 in the Article 5(1) and CEIT countries is technically and economically feasible. However, phase-out in 2005 would require accelerated investments to change to ODS-free technologies, also accepting HCFCs, in all industries and processes now using ODSs, including the servicing sector. This acceleration would require increased resources from the Multilateral Fund and GEF as well as increased institutional capacity for timely utilisation of these resources. Phase-out of HCFCs in new equipment and in servicing by 2005 in non-Article 5(1) countries is technically feasible but expensive with the technology available today and with possible consequences of increased energy consumption and greenhouse gas emissions. The cost and energy consequences can be more precisely determined as the EU proceeds with accelerated phase-out of HCFCs in new refrigeration and air conditioning equipment and foams and eventually in servicing. It is useful to compare the costs of equivalent emission reductions from recovery and destruction to the costs of curtailing new uses and servicing of existing equipment.

- **Synthesis Finding 8: Phase-out of methyl bromide under the current control schedule requires greater investment by users and by government authorities (TEAP)**

8. In some countries, methyl bromide use is prolonged by the abundant supply of methyl bromide and the costly and protracted registration and approval process for many alternatives and substitutes. The inability of consumers to identify products not grown or processed with methyl bromide diminishes the incentives to develop, approve, and implement alternatives. In many cases, alternatives are available but not yet approved by government authorities. In most countries, customers are unable to exercise market preference because they cannot easily determine which food products are grown or processed with methyl bromide. There is less market leadership in eliminating methyl bromide than was evident in other ODS sectors.

- **Synthesis Finding 9: Technical leadership and methyl bromide phase-out progress in Article 5(1) countries (TEAP)**

9. Suitable alternatives are available to allow substantial reductions in MB use in Article 5(1) countries provided that financing is available from the Multilateral Fund and markets in non-Article 5(1) countries continue to provide economic incentives for commercialisation and registration of alternatives. Since 1998 consumption has decreased at an average rate of about 5% per year with some Article 5(1) countries decreasing consumption by more than 20%. Fifteen Article 5(1) countries, with the full range of low to high intensity of methyl bromide uses, plan a full phase-out in 3 to 6 years.

- **Synthesis Finding 10: Large quantities of ODS are available for recovery and destruction (TEAP)**

10a. Foams, refrigeration, and fire protection equipment contain significant recoverable ODS inventories that will be emitted, unless regulatory and economic incentives compel recovery and destruction. 350,000 to 400,000 ODP-tonnes are contained in refrigeration equipment in 2002, with over 70% in commercial and industrial uses in non-Article 5(1) countries. 1.25 million ODP-tonnes are predicted to remain in installed foams in year 2010 with the majority in non-Article 5(1) countries. 450,000 ODP tonnes of halon 1301 and 330,000 ODP tonnes of halon 1211 are estimated in inventory. Only a portion of halon 1301 and very little halon 1211 is needed for future essential uses. The cost to recover and destroy ODS can be calculated as both the cost per ODP tonne destroyed and

the cost per carbon equivalent tonne destroyed, reflecting the benefits to both ozone layer and climate protection.

10b. Regulations that prohibit the use of recovered ODSs without proper incentives and oversight can be counter-productive to ozone protection if substances are intentionally vented to avoid the cost of proper disposal or if inefficient destruction processes increase near-term emissions when the ozone layer is most vulnerable.

- **Synthesis Finding 11: Opportunities exist to accelerate ozone layer protection and to reduce compliance costs through further economic rationalisation (TEAP)**

11a. The flexible implementation strategy adopted by the Montreal Protocol has thus far guided market transformation and regulatory incentives to phase-out ozone depleting substances cost effectively and with pragmatic exception for essential and non-emissive uses. The availability of a large quantity of ODS for recovery and destruction offers a further opportunity to help protect the ozone layer.

11b. The Protocol's definition of 'production' (Article 1, paragraph 5) allows Parties to produce ODS, even after phase-out, to the extent of ODS destroyed. Parties may wish to consider the opportunity to exempt production for approved essential and critical applications in non-Article 5(1) countries only if equal or greater ODP quantities are recovered and destroyed. Such offsetting recovery and destruction could be at a level that assures that the chlorine-equivalent loading of the stratosphere decreases.

## II. EXECUTIVE SUMMARY OF THE SCIENTIFIC ASSESSMENT PANEL REPORT

12. The provisions of the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer include the requirement that the Parties to the Protocol base their future decisions on the current scientific, environmental, technical, and economic information that is assessed through panels drawn from the worldwide expert communities. To provide that input to the decision-making process, advances in understanding on these topics were assessed in 1989, 1991, 1994, and 1998. This information helped support discussions among the Parties that led to the subsequent Amendments and Adjustments of the 1987 Protocol. The 2002 Scientific Assessment summarized here is the fifth in that series.

### A. RECENT MAJOR FINDINGS AND CURRENT SCIENTIFIC UNDERSTANDING

13. Since the *Scientific Assessment of Ozone Depletion: 1998*, numerous laboratory investigations, atmospheric observations, and theoretical and modeling studies have produced new key findings and have strengthened overall understanding of the ozone layer and its effect on ultraviolet (UV) radiation. These advances are highlighted in the following summary of the current understanding of the impact of human activities and natural phenomena on the ozone layer and the coupling of the ozone layer and the climate system.

#### (a) Changes in Ozone-Depleting Compounds

14. **In the troposphere (i.e., lower atmosphere), observations show that the total combined effective abundance of ozone-depleting compounds continues to decline slowly from the peak that occurred in 1992-1994. Total chlorine is declining, while bromine from industrial halons is still increasing, albeit at a slower rate than was occurring previously (and as reported in the 1998 Assessment).** Total tropospheric *chlorine* from the long- and short-lived chlorocarbons was about 5% lower in 2000 than that observed at its peak in 1992-1994, and the rate of change in 2000 was about -22 parts per trillion (ppt) per year (-0.6% per year). The once-dominant influence of methyl chloroform (CH<sub>3</sub>CCl<sub>3</sub>) on this total decline is diminishing because the atmospheric abundance of methyl chloroform is sharply decreasing. Total chlorine from the major chlorofluorocarbons (CFCs) is no longer increasing, in contrast to the slight increase that was occurring at the time of the 1998 Assessment. Specifically, in 2000, the atmospheric abundances of CFC-11 and CFC-113 continued to decrease, while the rate of increase of CFC-12 had slowed. Total tropospheric bromine from halons continued to increase at about 3% per year, which is about two-thirds of the rate for 1996 reported in the 1998 Assessment. The observed abundances of CFCs, hydrochlorofluorocarbons (HCFCs), and methyl chloroform in the lower atmosphere continue to be consistent with reported production and estimated emissions.

15. **Analyses of air trapped in snow since the late 19th century have confirmed that non-industrial sources of the CFCs, halons, and major chlorocarbons were insignificant.** Since the previous Assessment, analyses of firm air (i.e., air trapped in snow above glaciers) have revealed the abundance of long-lived atmospheric species at the time the air became trapped. As a result, trends in the atmospheric abundance for many ozone-depleting substances have been traced over the past century, to well before significant industrial sources of the compounds existed. These records show that the mixing ratios of the CFCs, halons, carbon tetrachloride (CCl<sub>4</sub>), methyl chloroform, and HCFCs in the oldest air sampled are negligible compared with the amounts measured in today's background atmosphere. Further, the deduced 20th century records for these compounds are broadly consistent with calculated histories based on records of industrial production. The data suggest that substantial natural sources exist for atmospheric methyl bromide (CH<sub>3</sub>Br). They also show increases

throughout the 20th century, but these increases do not allow unambiguous quantification of the industrial fraction of methyl bromide emissions in recent years. The estimate of this fraction, based on an assessment of understanding of the budget of this gas, remains at 10-40%, as given in the 1998 Assessment.

16. **The abundances of HCFCs in the lower atmosphere continue to increase.** HCFCs are among the gases used as transition substitutes for CFCs, halons, and chlorinated solvents. In the year 2000, HCFCs represented 6% of total chlorine abundance from anthropogenic gases in the lower atmosphere. The rate of increase in chlorine from HCFCs was constant at 10 parts per trillion per year from 1996 to 2000.

17. **Observations in the stratosphere indicate that the total chlorine abundance is at or near a peak, while bromine abundances are probably still increasing.** The sum of hydrogen chloride (HCl) and chlorine nitrate (ClONO<sub>2</sub>) is an effective surrogate for the abundance of stratospheric chlorine. An extended time series of ground-based measurements shows that the total stratospheric column amounts of these species, which have grown steadily for decades, have plateaued in recent years. Further, space-based measurements of HCl in the upper stratosphere indicate a broadly similar behavior. There are indications that bromine abundances in the stratosphere increased during the 1990s, but changes in stratospheric bromine are not as well characterized as those of stratospheric chlorine. These stratospheric changes are consistent with expectations based on the understanding of trace-gas trends in the troposphere, stratospheric chemistry, and atmospheric transport from the troposphere to the stratosphere.

18. **Very short-lived organic chlorine-, bromine-, and iodine-containing source gases have the potential to deplete stratospheric ozone, but quantitative estimation of their potentials is more challenging than for longer-lived species like CFCs.** The very short-lived compounds reside in the atmosphere for a few months or less because they are rapidly decomposed chemically in the troposphere. Yet, a fraction of their emissions and the products from their tropospheric destruction can potentially reach the stratosphere. For example, observations suggest that non-anthropogenic bromoform (CHBr<sub>3</sub>) produced largely in the oceans does make a non-negligible contribution to the total stratospheric bromine abundance. The magnitude of the ozone depletion by very short-lived compounds will depend critically on the location and season of their emissions and on the properties of their degradation products. The traditional use of a single number for their Ozone Depletion Potential (ODP), which is possible for longer-lived species, is therefore not directly applicable to the very short-lived species. Three-dimensional model simulations also suggest that very short-lived compounds emitted in the tropics would be more readily transported to the stratosphere than those emitted at higher latitudes, thus leading to greater ozone loss for tropical emissions. ODP values estimated by three-dimensional models are currently uncertain because of difficulties in modeling the complexities of transport processes and the lack of data on the products of the tropospheric degradation. A recent study on n-propyl bromide, one of the compounds proposed for possible future use, showed that for emissions that are uniform over the global land masses away from the poles, roughly 0.5% of the bromine emitted as n-propyl bromide reaches the stratosphere, resulting in an ODP of 0.04. Other ODP values reported in that study are up to 0.1 from tropical emission, and values up to 0.03 and 0.02 for emissions restricted to north of 20°N and 30°N, respectively. Therefore, the impact of very short-lived compounds can be significant if their emissions are large.

**(b) Changes in the Ozone Layer over the Poles and Globally**

19. **Springtime Antarctic ozone depletion due to halogens has been large throughout the last decade.** Since the early 1990s, the minimum total column (i.e., overhead) ozone amount has been ~100 Dobson units (DU). The monthly total column ozone amounts in September and October have continued to be about 40 to 50% below preozone-hole values, with up to a local 70% decrease for periods of a week or so. During the last decade, the average ozone hole area in the spring has increased in size, but not as rapidly as during the 1980s. The area of the ozone hole varies from one year to another, and it is not yet possible to say whether the area of the ozone hole has maximized. In recent years, the ozone hole has also persisted into early summer, increasing its impact on ultraviolet radiation.

20. **In some recent cold Arctic winters during the last decade, maximum total column ozone losses due to halogens have reached 30%.** Arctic winter/spring ozone loss is highly variable due to changes in stratospheric meteorological conditions from one winter to another, but it is now better understood because of numerous new observations and model comparisons. There is general agreement between analyses that quantify Arctic chemical ozone loss for the 1999/2000 winter/spring season. That well-studied year was distinguished by persistent low temperatures, an ozone loss reaching 70% near 20 km, and total column ozone losses greater than 80 Dobson units (~20-25%) by early spring. In contrast, during the warmer, more disturbed Arctic winter of 1998/1999, the estimated chemical loss was very small. Three of the last four Arctic winters have been warm, with little ozone loss; six of the previous nine winters were cold, with larger ozone losses.

