denser on average. This technique was also used in the second stage of the JILA experiments where laser cooling of gas was the first step. The most recent experiments are performed with rubidium-87 atoms, because it is possible to cool them to very low temperatures and make their de Broglie waves correspondingly large. This means that one should be able to observe BEC in a very dilute gas. The more dilute the gas the less likely the atoms are to stick together and be lost from the trap. Its properties are also easier to predict, and the BEC process is closer to an ideal case, that is, unpolluted by the effects of interactions.

The experiment at JILA used a combination of laser cooling and evaporation (*1*). Laser cooling the alkali atoms can be used to produce a gas at temperatures around 1 μK and densities of 10^{12} particles per cubic centimeter. The use of alkali atoms is critical as it is their ground-state structure that enables one to cool them to this low initial temperature. At this point the lasers have to be turned off as they cannot produce a colder, denser gas without the interaction between the particles in the presence of the laser causing heating. The atoms are then transferred to a magnetic trap that can be used to push toward BEC by using evaporative cooling. The end point is an assembly of atoms all in the same quantum state in the bottom of the trap.

Several other groups are close behind in the race (see the News story on p. 152) and will surely reach the finish line soon. This is really only the beginning for the field and should, I believe, be looked upon in the same way as the development of the laser. We have the prospect of manipulating and examining the behavior of assemblies of atoms all with the same wave function—very much like the photons (which are bosons too) released by stimulated radiative emission in a laser. The quantum nature of their wave functions is then brought up to the macroscopic—or more accurately, mesoscopic—domain. This will make it possible to explore a wide range of phenomena in macroscopic quantum systems. The condensates will also be a new laboratory for quantum statistical phenomena that are inaccessible to other conventional techniques. It should be possible, according to recent predictions, to tune the strength and sign of the weak interactions between the atoms. In principle, one can now study in real time phenomena that have been addressed only by theory: spontaneous symmetry breaking and decay of unstable macroscopic states. The technology, because of its essential simplicity, also has the possibility of being extended enormously to different atoms and other configurations. This will include the possibility of making extremely bright sources of atoms, a veritable atom laser, that is bound to have many applications in pure science and technology.

References and Notes

1. M. H. Anderson *et al.*, *Science* **269**, 198 (1995).
2. A. Griffin, D. W. Snoke, S. Stringari, Eds., *Bose-Einstein Condensation* (Cambridge University Press, Cambridge, 1995). This is an excellent set of review lectures on most aspects of BEC.
3. S. N. Bose, *Z. Phys.* **26**, 178 (1924); A. Einstein, *Sitzungber. K. Preuss. Akad. Wiss.* **1924**, 261 (1924); *ibid.* **1925**, 3 (1925).
4. P. Nozieres and D. Pines, *Theory of Quantum Liquids Vol 2: Superfluid Bose Liquids* (Addison Wesley, Redwood City, CA, 1990).
5. A. Vilenkin and E. P. S. Shellard, *Cosmic Strings and Other Topological Defects* (Cambridge University Press, Cambridge, 1994). This book has a very thorough account of phase transitions in the early universe.
6. J. L. Lin and J. P. Wolfe, *Phys. Rev. Lett.* **71**, 1222 (1993).
7. I. F. Silvera and J. T. M. Walraven, *ibid.* **44**, 164 (1980).
8. J. M. Doyle *et al.*, *ibid.* **67**, 603 (1991).

Methyl Chloroform and the Atmosphere

A. R. Ravishankara and D. L. Albritton

The atmospheric abundance of methyl chloroform, CH_3CCl_3, a compound of only anthropogenic origin, is actually decreasing because of emission reductions in compliance with the United Nations Montreal Protocol and its subsequent amendments. This observation, reported by Prinn and co-workers elsewhere in this issue (*1*), is based on data from surface-level monitoring stations. The observed trends in methyl chloroform abundance have a few straightforward scientific consequences and substantial policy relevance.

Methyl chloroform is the first substance regulated under the Montreal Protocol that has shown a distinct decrease in atmospheric abundance, not just a decrease in its rate of growth. The abundances of long-lived chlorofluorocarbons (CFCs) have also been affected under the Montreal Protocol. Not only have their growth rates slowed but they are now close to zero (see figure). In the next few decades, the abundance of these long-lived CFCs will also start decreasing. The first message from these findings is clear: Compliance with the Montreal Protocol will decrease the amount of chlorine-containing species in the atmosphere. Because the majority of the chlorine reaching the stratosphere is derived from anthropogenic releases into the atmosphere, the concentration of chlorine in the stratosphere will decrease. Further, because the evidence is conclusive that chlorine, with contributions from bromine-containing compounds, is responsible for the Antarctic ozone "hole" and because the weight of the evidence links anthropogenic chlorine and bromine to the well-documented global ozone depletion, the decrease in atmospheric chlorine levels should lead to a slow recovery in stratospheric ozone levels, if everything else (such as temperature, aerosol levels, and so forth) remains approximately the same.