21. **Ozone remains depleted in the midlatitudes of both hemispheres.** The global-average total column ozone amount for the period 1997-2001 was approximately 3% below the pre-1980 average values. Observed changes occur primarily in midlatitudes and in polar regions; no significant trends in total column ozone have been observed in the tropics (25°N-25°S). There are differences in ozone behavior between the two hemispheres. In particular, the average amounts of total column ozone over the period 1997-2001 were 3% and 6% below the pre-1980 values in the Northern Hemisphere midlatitudes (35°N-60°N) and the Southern Hemisphere midlatitudes (35°S-60°S), respectively. The seasonality of total column ozone changes (1997-2001 relative to pre-1980) is different in the Northern Hemisphere and Southern Hemisphere. Over Northern Hemisphere midlatitudes, the largest ozone decreases are observed during winter/spring (~4%), with summer/autumn decreases approximately half as large. Over Southern Hemisphere midlatitudes, long-term ozone decreases exhibit a similar magnitude (~6%) during all seasons.

22. **Models including observed changes in halocarbons, source gases, and aerosols (i.e., airborne fine particles) capture the observed long-term ozone changes in northern and southern midlatitudes.** The two-dimensional assessment models also reproduce much of the interannual ozone variations in the midlatitudes of the Northern Hemisphere, but do less well in the Southern Hemisphere. For example, observations show different ozone behavior in the Northern and Southern Hemispheres following the major eruption of the Mt. Pinatubo volcano in the early 1990s, whereas models that include aerosol-enhanced, halocarbon-ozone chemistry suggest hemispherically symmetric ozone loss during the post-eruption period. Changes in dynamical processes help to explain some of the ozone variations in Northern Hemisphere midlatitudes. They have also contributed to winter/spring trends in the Northern Hemisphere. However, because chemical and dynamical processes are coupled, their contributions to ozone changes cannot be assessed in isolation.

23. **Chemistry-climate models predict that springtime Antarctic ozone levels will be increasing by 2010 because of projected decreases of halogens in the stratosphere.** A return to pre-1980 total column ozone amounts in the Antarctic is expected by the middle of this century.

24. **Arctic ozone depletion is highly variable and difficult to predict, but a future Arctic polar ozone hole similar to that of the Antarctic appears unlikely.** Low ozone, as seen in some recent years, can however be expected again, and the Arctic stratosphere will be most vulnerable to other perturbations (for example, if there were to be an increase in the abundance of stratospheric aerosols from volcanic eruptions) during the next decade or so. Sustained very low Arctic ozone column amounts similar to those seen in the Antarctic are not predicted by the current chemistry-climate models. Such extreme ozone depletion during the next decade or so, when halogen abundances should still be close to their maximum, would require conditions that are unprecedented in about 40 years of Northern Hemisphere meteorological observations and, therefore, are considered highly unlikely to occur in the future.

25. **The global ozone layer recovery is expected to be linked mainly to decreasing chlorine and bromine loading, but other factors are likely to contribute.** The expected decrease in the amount of stratospheric chlorine and bromine over the next 50 years is predicted to lead to an increase in the global amount of total column ozone, although there are differences in the projected rate of this increase predicted by different models. Stratospheric cooling (due mainly to projected carbon dioxide (CO<sub>2</sub>) increases) is predicted to enhance the future ozone increase in the upper stratosphere. However, a reliable assessment of this effect on total column ozone is limited by uncertainties in the lower stratospheric response to these changes. Changes in atmospheric transport are difficult to predict, and their impact on stratospheric ozone could be either positive or negative. Projected increases in methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) are predicted to have small chemical effects on the rate of increase of global total column ozone in the next 50 years, but could become more significant later in the 21st century. Future changes in the ozone in the lower atmosphere are highly dependent upon the scenario adopted for future emissions of ozone precursors, but all scenarios adopted by the 2001 report of the Intergovernmental Panel on Climate Change (IPCC) lead to predicted increases in tropospheric ozone up to 2050.

#### (c) Changes in Ultraviolet Radiation

26. **Changes in the duration and spatial extent of the ozone hole are more important for Antarctic surface ultraviolet (UV) radiation levels than the annual ozone minimum.** Enhanced values of UV radiation continue to be observed at high latitudes in the Southern Hemisphere under the Antarctic ozone hole. The highest biologically weighted UV doses under the ozone hole are typically not observed in October when maximum ozone depletion occurs, but in November and early December when solar elevations are higher and low ozone values are still prevailing.

27. **Additional measurements continue to confirm that decreases in ozone column amounts lead to increases in UV radiation.** Calculations of UV irradiance based on relationships with total ozone and total irradiance (from pyranometers) suggest that UV irradiance has increased since the early 1980s by 6-14% at more than 10 sites distributed over mid- and high latitudes of both hemispheres. These results are consistent with spectral ultraviolet irradiance measurements and with estimates from satellite measurements. The complicated spatial and temporal distributions of the predominant variables that affect ultraviolet radiation at the surface (for example, clouds, airborne fine particles, snow cover, sea ice cover, and total ozone) continue to limit the ability to describe fully surface ultraviolet radiation on the global scale, whether through measurements or model-based approaches. As was noted in the previous Assessment, the spectral surface ultraviolet data records, which started in the early 1990s, are still too short and too variable to permit the calculation of statistically significant long-term (i.e., multidecadal) trends.

#### (d) The Ozone Layer and Climate Change

28. **The understanding of the impact of ozone depletion on climate change has been strengthened.** There has been a global and annual-mean cooling of the stratosphere over the past two decades, which can be largely attributed to the observed stratospheric ozone depletion and increases in well-mixed greenhouse gases and water vapor. As has been noted in past assessments, cooling of the lower stratosphere leads to cooling of the Earth's climate system. The vertical profile of ozone depletion in the lowermost stratosphere, which is an important factor in the magnitude of the radiative forcing, is now more accurately estimated from additional years of observations with reduced volcanic perturbations. Averaged ozone depletion has remained close to that of the late 1990s over much of the world, and therefore the recommended globally averaged radiative forcing of the climate system implied by this Assessment is the same as that recommended by the 2001 IPCC Assessment. The stratospheric radiative forcing due to ozone decreases since 1980 offsets about 20% of the positive forcing due to the increases in abundances of well-mixed greenhouse gases over that same time period.

29. **Other atmospheric changes influence both the ozone layer and the climate system.** Observations have provided stronger evidence for a widespread increase in stratospheric water vapor, which plays a role both in cooling the lower stratosphere and in depleting ozone through chemical interactions, thereby contributing to climate processes. However, the water vapor trends are not fully defined, nor are their cause understood. Methane, nitrous oxide, and carbon dioxide are all important greenhouse gases, and all exert some influence on ozone depletion. Further, surface ultraviolet radiation may be directly affected, both positively and negatively, by the effects of climate change (for example, changing cloudiness), making prediction of long-term changes in surface radiation arising from all causes quite uncertain.

30. **New research has begun to explore the coupling between climate change and the recovery of the ozone layer.** A number of models have been run to explore the feedback between climate and the ozone layer. As noted earlier, they have shown that past changes in ozone have contributed, together with well-mixed greenhouse gases, to a cooling of the stratosphere. Future changes in well-mixed greenhouse gases will affect the future evolution of ozone through chemical, radiative, and dynamic processes. In this highly coupled system, attribution is difficult; studies are ongoing. Stratospheric cooling (due mainly to projected carbon dioxide increases) is predicted to enhance future ozone amounts in the upper stratosphere. However, a reliable assessment of these effects on total column ozone is limited by uncertainties in lower stratospheric response to these changes.

## **B. ADDITIONAL SCIENTIFIC EVIDENCE AND RELATED INFORMATION**

### **(a) Halocarbon Abundances**

31. Trends of ozone-depleting substances in the atmosphere have been updated, and 20th century trends have been deduced from firn air. In 2000, tropospheric mixing ratios of CFC-11 and CFC-113 declined faster than in 1996, and mixing ratios of CFC-12 were still increasing, but more slowly. The rapid drop in global methyl chloroform emission has led to an exponential decay in its mixing ratio since 1998; mixing ratios of this gas in 2000 were less than one-half of the peak observed in 1992. The rate of decline observed for methyl chloroform during 2000 was about two-thirds of what it was in 1996.

32. The total effect of all ozone-depleting halogens in the atmosphere, as estimated by calculating chlorine equivalents from atmospheric measurements of chlorine- and bromine-containing gases, continues to decrease. As of mid-2000, equivalent organic chlorine in the troposphere was nearly 5%

below the peak value in 1992-1994. The recent decrease is slightly slower than in the mid-1990s, owing to the reduced influence of methyl chloroform on this decline.

33. Substantial reductions in the emissions of ozone-depleting substances during the 1990s as inferred from atmospheric measurements are consistent with controls on production and consumption in the fully amended and adjusted Montreal Protocol. Consumption in developing countries is now a significant contributor to global emissions. The year 1999 was the first in which production and consumption of a class of ozone-depleting substances (the CFCs) was restricted in all Parties to the Montreal Protocol. Atmospheric measurements are consistent with emissions derived from reported production data for CFCs.

34. The updated, best-estimate scenario for future halocarbon mixing ratios suggests that the atmospheric burden of halogens will return to the 1980 pre-Antarctic-ozone-hole levels around the middle of the 21st century, provided continued adherence to the fully amended and adjusted Montreal Protocol. Only small improvements would arise from further reduced production allowances in the future.

35. Discrepancies reported in past assessments between atmospheric observations and expectations based on industry-reported production and emissions have narrowed substantially for HCFC-142b. This improvement stems from a better description of the functions relating emissions to usage in foam applications.

#### **(b) Halocarbon Lifetimes**

36. The global lifetime of carbon tetrachloride is estimated to be about 26 years, or about 25% shorter than in the previous (1998) Assessment. This shorter lifetime stems from identification of an ocean sink that is inferred from widespread observations of carbon tetrachloride undersaturation in surface waters of the ocean. Emissions inferred from atmospheric measurements and this lifetime are about 7 times greater than the limits to global production set for 2005.

37. The lifetime of methyl chloroform has been revised from 4.8 years to 5.0 years based upon new observations. The implications of this change on estimates of atmospheric hydroxyl (OH) suggest lifetimes up to 5% longer for HCFCs, hydrofluorocarbons (HFCs), methane, and all other gases removed from the atmosphere by this important oxidant. These changes affect the Global Warming Potentials (GWPs) and Ozone Depletion Potentials (ODPs) calculated for these gases.

#### **(c) Methyl Bromide, Methyl Chloride, and Halons**

38. Atmospheric histories inferred from Southern Hemisphere air archives and Antarctic firm air suggest that, assuming similar changes have occurred in both hemispheres, the sum of organic bromine from methyl bromide (CH<sub>3</sub>Br) and halons has more than doubled since the mid-1900s.

39. A substantial imbalance remains in estimates of source and sink magnitudes for both methyl bromide and methyl chloride (CH<sub>3</sub>Cl); known sinks outweigh sources for both of these gases. New sources of methyl bromide from individual crops and ecosystems have been identified, and new sources of methyl chloride from tropical plants have been discovered. These findings have narrowed the budget imbalances for both of these gases.

40. The best estimate for the global lifetime of methyl bromide remains at 0.7 (0.5-0.9) years. Additional studies directly related to estimating loss processes for methyl bromide have narrowed the uncertainties slightly, but do not suggest large revisions to this lifetime. The fraction of emissions

derived from industrially produced methyl bromide is unchanged at 10-40% based upon the current understanding of source and sink magnitudes.

**(d) Very Short-Lived Ozone-Depleting Compounds**

41. Very short-lived natural and anthropogenic bromine and iodine source gases with surface concentrations of a few parts per trillion (ppt) could make a non-negligible contribution to the current inorganic bromine and iodine budgets, since the stratospheric concentrations of inorganic bromine and iodine are about 20 ppt and less than 1 ppt, respectively. The transport of inorganic bromine associated with very short-lived bromine source gases from the troposphere to the stratosphere may contribute to the stratospheric inorganic bromine budget.

42. The most efficient route for transport of very short-lived substances and their degradation products from the surface to the stratosphere is in the tropics. In the tropics, the vertical transport times from the boundary layer to the upper troposphere are short, and air that enters the stratosphere through the tropical tropopause may remain in the stratosphere for a year or longer. A significant fraction of the emitted very short-lived substances can be expected to reach the tropical tropopause layer because current estimates indicate that air at the base of the layer is replaced by convection from the tropical boundary layer on a time scale of 10 to 30 days. A few percent of the air in the tropical tropopause layer is expected to enter the stratosphere through the tropical tropopause. Other transport pathways exist in the extratropics for the transfer of very short-lived substances and their degradation products to the extratropical lower stratosphere.

43. The main uncertainties in estimating the impact of very short-lived source gases lie in the physical and dynamical processes transporting these substances into the stratosphere and in the chemistry of their degradation products. Given the complexity, three-dimensional numerical models are the preferred tools to evaluate the Ozone Depletion Potential for very short-lived source gases. Significant uncertainties exist in the treatment of dynamical and physical processes in such models.

44. Two model studies simulated the atmospheric distribution of bromoform ( $\text{CHBr}_3$ ), assuming a simplified ocean source that is uniform over space and time. The results indicate that the ocean source causes an average surface mixing of 1.5 ppt for bromoform and maintains about 1 ppt of bromine in the stratosphere. The simulation shows that one-half to three-fourths of the bromine from bromoform enters the stratosphere in the form of inorganic degradation products.

45. The Ozone Depletion Potential was calculated from three separate model studies for n-propyl bromide (n-PB,  $\text{CH}_3\text{CH}_2\text{CH}_2\text{Br}$ ). Reaction with hydroxyl (OH) removes n-PB, with local photochemical lifetimes in the tropical troposphere of about 10-20 days. Laboratory data, particularly on bromoacetone, indicate that n-propyl bromide degradation products have lifetimes shorter than a couple of days. Two of the three modeling studies provided values only for direct transport of n-PB to the stratosphere. The third study computed contributions from direct transport and the transport of degradation products to the stratosphere. In the latter study, values of the Ozone Depletion Potential are up to 0.1 for tropical emissions and 0.03 for emissions restricted to northern midlatitudes. In both cases, about two-thirds of the effect is from the transport of degradation products to the stratosphere.

46. Laboratory data on iodine chemistry have led to downward revision of the efficiency of iodine for depleting ozone in the stratosphere. The revised estimated efficiency factor (~150-300) is still higher than that of bromine (~45).

**(e) Polar Ozone**

### *Antarctic*

47. Springtime Antarctic ozone depletion remains very large (with daily local total column values reaching 60-70% less than pre-ozone-hole conditions), with minimum values of about 100 DU (Dobson units) seen every year since the early 1990s. These observations reflect the almost complete ozone loss in the 12-20 km range and do not imply that ozone recovery has begun. Such low ozone is consistent with current understanding of stratospheric chemistry and dynamics.

48. The area enclosed by the 220 DU contour (a measure of the severity of the ozone hole) shows an increase in recent years, so that it is not yet possible to say that the ozone hole has reached its maximum. Much of the change appears to be associated with processes at the edge of the polar vortex and is consistent with meteorological variability and the almost-constant halogen loading.

49. Observations show that the Antarctic polar vortex and the associated ozone hole persist later than during the 1980s. Over the last decade, the vortex has generally broken up in late November to early December, in contrast to breakup in early November during the 1980s.

50. Satellite and radiosonde observations show that the springtime Antarctic lower stratosphere has cooled. During the 1979-2000 period, the linear cooling trend exceeded 1.5 K/decade at 70°S. Modeling studies reaffirm that ozone loss is the major cause of the springtime cooling and the increased persistence of the Antarctic polar vortex. Well-mixed greenhouse gas increases contribute to the annually averaged cooling. Stratospheric water vapor increases may also be contributing.

51. Coupled chemistry-climate model simulations, which include the combined effects of the changes in halogens and well-mixed greenhouse gases, broadly reproduce past trends in the total column ozone over the Antarctic. These models suggest that the minimum column ozone occurs prior to 2010 and that recovery to 1980 levels may be expected in the middle of the 21st century. The model response for the past and future changes is driven mainly by the changes in stratospheric halogen loading, with ozone recovery occurring after the peak of halogen loading.

### *Arctic*

52. The magnitude of halogen-induced loss of ozone for all Arctic winters during the last decade has now been studied with a variety of observationally based approaches. There is generally good agreement between different analyses that quantify the chemical loss. In the 1999/2000 winter, for which the most comprehensive studies were conducted, agreement was better than 20% in the Arctic stratosphere at about 20 km.

53. The Arctic winter/spring total column ozone amounts continue to show a high interannual variability, reflecting the variable meteorology of the Northern Hemisphere stratosphere. Low column ozone amounts were present during the cold winter of 1999/2000. That year was distinguished by persistent low temperatures, a local loss reaching 70% at 20 km, and column losses greater than 80 DU (~20-25%). In the warmer, more-disturbed winters of 1998/1999 and 2000/2001, very small ozone loss was observed. Three of the last four Arctic winters have been warm, with little ozone loss; six of the previous nine winters were cold, with larger ozone losses.

54. Significant chemical loss of ozone (~0.5 parts per million) in the lower stratosphere during January has been observed in several cold Arctic winters, contributing about 25% to the overall loss of ozone over the winter. The observations indicate that the loss occurred exclusively during periods when the air masses were exposed to sunlight. Nevertheless, these January ozone losses cannot be fully explained with the current understanding of the photochemistry.

55. Coupled chemistry-climate models capture the typical interannual variability of Arctic ozone levels. Because Arctic temperatures are often near the threshold for polar stratospheric cloud (PSC) formation and hence the initiation of perturbed chemistry, there is a strong sensitivity to model temperature biases of only a few degrees Celsius. This places severe limits on the ability of the models to simulate past and predict future Arctic ozone behavior in winter.

56. A number of coupled chemistry-climate models run for this Assessment suggest that minimum Arctic ozone would occur within the next two decades, the timing of which will depend on the meteorology. Low ozone, as seen in some recent years, can be expected again, and the Arctic stratosphere will be most vulnerable to other perturbations (e.g., aerosols from volcanic eruptions) during the next decade or so. Total column ozone amounts in the Arctic similar to the extreme lows seen in the Antarctic are not predicted by these models (in contrast to earlier simpler calculations considered in the 1998 Assessment). These extremely low values would require conditions that are unprecedented in about 40 years of Northern Hemisphere meteorological observations.

57. Satellite and radiosonde observations show that the springtime Arctic lower stratosphere has cooled. However, because of large variability in the Arctic spring, the magnitude of the trend is uncertain there. A linear cooling trend (exceeding 1.5 K/decade) is observed during the 1979-2000 period at 70°N. Modeling studies now suggest that stratospheric ozone depletion has exerted an important influence on the springtime cooling of the Arctic lower stratosphere over the 1979-2000 period, but the degree of attribution is hindered by the large dynamical variability in that region.

58. Observations of bromine monoxide (BrO) in the winter Arctic vortex by in situ and remote detection techniques are in broad agreement and are consistent with a total bromine budget of  $\sim 20 \pm 4$  parts per trillion. Modeling studies of the latitudinal, seasonal, and diurnal variations in BrO column abundances agree well with observations from a number of ground sites, indicating that the processes that govern bromine partitioning and its budget in the polar regions are reasonably well understood.

59. Bromine measurements now allow for more accurate assessment of the contribution of bromine to polar ozone loss. At present, the fractional contribution of bromine to total ozone loss ranges between 30 and 60%, depending on temperature and abundances of chlorine monoxide (ClO). Considering the observed leveling off of the strength of sources of chlorine, the role of bromine in polar ozone loss will continue to increase relative to that of chlorine until the current upward trends of the bromine source gases reverse.

60. Removal of nitrogen compounds (denitrification) has been observed to occur in the Arctic lower stratosphere in several cold winters. Removal of up to 70% of the total reactive nitrogen was observed at some levels of the lower stratosphere in the winter of 1999/2000. Observations and modeling results show that denitrification in the 1999-2000 Arctic lower stratosphere increased ozone loss by as much as 30% at 20 km in spring.

61. The understanding of what causes denitrification has been improved considerably by the discovery in 1999-2000 of large nitric-acid-containing particles (with diameters of 10 to 20 micrometers) in the Arctic polar lower stratosphere. Sedimentation of these particles can account for observed Arctic denitrification, although the mechanism of formation of these sedimenting particles is uncertain. Therefore, sedimentation of ice containing dissolved nitric acid, which has been the generally assumed mechanism in global stratospheric models, is not the dominant mechanism in the Arctic.

62. The chemical composition of liquid and solid polar stratospheric cloud particles has been measured directly for the first time. Most of the measured compositions are in agreement with model

calculations for liquid particles and nitric acid trihydrate, which have been used in stratospheric models for many years. These measurements improve confidence in the particle types used in microphysical models that are central to simulations of polar ozone loss.

**(f) Global Ozone**

***Total Column Ozone***

63. Global mean total column ozone for the period 1997-2001 was approximately 3% below the 1964-1980 average. Since systematic global observations began, the lowest annually averaged global total column ozone occurred in 1992-1993 (about 5% below the pre-1980 average). These changes are evident in each available global dataset.

64. No significant trends in total column ozone have been observed in the tropics (25°N-25°S) for 1980-2000. A decadal variation of total column ozone (with peak-to-trough variations of ~3%) is observed in this region, approximately in phase with the 11-year solar cycle. Total column ozone trends become statistically significant in the latitude bands 25°-35° in each hemisphere.

65. There are a number of differences in total column ozone behavior between the two hemispheres:

- Averaged over the period 1997-2001, total column ozone in the Northern Hemisphere and Southern Hemisphere midlatitudes (35°-60°) were about 3% and 6%, respectively, below their pre-1980 average values.
- The seasonality of total column ozone changes (1997-2001 relative to pre-1980) is different in the Northern Hemisphere and Southern Hemisphere extratropics. Over Northern Hemisphere midlatitudes, larger ozone decreases are observed during winter/spring (~4%), with summer/autumn decreases approximately half as large. Over Southern Hemisphere midlatitudes, long-term ozone decreases exhibit a similar magnitude (~6%) during all seasons.
- Pronounced negative anomalies are observed in the Northern Hemisphere midlatitudes time series during 1992-1995 in the winter/spring seasons. Similar anomalies are not seen in the Southern Hemisphere midlatitudes.
- There is a sharp drop in ozone at Southern Hemisphere midlatitudes during 1985-1986. A similar drop is not observed in the Northern Hemisphere.

***Vertical Ozone Distribution***

66. Ozone profile trends derived from the Stratospheric Aerosol and Gas Experiment (SAGE) satellite instrument show significant negative trends over latitudes 60°N to 60°S for altitudes ~35-50 km (with extremes near 40 km). Trend maxima of -7 to -8%/decade over the period 1979-2000 are observed in the 35°-60° latitude bands of both hemispheres, with no significant interhemispheric differences. These satellite results are in good agreement with independent Umkehr ozone measurements over the Northern Hemisphere midlatitudes.

67. The updated SAGE data reveal significant negative trends extending throughout the tropics in the small amount of ozone above 30 km, a feature not observed in previous assessments based on shorter time records.

68. The observed ozone depletion in the upper stratosphere is consistent with observed changes in anthropogenic chlorine. The vertical and latitudinal profiles of trends in the upper stratosphere are

reproduced by photochemical models, but the magnitude of changes are sensitive to concurrent trends in temperature and methane (CH<sub>4</sub>).

69. Long-term ozonesonde measurements are primarily available for the Northern Hemisphere midlatitudes. Whereas ozone between 20 and 27 km decreased continuously during 1980-2000, ozone between 10 and 20 km decreased through the early 1990s and was relatively constant thereafter. This behavior is consistent with observed changes in Northern Hemisphere midlatitude column ozone.

### ***Ozone-Related Constituents***

70. Stratospheric aerosol variability over the past 25 years has been dominated by the effects of episodic volcanic eruptions, with subsequent recovery. Following the large eruption of Mt. Pinatubo in 1991, relaxation to a nonvolcanic level continued to at least 1999. There is currently no evidence of a trend in the nonvolcanic aerosol loading.