The abundance of methyl chloroform has already decreased because its atmospheric lifetime is comparable with the time scale over which it has been regulated; hence, the atmospheric response to reduced emissions is relatively prompt. Shorter lived chlorine compounds will decrease in abundance more quickly; hence, the earliest contribution to the recovery of the stratospheric ozone layer will come from the shortest lived compounds. Methyl chloroform is the forerunner in this category. Therefore, the second message associated with the methyl chloroform observations is simply that the atmosphere responds more quickly to reductions in emissions of shorter lived compounds.

This simple and obvious, yet profound, point has several implications. For example, if future work were to suggest that any of these new chemical species have unexpected deleterious effects on the atmosphere, then their emission could be curtailed and atmospheric recovery would be rapid. Furthermore, for equal emissions, a shorter lived species would not build up to as high an abundance as a longer lived molecule would. [For example, even though the emissions of methyl chloroform (600 to 700 kilotons per year) were almost double those of CFC-12 (~400 kilotons per year) during the 1980s, its atmospheric abundance was one-fourth that of CFC-12; see figure.] The above implications are true for all chemicals released into the atmosphere. Therefore, if a more rapid recovery were deemed desirable, a shorter lived chemical would be more effective in

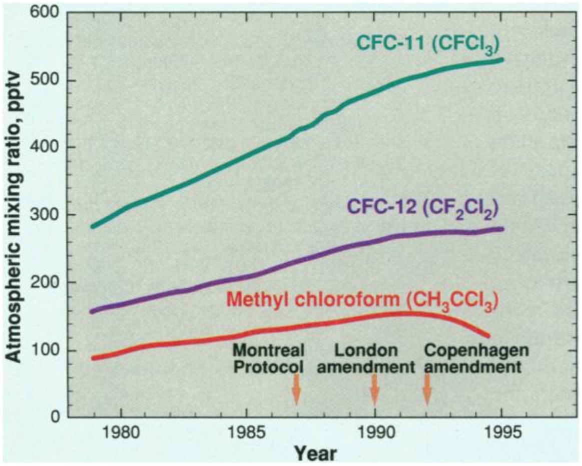
---

The authors are at the National Oceanic and Atmospheric Administration (NOAA), Aeronomy Laboratory, 325 Broadway, Boulder CO 80303, USA.

comparison with a longer lived one, when all other factors are similar.

Another aspect of the methyl chloroform story is its implication to the atmospheric abundance of the hydroxyl radical, OH. This chemical species, one of the most important reactive atmospheric constituents, may be ranked just below oxygen and ozone in significance to the chemistry of the atmosphere. The hydroxyl radical controls the atmospheric abundance of a large number of natural and anthropogenic chemicals that enter the atmosphere. It has been commonly called, and without exaggeration, "nature's scavenger." Because OH is so reactive, it is very short-lived, and its abundance is very low—only a few OH molecules in 10^{15} molecules of air. The abundance of OH varies with solar light level, pressure, temperature, and concentrations of various gases such as O_3, H_2O, nitrogen oxides, and hydrocarbons. Because of changes in these quantities, the concentration of OH is expected to vary over many orders of magnitude from location to location and over short periods of time. Obtaining a direct measure of the lower atmospheric concentrations of OH has been a long, arduous, and somewhat unsuccessful task. Some recent direct measurements (*2*) in the lower part of the atmosphere are considered reliable and have shown that we cannot yet accurately calculate the abundance of this molecule.

So, how can we estimate the abundance of this important species, either at one location at a given time or "globally"? What is often needed is an OH abundance representative of a global or broad regional scale; for example, the atmospheric lifetime of chemical species that are reasonably well mixed in the troposphere can be calculated if the average OH concentration is known. Obviously, it cannot be a simple average, because the effectiveness of OH to react with various species changes with temperature, and hence with location, season, time of day, and so forth.