71. Stratospheric water vapor measurements at a single location (Boulder, Colorado, U.S., 40°N) for the period 1981-2000 show a statistically significant increase of approximately 1%/year over altitudes 15-28 km. For the shorter period 1991-2001, global satellite measurements covering latitudes 60°N-60°S show a similar trend of 0.6-0.8%/year for altitudes ~25-50 km, but no significant trend at lower altitudes. The increases in water vapor are substantially larger than can be explained by tropospheric methane trends. Characterization of stratospheric water vapor trends is limited by the lack of global long-term measurements.

72. Stratospheric column nitrogen dioxide (NO<sub>2</sub>) measurements from Lauder, New Zealand (45°S), for 1981-2000 and Jungfraujoch, Switzerland (46°N), for 1985-2001 show statistically significant positive trends of approximately 5%/decade. There are also transient decreases observed after the El Chichón and Mt. Pinatubo eruptions, which are broadly simulated by models that include heterogeneous chemistry on sulfate aerosols.

### ***Stratospheric Temperature***

73. Observations indicate that, on an annual- and global-mean basis, the stratosphere has cooled over the last two decades. In the lower stratosphere, global and annual mean temperatures for the late 1990s are approximately 1 K lower than values in the late 1970s. Significant annual-mean cooling of the lower stratosphere over the past two decades is found over midlatitudes of both hemispheres (approximately 0.6 K/decade), but no significant trends are observed near the equator. The annual-mean temperature trends in the upper stratosphere are larger, with an approximately globally uniform cooling over 1979-1998 of about 2 K/decade near the stratopause (~50 km).

74. Modeling studies indicate that changes in ozone, well-mixed greenhouse gases, and stratospheric water vapor can explain the major features of the observed global and annual-mean stratospheric cooling over the past two decades. Cooling due to ozone depletion dominates over the impact of well-mixed greenhouse gases in the lower stratosphere, while upper stratospheric temperature trends are due, roughly equally, to ozone and well-mixed greenhouse gas changes.

### ***Attribution of Past Changes in Ozone***

75. The vertical, latitudinal, and seasonal characteristics of changes in midlatitude ozone are broadly consistent with the understanding that halogens are the primary cause, in line with similar conclusions from the 1998 Assessment.

76. Assessment models forced by observed changes in halocarbons, source gases, and aerosols broadly reproduce the long-term changes observed in midlatitude total column ozone (35°N-60°N and 35°S-60°S) from 1980 to 2000, within the uncertainties of the observations and model range. However, the range of model results is large over Southern Hemisphere midlatitudes, which is at least partly due to their differing treatments of the Antarctic ozone hole. In addition, models suggest that the chemical signal of ozone loss following the major eruption of the Mt. Pinatubo volcano in the early 1990s should have been symmetric between the hemispheres, but observations show a large degree of interhemispheric asymmetry in midlatitudes.

77. There is increased evidence that observed changes in atmospheric dynamics have had a significant influence on Northern Hemisphere midlatitude column ozone on decadal time scales. Natural variability, changes in greenhouse gases, and changes in column ozone itself are all likely to contribute to these dynamical changes. Furthermore, because chemical and dynamical processes are coupled, their contributions to ozone changes cannot be assessed in isolation.

### ***Future Ozone Changes***

78. The expected decrease in stratospheric chlorine loading over the next 50 years is predicted to lead to an increase in the global total column ozone, although there are differences in the rate of increase between different two dimensional assessment models. Future ozone levels will also be influenced by other changes in atmospheric composition and by climate change. Because of year-to-year variability, it could take as long as a decade to demonstrate a leveling of total column ozone.

79. Stratospheric cooling (due mainly to projected CO<sub>2</sub> increases) and the chemical influence of stratospheric methane increases are predicted to enhance future ozone increases in the upper stratosphere. However, a reliable assessment of these effects on total column ozone is limited by uncertainties in lower stratospheric response to these changes.

80. Projected increases in methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) (from the scenarios of the Intergovernmental Panel on Climate Change, 2001) are predicted to have small effects on the rate of increase of global column ozone in the next 50 years, when chlorine changes are the dominant effect. After that time, changes in CH<sub>4</sub> and N<sub>2</sub>O become relatively more important.

### **(g) Ultraviolet Radiation**

81. Annually averaged erythemal irradiance, as reconstructed from pyranometer (total irradiance), total ozone, and other meteorological measurements, increased by about 6-14% over the last 20 years at several mid- to highlatitude sites. Pyranometer and other meteorological data serve as proxies for parameters, other than ozone, that affect ultraviolet (UV) radiation. At some sites approximately half of the changes can be attributed to total ozone changes. These reconstructions are not UV measurements, and they contain several assumptions on the nature of radiative transfer. The reconstructions should be not be considered to be representative on a global scale. It is believed that the increases of UV irradiance derived from the ground-based reconstructed data are clear indicators of the long-term changes that have occurred since the 1980s.

82. There is clear evidence that the long-term UV changes are not driven by ozone alone, but also by changes in cloudiness, aerosols, and surface albedo. The relative importance of these factors depends on the local conditions. Results from studies using ground-based and aircraft instruments suggest that the influence of tropospheric aerosols on UV irradiance may be larger than previously thought and may affect large areas of the globe.

83. UV increases associated with the ozone decline have been observed by spectral measurements at a number of sites in Europe, North and South America, Antarctica, and New Zealand. Episodes of elevated UV irradiance associated with low total column ozone amounts continue to occur in spring in mid-to-high latitudes.

84. Satellite estimates of surface UV radiation from the Total Ozone Mapping Spectrometer (TOMS) dataset have been compared with ground-based measurements at several more sites since the previous Assessment. In general the estimates capture short-term and long-term variability. However, the estimates are systematically higher than ground-based measurements at many sites. The differences in monthly average erythemal UV irradiance range from about 0% at some clean sites to 40% at one site in the Northern Hemisphere. The fact that the agreement is better at the cleaner sites suggests that the differences are caused by aerosols and/or pollutants near the ground. New UV maps that include additional influencing parameters (e.g., cloud cover and albedo) derived from other satellite data, when taken together with TOMS or Global Ozone Monitoring Experiment (GOME) ozone data, yield better agreement with ground-based data.

85. In the Antarctic, ozone depletion has been the dominant factor for increases in UV irradiance. The future evolution of UV radiation is therefore expected to follow the ozone recovery. However, because of changes in other influencing factors, such as changes in cloud cover, aerosols, or snow/ice cover, UV radiation may not return exactly to pre-ozone-hole values.

86. Elsewhere, including the Arctic, the impact on UV radiation of other influencing factors can be comparable to the impact of ozone depletion. The large uncertainties in future changes of these other factors prevent reliable predictions on the future evolution of UV irradiance. Furthermore, climate-change-induced trends in cloudiness and snow/ice cover are expected to be seasonally and geographically dependent, leading to differences in future UV irradiance in different parts of the world.

87. A reanalysis of TOMS satellite data with respect to the influence of changes in cloudiness over Europe has confirmed that UV increases due to ozone depletion are partly masked by the increased cloudiness in some regions.

### C. IMPLICATIONS FOR POLICY FORMULATION

88. The results from over three decades of research have provided a progressively better understanding of the interaction of humankind and the ozone layer. New policy-relevant insights into the roles of ozone-depleting gases have been conveyed to decision-makers through the international state-of-understanding assessment process. The research findings in the *Scientific Assessment of Ozone Depletion: 2002* that are summarized above are direct current scientific input to governmental, industrial, and policy decisions associated with protection of the ozone layer.

89. **The Montreal Protocol is working, and the ozone-layer depletion from the Protocol's controlled substances is expected to begin to ameliorate within the next decade or so.** The effectiveness of the Protocol is and will be shown by several indicators. Global observations show that the total combined effective abundances of anthropogenic chlorine-containing and bromine-containing ozone-depleting gases in the *lower atmosphere* (troposphere) peaked in the 1992-1994 time period and are continuing to decline. Furthermore, observations indicate that the *stratospheric* abundances of ozone-depleting gases are now at or near a peak. Thereafter, stratospheric ozone should increase, all other influences assumed constant, but ozone variability will make detection of the onset of the long-term recovery difficult. For example, based on assumed compliance with the amended and adjusted Protocol by all nations, the Antarctic ozone "hole," which was first discerned

in the early 1980s, is predicted to disappear by the middle of this century—again with all other influences assumed constant.

**90 The ozone layer will remain particularly vulnerable during the next decade or so, even with full compliance.** With the atmospheric abundances of ozone-depleting substances being near their highest, the human-influenced perturbations will be at or near their largest. Relative to the pre-ozone-hole abundances of 1980, the 1997-2001 losses in total column (i.e., overhead) ozone amounts are:

- about 4% at northern midlatitudes in winter/spring;
- about 2% at northern midlatitudes in summer/fall; and
- about 6% at southern midlatitudes on a year-round basis.

Calculations yield that such changes in ozone correspond to increases in surface erythemal radiation of at least 5, 2, and 7%, respectively, if other influences such as clouds remain constant. In Antarctica, the monthly total column ozone in September and October has continued to be about 40 to 55% below the pre-ozone-hole values, with up to a local 70% decrease for periods of a week or so. Arctic ozone is highly variable. Estimates of the cumulative winter/spring losses in the total column ozone amounts during the last 4 years range up to about 25%. Calculations of corresponding increases in surface erythemal radiation are about 70 to 150% in the Antarctic springtime, with up to 300% increases for the short-lived local ozone decreases. In the Arctic winter/spring, the corresponding calculated increases are up to 40%. Furthermore, if there were to be an increase in the abundance of stratospheric particles from a major volcanic eruption like that of Mt. Pinatubo in 1991, then the peak losses in total column ozone and the increases in ultraviolet radiation could be larger. In the highly variable Arctic, larger depletion would be expected if an unusually and persistently cold Arctic stratospheric winter like that of the 1999/2000 winter/spring were to occur; conversely, smaller depletions are expected in particularly warm years.

**91. Approaches to accelerating the recovery of the ozone layer are limited.** This Assessment has made hypothetical estimates of the *upper limits* of improvements that could be achieved if global anthropogenic *production* of ozone-depleting substances were to stop in 2003 or if global anthropogenic *emissions* of ozone-depleting substances were to stop in 2003. Specifically:

- *Production.* Relative to the current control measures (Beijing, 1999) and recent production data, the equivalent effective stratospheric chlorine loading above the 1980 level, integrated from 2002 until the 1980 level is reattained (about 2050), could be decreased by the following amounts:
  - 5%, if production of hydrochlorofluorocarbons (HCFCs) were to cease in 2003.
  - 4%, if production of chlorofluorocarbons (CFCs) were to cease in 2003.
  - 4%, if production of methyl bromide were to cease in 2003.
  - 1%, if production of halons were to cease in 2003.
  - 0.3%, if production of methyl chloroform were to cease in 2003.These percentages would be about a factor of 2 smaller if the decreases were compared with the loading integrated from 1980, which is when significant ozone depletion was first detected. A hypothetical elimination of all anthropogenic production of *all* ozone-depleting substances would advance the return of stratospheric loading to the pre-1980 values by about 4 years.
- *Emissions.* Similarly, the equivalent effective stratospheric chlorine loading above the 1980 level, integrated from 2002 until the 1980 level is reattained (about 2050), could be decreased by the following amounts:
  - 11%, if emissions of halons were to cease in 2003.
  - 9%, if emissions of chlorofluorocarbons (CFCs) were to cease in 2003.

- 9%, if emissions of hydrochlorofluorocarbons (HCFCs) were to cease in 2003.
- 4%, if emissions of methyl bromide were to cease in 2003.
- 3%, if emissions of carbon tetrachloride were to cease in 2003.
- 2%, if emissions of methyl chloroform were to cease in 2003.

Again, these percentages would be about a factor of 2 smaller if the decreases were compared with the loading integrated from 1980, which is when significant ozone depletion was first detected. A hypothetical elimination of all emissions derived from industrial production of *all* ozone depleting substances would advance the return of stratospheric loading to the pre-1980 values by about 10 years.

92. **Failure to comply with the Montreal Protocol would delay or could even prevent recovery of the ozone layer.** For example, continued constant production of ozone-depleting substances at the 1999 amount would likely extend the recovery of the ozone layer well past the year 2100. The total atmospheric abundance of ozone-depleting gases will decline to pre-Antarctic-ozone-hole amounts only with adherence to the Montreal Protocol's full provisions on production of ozone-depleting substances.

93. **Estimating the impacts of very short-lived ozone-depleting substances on depletion of the ozone layer requires new approaches, and, as requested by the Parties, this Assessment has described one such scientific approach.** The traditional concept of a *single-valued* Ozone Depletion Potential (ODP) is not directly applicable for these very short-lived ozone-depleting substances, because their impacts on the ozone layer will depend on the season and location of their emissions. These impacts would need to be assessed on a case-by-case basis, taking into account how much, when, and where they are emitted. Such estimates can provide insight into the stratospheric contribution of natural emissions of these very short-lived substances (for example, bromoform) and can provide scientific input into decisions associated with their industrial production/uses (for example, n-propyl bromide).

94. **The issues of ozone depletion and climate change are interconnected.** The ozone-depletion phenomenon and the greenhouse-warming phenomenon share many common chemical and physical processes. For example, as the atmospheric abundances of the CFCs decline because of the Montreal Protocol's provisions, their greenhousewarming contributions will decline. On the other hand, use of hydrofluorocarbons (HFCs) and HCFCs as substitutes for CFCs would cause the greenhouse-warming contributions of these new compounds to increase. Indeed, global observations of many HFCs and HCFCs, as well as of hydrogen fluoride, confirm that these contributions are currently increasing. As other examples, potential decisions associated with methane, nitrous oxide, and carbon dioxide stemming from their greenhouse roles will also have direct and indirect effects on stratospheric ozone. And, because ozone depletion acts to cool the climate system, recovery of the ozone layer over coming decades would tend to warm the climate system.

### III. EXECUTIVE SUMMARY OF THE ENVIRONMENTAL EFFECTS ASSESSMENT PANEL REPORT

#### A. OZONE AND UV CHANGES

95. **Atmospheric ozone remains depleted.** Antarctic ozone losses have remained similar each spring in recent years. In the Arctic, the ozone losses can be substantial, but only during winters when stratospheric temperatures fall below a critical threshold. Outside the Polar regions, ozone losses are less severe. Relative to 1980, the 1997-2000 losses in total ozone are about 6% at southern mid-latitudes on a year-round basis. At northern mid-latitudes the ozone losses are about 4% in winter/spring season, and 2% in summer/autumn. In the tropics, there have been no significant changes in column ozone. Globally, the annual average ozone loss is approximately 3%. These changes are in broad agreement with model calculations.

96. **Although the quality, quantity, and availability of ground-based UV measurements continue to improve, a global-scale assessment from them is not yet available.** The complicated spatial and temporal distributions of the predominant variables that affect ultraviolet radiation at the surface (for example, clouds, airborne fine particles, snow cover, sea ice cover, and total ozone) continue to limit the ability to describe fully surface ultraviolet radiation on the global scale, whether through measurements or model-based approaches.

97. **Spectral surface ultraviolet data records, which started in the early 1990s, are still too short and too variable to permit the calculation of statistically significant long-term (i.e., multi-decadal) trends.** However, long-term increases in peak UV levels have been observed at a few sites, and the measured increases are in agreement with model calculations. Progress has been made inferring historical levels of UV radiation using measurements of ozone from satellites in conjunction with measurements of total solar radiation obtained from extensive meteorological networks.

98. **Long-term effects on UV radiation from changes in cloud and snow cover have been observed.** At two of three sites in Canada the increases in UV-B radiation were as expected from the changes in stratospheric ozone concentrations that have occurred, while at another site the UV-B trend was much larger as a result of additional long-term changes in snow cover and cloud. This indicates potentially complex interactions between climate change and UV-B radiation. Cloud reflectance measured by satellite has shown a long-term increase in some regions (e.g., in Antarctica), which would tend to reduce the UV-B radiation. In other regions (e.g., in the tropics) there have been decreases in cloud cover. These changes in cloud cover are not yet satisfactorily explained by models. Future changes in cloud cover and tropospheric air quality (especially aerosols) may modify significantly the UV exposures experienced at the Earth's surface.

99. **Anthropogenic aerosols play a more important role in attenuating UV radiation than has been assumed previously.** Comparisons between UV measured at the Earth's surface and satellite data indicate that satellite estimates are too large in polluted locations, and thus aerosols are more important than previously thought. The effects of pollution originating from urban and industrial areas may extend over wide geographical areas. Episodes of biomass burning, which contribute to enhanced particulates and gas composition, can decrease UV-B at the Earth's surface and in the troposphere.

100. **Future changes in well-mixed greenhouse gases will affect the future evolution of ozone through chemical, radiative, and dynamic processes.** In this highly coupled system, an evaluation of the relative importance of these factors is difficult; studies are ongoing. Stratospheric cooling (due mainly to projected carbon dioxide increases) is predicted to increase ozone amounts in the upper

stratosphere. However, a reliable assessment of these effects on total column ozone is limited by uncertainties in lower stratospheric response to these changes.

## **B. HEALTH**

**101. New studies continue to confirm the adverse effects of UV-B radiation on the eyes, skin, and immune system.** Although no new health effects have been discovered, many improvements have been made in understanding the mechanism of action of UV-B, thereby reducing the level of uncertainty in predictions regarding the health consequences of ozone depletion.

**102. Studies on the ocular effects of UV radiation strengthen the association between UV-B exposure and the development of age-related cortical cataract.** New epidemiological studies confirm the role of UV radiation in the formation of cortical cataract, and studies in various animal models strongly implicate UV-B radiation as the primary cause of this condition.

**103. New animal models for UV-induced cutaneous melanoma and basal cell carcinoma have been developed.** These models are being used to determine how UV radiation causes or contributes to the development of these skin cancers. Interestingly, induction of melanoma in a transgenic mouse model occurred only when animals were exposed to UV radiation early in life. Similar results were obtained in an opossum model. These findings support those from epidemiological studies suggesting that exposure to UV radiation early in life is an important risk factor in the subsequent development of melanoma. In both models, UV-B, rather than UV-A radiation seems to play the more important role in melanoma induction.

**104. Specific genes and biochemical pathways in cells that contribute to skin cancer development have been identified.** Such studies improve our understanding of the involvement of UV radiation in skin cancer induction and may eventually allow the identification of persons at greatest risk of developing UV-induced cancers of the skin.

**105. New studies indicate that the risk of skin cancer development can be reduced by certain interventions.** Regular use of sunscreens reduced the incidence of squamous cell cancers in adults, and applying DNA repair enzymes to the skin of persons with a genetic susceptibility to skin cancer reduced the development of precancerous lesions.

**106. Research on the immunological effects of UV irradiation continues to improve our understanding of the mechanisms by which UV radiation reduces immune function.** However, many questions remain as to the significance of these effects for allergies, autoimmune diseases, vaccinations, and cancers of internal organs.

**107. Studies in animal models of infectious diseases provide compelling evidence that UV-B radiation can increase the incidence, severity, and duration of a variety of diseases.** Some of these effects are subtle and thus will be difficult to detect in epidemiological studies of infectious diseases in human populations. Nonetheless, evidence continues to accumulate suggesting associations between sunlight exposure and reduced efficacy of vaccinations and exacerbation of infectious diseases, particularly those caused by herpes viruses (cold sores, and shingles).

**108. Phase-out of the ozone-depleting chemical, methyl bromide, may lead to increased use and numbers of other pesticides.** In locations where these chemicals are well regulated, additional health risks are expected to be small. However, in locations where controls are lax, there is reason to be concerned that increased use may lead to additional health risks.

109. **Interactions between global climate change and ozone depletion are likely to influence the risk of adverse effects of UV-B radiation on health.** This influence could be either positive or negative and thus introduces greater uncertainty into the estimates of health effects. For example, increased temperature could increase the incidence of skin cancer, but it might also alter behavior by reducing the hours spent outdoors. Global climate change may also extend the period of ozone depletion, which would further increase the incidence of skin cancer. Changes in the geographic distribution of pesticide use resulting from climate change could introduce adverse health effects in some regions and reduce them in others. Similarly, shifts in the geographic distribution of vectors harboring infectious agents, coupled with impaired immune function, could have a greater impact on infectious diseases than anticipated from ozone depletion alone.

### C. TERRESTRIAL ECOSYSTEMS

110. **Interaction of ultraviolet radiation with other global climate change factors may affect many ecosystem processes.** Examples of such processes and attributes that may be modified include plant biomass production, plant consumption by herbivores including insects, disease incidence of plants and animals, and changes in species abundance and composition. In these and other studies there is a need for long-term experiments.

111. **A meta-analysis, with quantitative and statistical information has been used to assess how well overall research predicts common trends and results from different species of plants from experiments conducted outdoors using UV lamp systems.** This analysis showed that of the physiological and morphological traits, overall significance of elevated UV-B was found for decreased plant height and leaf area, increased phenolic compounds and sometimes reduced shoot mass.

112. **Fungi and bacteria exposed to sunlight can be directly damaged by enhanced UV-B.** The species composition and biodiversity of bacteria and fungi growing on plants can be changed by UV-B. Biodiversity can be either increased or decreased. For pathogens, elevated UV-B can either increase or decrease the severity of disease development in plants.

113. **Exposure of plants to enhanced UV-B can result in altered disease and herbivory intensity.** UV-B often decreases the intensity of insect herbivory and this likely involves plant tissue chemical changes, such as altered phenolic chemistry. The influence of UV-B on pathogen attack on plants can involve both changes in host plant chemistry and direct effects on pathogens. This can either increase, or decrease pathogen attack in different species of plants.

114. **Common higher plant responses to elevated UV-B may be lessened by elevated CO<sub>2</sub>.** In cases where enhanced UV-B reduces plant growth (height, leaf area and sometimes shoot mass), elevated CO<sub>2</sub> can often overcome these reductions.

115. **Water limitation may decrease the sensitivity of some plants to enhanced UV-B.** Plants, especially those of agricultural use, experiencing drought stress are often less responsive to enhanced UV-B. Plants from some environments, such as Mediterranean scrub vegetation, may be more tolerant to drought stress if exposed to elevated UV-B.

116. **The effects of UV-B on plant growth reductions are often accompanied by greater DNA damage.** UV-B can affect several critical macromolecules, such as nucleic acids, proteins and lipids. The mechanisms that mediate growth inhibition by UV-B under natural conditions are still poorly understood. However, correlative evidence suggests that DNA damage may play a significant role.

117. **Increasing temperatures can promote repair of UV-B damage to DNA, although combining extreme temperatures and enhanced UV-B can cause unexpected results.** DNA damage is repaired more effectively if not limited by low temperatures. Thus, repair is promoted by warming under certain circumstances, and this may lessen the inhibitory effects of UV-B on plant growth. Some responses to extreme temperatures will be modified in unexpected ways by enhanced UV-B; for example, there is evidence for substantially increased frost sensitivity of some sub-Arctic heath species. There is a need for further research in this area in relation to climatic change trends.

#### **D. AQUATIC ECOSYSTEMS**

118. **Recent results continue to confirm the general consensus that solar UV negatively affects aquatic organisms.** Reductions in productivity, impaired reproduction and development and increased mutation rate have been shown for phytoplankton, fish eggs and larvae, zooplankton and primary and secondary consumers exposed to UV radiation. UV-B related decreases in biomass productivity are relayed through all levels of the food web, possibly resulting in reduced food production for humans, reduced sink capacity for atmospheric carbon dioxide, as well as changes in species composition and ecosystem integrity.

119. **It is at the ecosystem level where assessments of anthropogenic climate change and UV-related effects are interrelated and where there is the potential for both antagonistic and synergistic effects.** Recent studies have shown that these changes may lead to loss of ecosystem resilience. In some aquatic ecosystems the onset of spring phytoplankton blooms and spawning in invertebrates and vertebrates coincides with dramatic ozone depletion as well as shifts in several climate-related parameters.