The atmospheric abundances of CFC-11, CFC-12, and methyl chloroform as they have changed over the last two decades. The CFC-11 and -12 data are from (*3–5*). The methyl chloroform data is from (*1*) for the Ireland and Oregon sites. There are differences in the abundances depending on the latitude. Such differences are not shown here. The lines are meant to be representative of the data rather than being exact.

Methyl chloroform has afforded a unique approach to estimating the global abundance of OH. The variation in the rate coefficient with temperature for the reaction of OH with methyl chloroform is similar to that of many other species containing C-H bonds. Because methyl chloroform is solely anthropogenic and because we have reasonably good estimates of its release rates, the "average" OH concentration can be calculated by knowing the atmospheric abundance of methyl chloroform and its rate of change with time. Such calculations have been made for many years, and the derived value of OH has been used for calculating atmospheric lifetimes and indices such as ozone depletion potentials (ODPs) and global warming potentials (GWPs) for many environmentally important chemical species. Because of improvements in the calibration techniques, Prinn *et al.* now report a "global" OH value that is ~20% higher than that adopted earlier (*1*). This value decreases by 20% the ODP and GWP of compounds that are removed mostly by reaction with OH, which are most of the CFC substitutes and methyl bromide, the latter being a compound of intense interest in the ozone-depletion issue.

The changes in the reported ODPs and GWPs of compounds due to refinements in scientific understanding (for example, the above noted increase in the calculated OH abundance) brings up an important point. The relative indices of similar molecules are more robust than the absolute ODP and GWP numbers. Part of the difficulty in defining absolute ODP and GWP numbers stems from having to compare the effectiveness of a CFC substitute, for example, against a reference of CFC-11 (as in the case of ODP) and a reference of carbon dioxide (in the case of GWP), both of which are removed from the atmosphere by pathways other than reaction with OH. (CFC-11 is photolyzed in the stratosphere, and carbon dioxide is primarily removed by the oceans.)

The interpretation of the methyl chloroform abundance and its temporal and spatial evolution has not been very straightforward for three reasons: (i) the emissions are mostly in the Northern Hemisphere, (ii) the transport to the Southern Hemisphere occurs on time scales that are not too different from the atmospheric lifetime of methyl chloroform, and (iii) the emissions are not constant in time. But this complexity will likely be less in the future. When its emissions are essentially stopped, methyl chloroform will be better mixed between the hemispheres, and the temporal variation of its abundance will then be easier to interpret. Furthermore, information can then be extracted from atmospheric measurements. For example, the atmospheric abundance of methyl chloroform should decrease exponentially with a time constant that is directly proportional to the OH abundance. Any deviations in this rate of change will be more easily detected. Such deviations are likely to represent changes in the OH abundances and, indirectly, the oxidizing capacity of the atmosphere. Changes in the uptake of methyl chloroform due to oceans (*6*) may manifest in interhemispheric gradients. Therefore, global atmospheric measurements of methyl chloroform are very useful until its abundances are too low to measure precisely.

Although methyl chloroform has provided a way to estimate "global" OH concentrations, how could one determine OH abundance on a hemispheric or continental scale? Such estimates are essential for deriving the residence times of compounds that have lifetimes in the range of weeks to months and for understanding and improving urban and rural air quality. It will not be possible, or advisable, to directly measure OH in enough places and with sufficient frequency to obtain a usable average value that is representative of such scales. Two approaches seem viable: (i) improve our understanding of OH formation and removal processes by direct measurements and comparison with model calculations, such that OH levels could be more confidently calculated, and (ii) inventory the amount and release locations of short-lived chemicals, including new CFC substitutes, that are removed predominantly by reaction with OH, and measure their atmospheric abundances at enough locations as a function of time to determine OH abundances. When the agreement between these two methods is good, we can be confident of a good measure of this elusive, reactive, and essential species in the atmosphere.

References and Notes

1. R. G. Prinn *et al.*, *Science* **269**, 187 (1995).
2. F. Eisele *et al.*, *J. Geophys. Res.* **99**, 18605 (1994).
3. J. Elkins *et al.*, *Nature* **364**, 780 (1993), and subsequent data from Elkins, private communication.
4. D. M. Cunnold *et al.*, *J. Geophys. Res.* **99**, 1107 (1994).
5. R. G. Prinn, private communication.
6. J. H. Butler *et al.*, *J. Geophys. Res.* **96**, 22347 (1991).
7. We thank R. G. Prinn and J. W. Elkins each for providing data before publication. We also thank S. Solomon and J. Daniel for helpful discussions. This work was supported in part by NOAA Climate and Global Change Program.