120. **Polar ecosystems are particularly sensitive to change, because the freeze/thaw boundary applies critical limits to subsequent environmental responses** including: air and water temperature; the timing, extent and duration of ice and snow cover; changes in the surface albedo; changes in water column colored dissolved organic matter (CDOM) concentrations; and the level of solar radiation and the extent of its penetration. Such changes, which may be driven by climate variability, may be more important for UV-B exposure levels and spectral balance between UV-B and visible radiation than ozone depletion.

121. **Solar UV penetrating the top layers of the water column markedly affects zooplankton, as well as larval stages of primary and secondary consumers.** The effect of solar UV is strongly modified by other environmental factors, such as variability in cloud cover, water temperature, mutual shading in algal blooms and depth of mixing layer. Although the primary causes for a decline in fish and shellfish populations are predation and poor food supply for larvae, over-fishing of adults coupled with increased water temperature, pollution and disease, and exposure to increased UV-B radiation may contribute to that decline. For amphibians, climate-induced reductions in water depth at sites where eggs are laid have caused a high mortality of embryos due to increased exposure to solar UV-B and subsequent vulnerability to infection.

122. **In addition to increasing solar UV-B radiation, aquatic ecosystems are confronted with other environmental stress factors including increased nutrient input, pollution, acidification and global climate change.** In turn, climate change will result in temperature and sea level change, shifts in the timing and extent of sea ice cover, changes in salinity and altered stratification of the water column, and wave climate and ocean circulation. These effects will be linked by pronounced feedback mechanisms, which are not yet completely understood. The resulting complex changes are likely to have significant impacts that will vary both spatially and temporally.

## E. BIOGEOCHEMICAL CYCLES

**123. Global warming and enhanced UV-B radiation interact to affect a range of biogeochemical processes.** On land, warming increases microbial activity, nutrient cycling, and greenhouse gas emissions from soils, whereas increased UV-B can retard or accelerate these processes. In aquatic systems, warming also increases microbial activity. The exposure of organisms to UV is amplified by increased water stratification and changed mixing of surface waters that are related to global climate change.

**124. Interactions between UV-B radiation and increased ocean temperatures affect sulfur emissions that influence the balance between incoming and outgoing radiation in the marine atmosphere.** Enhancements of sulfur transfer from the ocean to the atmosphere are linked to changes in ocean surface layer mixing, induced by global warming, increased UV-B exposure, and UV-B inhibition of bacterial growth. Oceanic sulfur emissions can influence cloud characteristics that in turn affect radiation in the marine atmosphere.

**125. There is new evidence that UV accelerates decomposition of the colored organic matter that runs off from land into the ocean.** Previously, it was believed that land-derived organic matter was mainly lost by biological oxidation and burial in coastal zones where sedimentation is high. Now, it is known that UV plays a central role in the removal of this organic matter.

**126. The exchange of trace gases between terrestrial systems and the atmosphere is influenced by changes in UV-B.** Additional research on UV-induced carbon monoxide production from dead plant matter in terrestrial ecosystems indicates that the global annual carbon monoxide input from this source to the atmosphere is significant. Solar UV-induced nitrogen oxide production has been observed in snowpacks located at diverse sites in Greenland, Antarctica, Canada and the northern United States. The UV-driven emissions of carbon monoxide and nitrogen oxides may change local concentrations of tropospheric ozone.

**127. Important components of the terrestrial nitrogen cycle are sensitive to enhanced UV-B radiation.** In the Northern Arctic, where unavailable nitrogen severely limits plant growth, nitrogen fixation by free-living blue-green algae was retarded by enhanced UV-B. Potential nitrogen fixation by symbiotic algae in a sub-Arctic lichen species was also reduced in the long term. In addition, enhanced UV-B increased nitrogen immobilized by soil bacteria in the sub-Arctic, making nitrogen less available for plant production.

**128. Enhanced UV-B radiation accelerates the decomposition of colored dissolved organic matter (CDOM) entering the sea via terrestrial runoff,** thus having important effects on oceanic carbon cycle dynamics. UV-induced changes in visible light absorption by CDOM can affect the accuracy of estimates of coastal oceanic productivity based on remote sensing of ocean color.

**129. Several important sources of natural ozone depleting halogenated substances have been identified in the terrestrial biosphere and explain deficits in global budgets.** Calculations of global atmospheric budgets of methyl bromide and methyl chloride indicate large missing sources. Recent experimental data indicate that natural emissions of these gases from terrestrial ecosystems, particularly salt marshes, account for a significant part of these missing sources. Emissions appear to result from an active process strongly related to diurnal incident light levels. Methyl chloride and methyl bromide participate in ozone-depleting processes.

## F. AIR QUALITY

130. **The effect of stratospheric ozone depletion on tropospheric ozone trends is significant, but small compared to the anthropogenic emissions in air-polluted areas.** Model and experimental studies suggest that the impacts of stratospheric ozone depletion on tropospheric ozone are different at different altitudes and for different chemical regimes. A measurable effect on concentrations will be expected only in regions where local emissions make minor contributions. The vertical distribution of NO<sub>x</sub>, as well as the emission of volatile organic carbons and abundance of water vapour, are important influencing factors.

131. **Risks from the effects on humans and the environment of trifluoroacetic acid (TFA) and chlorodifluoroacetic acid (CDFA) produced by atmospheric degradation of HCFCs and HFCs are judged to be minimal.** TFA has been measured in rain, rivers, lakes, and oceans, the ultimate sink for these and related compounds. Anthropogenic sources of TFA other than degradation of HCFCs and HFCs have been identified.

132. **Interactions between ozone depletion and climate change will have an impact on tropospheric hydroxyl (OH) radical concentration, the “cleaning” agent of the troposphere.** Stratospheric ozone depletion leads to an increase in concentration of the OH radical in the troposphere. Increases in the concentration of gases such as volatile organic compounds will act as a sink for OH in the troposphere. Aerosols can also act to reduce UVB in some circumstances and hence reduce OH. Changes in cloudiness and temperature will also have an effect. All of these can be influenced by climate change. The net change in air quality and chemical composition in the troposphere will depend on the balance between these effects.

133. **Changes in the aerosol content of the atmosphere resulting from global warming may affect ozone photolysis rates and hence reduce tropospheric ozone concentrations.** Model and field studies show that a reduction in the ozone photolysis rate and ozone production in the troposphere is to be expected in the presence of increased absorbing aerosols in the troposphere.

## G. MATERIALS

134. **Climate change is likely to modify the rates of UV-induced degradation of natural and synthetic materials.** In regions of the world with high UV-B levels, increase in the ambient temperature will have a marked influence in increasing the rate of light-induced degradation of materials. This is particularly true of plastics and wood used in building construction. Increased humidity can also have a similar effect on some materials when coupled with high UV, especially at the high ambient temperatures.

135. **New varieties of commodity plastics with improved properties are emerging and these too can be stabilized effectively with existing light stabilizers.** Recent improvements in catalysts have led to the discovery of metallocene plastics (polyethylenes and polypropylenes) that have improved properties including slightly better UV resistance compared to the conventional varieties. Commonly used conventional light stabilizers were found to be effective in stabilizing these varieties of thermoplastics as well.

136. **Recent data suggest synergistic improvement in light-stabilizer effectiveness when mixtures of conventional HALS stabilizers are used in plastics.** Hindered amine light stabilizers (HALS) are commonly used as a light stabilizer with common plastics. Mixtures of two or more of these were recently reported to perform even better as light stabilizers of plastics. Increasing the light stabilizer effectiveness is important to minimize the cost of stabilization of plastics formulations against the damage caused by UV radiation and climate change.



## **IV. EXECUTIVE SUMMARY OF THE TECHNOLOGY AND ECONOMIC ASSESSMENT PANEL REPORT**

### **A. INTRODUCTION**

137. Since the 1998 Assessment of the Technology and Economic Assessment Panel (TEAP), a large number of technical developments have taken place. The direction many of these developments have taken could not have been predicted in 1998. Hydrocarbon refrigerants are capturing greater market share and CO<sub>2</sub> is commercialised in some refrigeration sub-sectors, including heat pump water heaters, and proposed in vehicle air conditioning. Newly available HFCs are currently being introduced into some foam sectors, but price and responsible use criteria are limiting the uptake to specific applications where they are needed. Large quantities of ODSs are potentially available for destruction with significant efforts underway in Australia, Canada, Europe, and Japan.

138. The Panel's Technical Options Committees, on aerosols, MDIs, miscellaneous uses and CTC (ATOC), on foams (FTOC), on halons (HTOC), on methyl bromide (MBTOC), on refrigeration and AC (RTOC), and on solvents (STOC) have each issued a 2002 Assessment Report. The Executive Summaries of these reports form the body of the 2002 TEAP Assessment Report and their Abstract Executive Summaries form the Executive Summary of the 2002 TEAP Assessment Report.

139. During the year 2002, separate Task Forces under the TEAP have reported their findings, which are part of the TEAP Progress Report, published April 2002. In particular the findings of the Task Force on Collection, Recovery and Storage (TFCRS) are interlinked with the results reported by the different TOCs in their 2002 Assessment Reports. The summary of these findings was thought to be so important that it should again be part of the TEAP 2002 Assessment Report.

140. The following structure has been adopted in each section:

- Current status; what has been achieved
- What is left to be achieved
- The way forward.

This structure does not apply to the Executive Summary of the TFCRS Report.

### **B. AEROSOLS, STERILANTS, MISCELLANEOUS USES AND CTC TOC**

#### **(a) MDIs for Asthma and COPD**

##### *Current status*

141. Asthma and COPD have remained common and their prevalence is increasing world-wide. Technical barriers for CFC-free MDIs are currently being overcome. A range of alternatives, including CFC-free MDIs and DPIs, are now available increasingly around the world. In 2001, each of the three inhaler types, i.e., (1) the CFC-containing MDI inhalers, (2) the CFC-free MDI inhalers and (3) the DPI inhalers had one third of the market in the European Union.

##### *What is left to be achieved*

142. The remaining 7,000 ODP tonnes of CFCs used annually in MDIs for asthma/COPD can be phased out. The timing is difficult to predict, but it depends on:

- the availability of affordable alternatives
- the adoption and effectiveness of transition strategies by Parties.

### *The way forward*

143. Parties could aid their transition by collecting data on the local availability of alternatives. However, the availability of alternatives alone does not drive transition to completion, and effective transition strategies are needed. Some non-Article 5(1) Parties have developed transition strategies for the phase-out of the production of CFC containing MDIs. As of November 2002, ten Parties (out of 43 non-Article 5(1) Parties) had submitted transition strategies to the Ozone Secretariat.

#### **(b) Aerosols, Sterilants and Miscellaneous Uses**

##### *Current status*

144. In the last four years there has been a substantial phase-out of CFCs in non-MDI aerosols. Between 1997 (14,700 ODP tonnes) and 2001 (4,300 ODP tonnes) there was a 71% reduction in the CFC consumption that remained in Article 5(1) Parties and CEIT.

145. The use of CFCs for sterilisation has been phased out in most non-Article 5(1) Parties. Many alternatives have been developed.

146. Most miscellaneous uses have been phased out, whilst some laboratory uses still remain under a global exemption. However three uses (the testing of oil, grease and total petroleum hydrocarbons in water; testing of tar in road-paving materials; and forensic fingerprinting) were eliminated from the exemption.

##### *What is left to be achieved*

147. A complete phase-out for non-MDI aerosols is achievable. There are difficulties including the availability of hydrocarbon aerosol propellants, the conversion of small CFC users, and also the conversion of non-MDI pharmaceutical aerosols.

148. There remain about 500 ODP tonnes of CFCs used annually in sterilants in some Article 5(1) and CEIT Parties.

149. Regarding miscellaneous uses, about 1,000 ODP tonnes of CFCs are used for tobacco expansion in China and 1,500 ODP tonnes of CFCs and CTC world-wide for laboratory and other miscellaneous uses.

##### *The way forward*

150. A complete phase-out of the remaining CFCs for the use in non-MDI aerosols requires specific actions from Government/Ozone officers and may need technical and financial assistance.

151. Sterilisers are expensive equipment, which are needed to provide good quality health care. Drop-in substitutes are available at a higher cost, reason for which financial assistance may be needed in Article 5(1) countries.

152. Use of CFCs for tobacco expansion in China is scheduled for phase-out by 2007. Continued use for laboratory and analytical applications under the global exemption requires that all Parties adopt packaging and reporting systems as specified in the exemption. Licensing systems will be needed in order to manage supplies of ODS into the laboratory and analytical sector.

**(c) Carbon Tetrachloride**

*Current status*

153. The primary source of atmospheric emissions of CTC is from manufacturing facilities that use it as a feedstock to produce CFCs. Through closures of facilities substantial reductions have been achieved recently and more are expected in the future.

*What is left to be achieved*

154. CTC emissions from process agent use in non-Article 5(1) Parties are estimated at 220 ODP tonnes annually, but emissions are very difficult to estimate in Article 5 (1) Parties. A number of applications for CTC exist in Article 5(1) Parties, although it is not clear which exact amount can be attributed to CFC production, feedstock, process agent, and other applications such as solvents; further data on consumption and emissions are required. The extent of inadvertent production of CTC in other chemical production processes in both Article 5(1) and non-Article 5(1) countries is currently unknown.

*The way forward*

155. Emissions from feedstock and process agent uses in Article 5(1) Parties require special attention from the Montreal Protocol Parties. Close co-operation of the Technology and Economic Assessment Panel with the Science Assessment Panel will be required to better estimate inadvertent emissions and more closely examine their implications.

**C. RIGID AND FLEXIBLE FOAMS TOC**

*Current status*

156. The phase-out of ODS in the foam sector has forced the industry to innovate faster than ever before. The first technology transition in the early 1990s led to the introduction of transitional substances such as HCFCs as well as the increasing use of hydrocarbons and other non-ODSs. This transition step is still taking place in Article 5(1) countries. Meanwhile, attention in non-Article 5(1) countries is on phasing out transitional HCFCs. This is concentrating attention on the emerging HFC-based technologies as well as the further optimisation and use of hydrocarbon and CO<sub>2</sub> technologies, which are continuing to gain market share in several sub-sectors.

157. The phase-out of CFC use in the polyurethane flexible foam sector is now largely complete, even in Article 5(1) countries, although some small discontinuous processes still represent a challenge. In the flexible sector there has been little use of transitional technologies.

158. In the appliance polyurethane rigid foam sector, there has been a tendency to switch in one-step transition to hydrocarbons. The exception is the market in North America, which over the coming months is likely to move substantially to HFC use, as HCFC-141b is phased-out in the United States. CFC usage has been all but phased out in the construction foam markets, although transitions out of HCFCs are proving difficult within the smaller site-applied products such as spray foam.

159. The use of CFCs in foams has been reduced by over 90% since its peak in 1988 and HCFC use is also in decline from its peak in 2000. For the first time, the ozone depleting impact arising from new consumption of each class of blowing agent -if and when emitted- has become comparable in magnitude.

### *What is left to be achieved*

160. Liquid HFC blowing agents have been commercially introduced and work is ongoing to define responsible use criteria in the light of the significant global warming potential of these materials. Nonetheless, HFCs can be used responsibly in many applications where they offer additional energy efficiency benefits or particular product/process safety.

161. The plight of the small- and medium-sized enterprises (SMEs) also remains to be addressed. This is most severe in non-Article 5(1) countries where no transitional assistance exists. However, even in Article 5(1) countries, there is continuing concern that uncertainty over the future supply of alternatives is delaying phase-out of CFCs. This is particularly an issue for plants where cost-effectiveness considerations dictate the use of transitional technologies.

162. As annual consumption of ODSs decreases, the focus is shifting towards the management of emissions from delayed release sources such as closed cell foams. Both Japan and Europe have already taken steps related to resource recovery and ODS destruction from appliances. However, recovery of ODSs from buildings is likely to pose a more significant and costly challenge. This may be a further driver towards HC or CO<sub>2</sub> options or wider changes in building practice to facilitate recovery. Progress in this area will also have valuable benefits for the new generation of foam technologies.

### *The way forward*

163. For SMEs and particularly low volume users, there is no economically feasible solution unless the financial implications of investments are overcome. In many foam sectors, the alternative blowing agents are hydrocarbons, which are less expensive than HFC blowing agents but require expensive investments to satisfy safety requirements. A solution might be interest-free loan schemes, even in non-Article 5(1) countries, where the investment cost is repaid from savings in blowing agent expense. However, no such schemes are yet being considered.

164. The technical and economic feasibility of the recovery of blowing agents from foam at end-of-life will continue to be an area of significant study over the next few years. The requirements of the Montreal Protocol and most national implementation procedures provide little economic incentive. However, recovery and destruction would be economic if credit was given to mitigation of greenhouse gas emissions also, in addition to the direct benefit to the ozone layer. Regulatory or trading schemes would have to reclassify ODS destruction to engage the necessary economic drivers.

## **D. HALONS TOC**

### *Current status*

165. Halon fire extinguishants are no longer necessary in virtually any new installations, with the possible exceptions of engine nacelles and cargo compartments on commercial aircraft and crew compartments of combat vehicles. The very high cost of replacing many existing halon systems with substitutes, replacements or other alternative fire protection measures continues to be a major impediment to eliminating continued use of halons.

166. Although potential alternatives exist for both engine nacelles and cargo bays of commercial aircraft it is disturbing to report that new airframes are still being designed and certified with halons as the required fire extinguishant due to regulatory requirements. Parties may wish to consider requesting the International Civil Aviation Organization (ICAO) to act with the TEAP HTOC as a co-

ordinating body in development of a timely plan of action to eliminate regulatory requirements for halons on new airframes. Airframe Certification Agencies and Airframe Manufacturers may want to participate in this effort.

*What is left to be achieved*

167. Some Parties have enacted regulations requiring existing halon systems to be decommissioned and the halons from these systems destroyed. Although most halon 1211 and a portion of halon 1301 in inventory will not be required to meet future needs such measures require careful planning to ensure that sufficient stocks of halon 1301 remain available to meet future critical needs of both Article 5(1) and non-Article 5(1) Parties. Users that have critical halon needs should consider making arrangements to ensure a secure supply, either individually or in partnership with other critical users. This effort would likely include obtaining the additional halon necessary to meet their future requirements and expansion of existing or construction of new secure storage facilities that would include necessary leak prevention and monitoring measures.

*The way forward*

168. An alternative to the creation of large halon stockpiles would be a decision to allow Parties to earn credits for destroyed or converted halon by technologies approved by the Parties. These credits would be eligible to be carried forward for possible future critical uses to be approved (Article 1, Paragraph 5, read with Article 7, allows credits for production. However, since the control measures are for each year, the credit is in the year of destruction and not for future use). Such a provision would be an incentive to collect and destroy halons, would deter emissions from halon banks which may be found surplus to requirements, and could help eliminate the reluctance to retrofit of existing applications that results from the current oversupply of halon. A bolder market-based strategy to achieve these objectives could be trading in credits obtained by destruction of halons or allowing such credits to be used for essential/critical uses of other ODS.

169. The HTOC will invite TEAP and its other TOCs to consider the potential advantages and disadvantages of such an approach to other ODS use sectors. In 2003, the Halon Technical Options Committees will further explore options to reduce halon emissions.

**E. METHYL BROMIDE TOC**

*Current status*

170. Production of MB for controlled uses was reported to be about 62,757 metric tonnes in 1998; it was reduced to at least 49,566 tonnes in 1999 and at least 46,055 tonnes in 2000. Non-Article 5(1) countries have reduced controlled MB consumption by about 56% from the 1991 baseline, in advance of the Protocol requirements. Controlled MB consumption in Article 5(1) countries rose from about 8,460 tonnes in 1991 to about 17,600 tonnes in 1998. Based on Ozone Secretariat data reported so far, Article 5(1) MB consumption was reduced to about 16,440 tonnes in 2000. Between 1998 and 2000, national MB consumption fell by more than 20% in some Article 5(1) countries.

171. The decline in total global consumption of MB is attributed largely to reductions for soil fumigation. This has been achieved mainly by the adoption of transitional strategies, such as replacing MB used alone with MB/chloropicrin mixtures, and to a lesser extent by adoption of alternatives, principally alternative fumigant mixtures and soil-less culture systems. Alternatives adopted for durable commodity and structural treatments are principally phosphine fumigations and, in specific situations, heat treatments.

172. By December 2002 the Multilateral Fund (MLF) had approved a total of 232 MB projects in more than 63 countries. This included 44 demonstration projects for evaluating and customising alternatives, 38 projects for phasing-out MB and 150 other projects for information exchange, awareness raising, policy development and project preparation. Further MB replacement activities have been funded directly by Article 5(1) countries and/or agricultural producers, bilateral assistance and the Global Environment Facility.

173. With two exceptions (control of ginseng root rot and stabilisation of high-moisture fresh dates), the completed demonstration projects, for all Article 5(1) locations and all crops or situations tested, identified one or more alternatives comparable to MB in their effectiveness in the control of targeted pests and diseases. In many cases, combined techniques have provided more effective results than individual techniques, particularly when they are part of an integrated pest management (IPM) program.

174. Projects in Article 5(1) countries have demonstrated that a similar range of alternatives to those in non-Article 5(1) countries can be successfully adopted. Differences in costs and resource availability can lead to a preference for different alternatives in Article 5(1) compared to non-Article 5(1) countries. Demonstration projects showed that it is feasible to introduce the tested alternatives into Article 5(1) countries and adapt them successfully within 2-3 years, in some cases even including registration of pesticide products.

175. Systems for recapture of methyl bromide based on activated carbon absorption have recently been commercialised. The driving force has been local regulations on air quality to protect workers and the general community. MB recapture is not likely at present to be used on farms in a significant way. Practically, the scope for recovery of MB after fumigations is likely to be restricted to treatments carried out in enclosures, i.e. space fumigations, particularly QPS-related, of commodities, structures and transport, with subsequent destruction of the captured MB.

#### ***What is left to be achieved***

176. MBTOC could find no existing technical alternatives for about 3200 metric tonnes of MB per annum used for non-QPS treatments. This implies that there are existing alternatives for more than 93% of year 2000 consumption of MB, excluding QPS. However, some of these alternatives may not be available in practice as a result of various constraints, particularly lack of registration for use on the particular crop or foodstuff to be treated. Significant effort must now be undertaken to register and implement these alternatives and to optimise their use. Some countries have registered some alternatives in recent years and some large volume consuming countries are currently considering registration for certain alternatives. There is the possibility that further registrations for use will be completed prior to the 2005 phase-out in some non-Article 5(1) countries.

177. With regard to Decision IX/5(1e), experience with demonstration and investment projects to date, such as those supported by the Multilateral Fund, indicates that the many technical, climatic, social and economic barriers to MB alternatives present in diverse Article 5(1) regions can be successfully overcome. The commercial availability of certain alternatives for some applications in Article 5(1) countries is of continued concern.

178. Adapting the alternatives to the specific cropping environment and local conditions of particular Article 5(1) countries is essential to success. For example, local materials such as coconut coir and rice hulls have made it possible to adapt substrate systems that would normally have required know-how and technically-demanding materials (e.g. rockwool) not widely available in Article 5(1) countries.

### *The way forward*

179. MB alone, or in mixtures with chloropicrin, is still being used for preplant soil disinfestation to manage the range of crop/pathogen complexes reported in the 1998 Report. The major crops for which MB is still widely used in some regions include: cucurbits, pepper, tomatoes, perennial fruit and vine crops, ornamentals, strawberry fruit and turf. MB may also be used in the production of propagation material for forests, fruit and vine crops, strawberries, ornamental trees and tobacco.

180. Although significant progress in developing alternatives to MB has been made since the publication of the 1998 report, the complexity of soil pathogen and weed problems in different countries and the diversity of environments in agriculture require the continuing development and adaptation of non-chemical and chemical methods. Further investment in research and technology transfer will be necessary to implement alternative pest management systems effectively in all countries.

181. TEAP reported previously that QPS use is increasing in some countries and estimated that approximately 22% of MB consumption was used for QPS treatments. Following Decision XI/13, MBTOC will, *inter alia*, report on the feasibility of alternatives in 2003. MBTOC noted more than 300 examples of alternatives to MB approved for quarantine treatment of perishables and more than 70 approved as QPS treatments for durable commodities. There is scope for the further development of alternatives in the QPS area.

182. On the basis of 70% recapturable MB, fitting of recapture and destruction equipment to QPS commodity treatments could prevent about 7,000 metric tonnes of MB emissions entering the atmosphere. Existing and anticipated MB projects are due to lead to the phase-out of 10,000 tonnes of MB before about 2008 in Article 5(1) countries.

## **F. REFRIGERATION, AC AND HEAT PUMPS TOC**

### *Current status*

183. In the last decade, the refrigeration, air conditioning and heat pump industry made tremendous technical progress and complied with the Montreal Protocol through phasing out CFCs and, in several applications, HCFCs as well. The mobile air conditioning and the domestic refrigeration industries have shifted rapidly from CFC-12 to non-ODS refrigerants. Other applications, such as chillers and commercial refrigeration, have shifted from CFCs to HCFCs and HFCs or other fluids.

184. The requirement to phase out CFCs and eventually other ODS, along with considerations to reduce global warming impacts, has spurred unprecedented transitions. Differences in timing and in choosing options between countries have been influenced by regional and national regulations. The primary solutions for new equipment are summarised below by application:

- *domestic refrigeration*: HFC-134a and isobutane (HC-600a),
- *commercial refrigeration*: HCFC-22 and mainly R-404A in supermarket systems, HCs in some self-contained units as well as in a few indirect systems, and to a small extent carbon dioxide (R-744),
- *industrial refrigeration*: ammonia (R-717), HCFCs, HFCs and to some extent carbon dioxide for low temperature,
- *transport refrigeration*: HFCs for the majority of applications,
- *stationary air conditioning equipment*: HCFC-22 (in about 90% of the equipment), with the remainder using the currently produced HFCs and HFC blends, and, to a lesser extent, HCs,

- *chillers*: HCFCs (primarily HCFC-22 in small and HCFC-123 in centrifugal chillers), HFCs (primarily HFC-134a and, in smaller equipment, also blends), and much less commonly ammonia and HCs,
- *heat pump water heaters*: HCFC-22, HFC-134a, propane (HC-290), R-410A, and to some extent carbon dioxide,
- *mobile air conditioning*: HFC-134a for virtually all new vehicles (being the global choice).

185. The above solutions are also being applied in Article 5(1) countries, where in several sectors the conversion is not complete, however, the number of conversions is steadily increasing. There still is a certain amount of new equipment manufactured with CFCs, also in domestic, but particularly in commercial and transport refrigeration.

#### ***What is left to be achieved***

186. Worldwide, a significant amount of installed refrigeration equipment still uses CFCs and HCFCs. As a consequence, service demand for CFCs and HCFCs remains high. The refrigerant demand for these service needs is best minimised by preventive service, containment, retrofit, recovery and recycling. Recovery at decommissioning or scrapping of equipment, not only in the case of refrigerators, is an important topic, which receives increasing attention now that the non-Article 5(1) ODS consumption has been restricted to essential uses. The first step in addressing the refrigerant conservation topics cited above is through training of installers and service technicians, together with certification and regulations. Countries where programs have been successful have had comprehensive regulations requiring recovery and recycling.

#### ***The way forward***

187. Current developments concentrate on increasing use of HFCs as well the non-fluorocarbon options mentioned above in most sectors, with emphasis on optimising system efficiency (COP) and reducing emissions of high-GWP refrigerants. A high degree of containment, in fact, applies to all future refrigerant applications, either for decreasing climate impact or for safety reasons. Additional research and development is ongoing all over the world (i) to enhance the development status and the quality of the equipment using the current alternatives, and (ii) to investigate the potential of other long term in-kind and not-in-kind solutions, seeking both lower environmental impact including higher energy efficiency and improved safety characteristics.

## **G. SOLVENTS, COATINGS AND ADHESIVES TOC**

### *Current status*

188. The achievements of the Solvents, Coatings and Adhesives Technical Options Committee (STOC) have further consolidated its past work, while examining new developments in terms of replacement technologies, market evolutions, solvents toxicology etc. In particular, the STOC has assessed the market potential for n-propyl bromide in the light of concern for ozone depletion and health impacts from human exposure. It has also given particular attention to the specific needs of Article 5(1) countries. Almost a total phase-out of the use of Annex A, Annex B and Annex C, Group III controlled solvents has now been achieved in non-Article 5(1) countries. There are still a few cases of users relying on stockpiled or recycled materials, but these stocks must be exhausted in the near future. A very small amount of ODS solvents has been necessary for a few Essential Use Exemptions granted by Parties. The STOC believes that the unexpected 1,1,1-trichloroethane emissions measured in Europe probably come from landfills where drums of used solvents may have been dumped many years ago. In addition, HCFC-141b is being rapidly phased out as a solvent in the European Union and the USA. Subsidiaries and suppliers of multinational companies in Article 5(1) countries have long ago finished their phase-out and the MLF has completed a few major solvents projects. However, very few projects have been completed with small and medium enterprises (SMEs) and users (SMUs) consuming less than 5 ODP tonnes of solvents. There are many thousands of such users, consuming a major part of the remaining usage.

### *What is left to be achieved*

189. There is much left to be achieved in the Solvents Sector. Effort is still required to phase out ODS solvents in Article 5(1) countries, and especially the small- and medium-sized users (SMUs). In particular, there is concern about the use of carbon tetrachloride (CTC) for solvent applications by both large and small enterprises in some countries. A few important CTC projects are currently being developed by the Implementing Agencies, but these represent only a fraction of the total consumption. One other obstacle that has been identified is illegal imports into, mostly, Article 5(1) countries that have already enacted restrictive legislation. These may represent a considerable proportion of baseline quantities, in some cases, and, of course, are not reported. This, and other factors, may mean that the total global OD solvents consumption is currently significantly higher than is reported.

### *The way forward*

190. Delaying the phase-out of production and imports of Annex A and Annex B solvents will involve greater difficulty and larger costs than doing it now. This will inevitably cause hardship, especially for the many SMEs. The STOC is developing an e-mail and Internet infrastructure that will allow National Ozone Units (NOUs) to obtain detailed expert technical information free-of-charge, for rapid response in each sub-sector. This report is the first step with stand-alone, sub-sectoral chapters, for easy translation into languages, each with e-mail addresses of experts for consultation. The STOC also needs to address the increasing use of HCFC-141b solvents in Article 5(1) countries, sometimes as substitutes for non-OD solvents. There are no technical barriers to a total and immediate phase-out of the use of CTC, CFC-113, 1,1,1-trichloroethane and HCFC-141b solvents in nearly all applications.

## **H. COLLECTION, RECLAMATION AND STORAGE TASK FORCE**

191. The Task Force on Collection, Reclamation and Storage (TFCRS) assessed use patterns, associated emissions and aspects of collection and storage of ODS from all relevant use sectors. The assessment takes into account the different situations in Article 5(1) Parties, where production takes place for the Article 5(1) Parties (under “Basic Domestic Needs”) and the situation of non-Article 5(1) Parties, some of which are still manufacturing. The TFCRS Report also presents an overview of ODS inventories and their management in the different sectors and provides first estimates of historic and actual emission patterns from the different use sectors.

### **(a) Types of Emission**

192. ODS can be emitted at various stages in the lifecycle of production, distribution, use, and disposal. Emission estimates for any given year need to account for early emissions of recently ‘consumed’ ODS as well as delayed emissions of historically used ODS. This is because emissions from both developed and developing countries will continue for many years after the phase-out of ODS production.

193. Because the TFCRS Report addresses management of ODS currently in use, it categorises sectors based on emissions profiles. Solvents, aerosol products (including MDIs), methyl bromide and flexible foams emit ODS soon after initial use, and for a relatively short period of time. The report terms these “early emissions.” Refrigeration and air conditioning equipment, rigid foams and halon equipment emit small quantities of ODS over very long periods of time after initial use. The timeframe over which these uses emit ODS range from years to decades. The report terms these “delayed emissions.”

194. The main focus of the TFCRS Task Force was on uses with delayed emissions, because those are uses that have the largest inventories of ODS and offer the greatest opportunities to destroy or recycle large quantities of ODS.

195. The focus for early emissions is on non-Article 5(1) Parties essential uses and on current and/or recent use in Article 5(1) Parties. The focus for delayed emissions is on inventories of ODS originating from sustained non-Article 5(1) and the increasing inventories present in the same applications in Article 5(1) Parties.

### **(b) Technical feasibility of Collection, Recovery & Storage**

196. It is technically feasible to collect and recover all ODS retained in inventories. In refrigeration and halon equipment the ODS is already contained in readily accessible containers. In the case of other applications, the ODS can be in locations which are much more difficult to access (e.g. cavity wall rigid foam insulation).

197. For many rigid foams including those contained in refrigerators, the recovery and destruction steps can be combined and the decision may be made that it is more cost-effective to directly incinerate a product containing the ODS than to extract the ODS for subsequent destruction.

198. It is technically feasible to recover methyl bromide used as a post harvest, structural or transport fumigation (about 26 % of current methyl bromide uses, including for QPS) for destruction. The surplus methyl bromide can be adsorbed and then directly treated for destruction either chemically or by incineration.

### **(c) Inventories and Collection Potential**

199. It has been known for quite some time that the ODS inventories stored in delayed emission applications are substantial. This assessment has better quantified these amounts. Inevitably, the assessment has involved a combination of 'top-down' and 'bottom-up' modelling and will be the subject of continuous refinement as more information emerges.

- Between 350,000 and 400,000 ODP-tonnes of CFCs are estimated to be contained in refrigeration equipment in 2002;
- 1.25 million ODP-tonnes of CFC-11 are predicted to remain in installed foams in year 2010 with the majority in non-Article 5(1) countries;
- 450,000 ODP-tonnes of halon 1301 and 330,000 ODP-tonnes of halon 1211 are installed in fire fighting equipment in year 2002.

200. However, it is important to recognise that not all of this material will be accessible for collection and recovery, since decommissioning at end-of-life needs to take place first. The annual quantities of refrigerants potentially available for destruction are estimated to be around 9,000 ODP-tonnes. The quantities of blowing agents expected to be recovered from domestic refrigerators, are expected to reach a rate of between 10,000 and 11,000 ODP-tonnes per annum with the currently installed recovery capacity. This could be increased by further investment but is likely to require additional local legislation. Sizeable amounts of halon 1211 could be collected for subsequent destruction.

### **(d) Economic Implications of Collection, Recovery & Storage**

201. The TFCRS report has not made a detailed assessment of the costs of collection, recovery and storage at the global level, since the range of technical options available and the cost of local logistics are highly variable. Economic feasibility is demonstrated by examples of established commercial infrastructures. These exist in several sectors and in several regions of the world. The recovery of blowing agents from refrigerator cabinets costs approximately US\$60-100 per kg of CFC-11. The cost equates to approximately US\$25-35 per tonne of CO<sub>2</sub> equivalent. This is well within the range of investments being considered for CO<sub>2</sub> emission abatement in other sectors.

### **(e) Barriers to Collection, Recovery & Storage**

202. There are many barriers to the application of effective collection, recovery and storage. Examples of these can be listed as follows:

- Lack of appropriate legislation and infra-structures to ensure end-of-life decommissioning;
- Financial resistance where the 'polluter' (manufacturer or owner) has to pay;
- Installations of rigid construction foam can be within building structures that prohibit effective collection;
- Waste transportation management restricts movements within some countries and internationally.

### **(f) Conclusions**

203. The collection, recovery and storage of ODS is technically feasible and economically viable. The adoption of such measures depends to a large degree on the regulatory structures, the collection and recovery infrastructures and the way in which the financial burden is allocated.