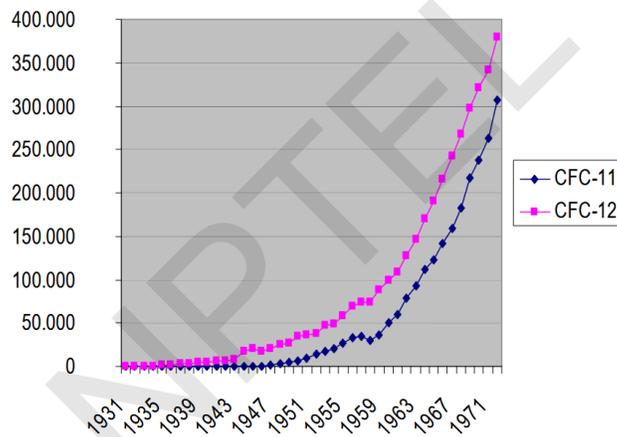


Climate Change Science
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Lecture – 18
Ozone depletion(continued)

In this lecture, we will continue our understanding of the role of chlorofluorocarbon. It was invented in 1931, if you recall. Soon after the invention, the number of refrigerators increased rapidly in the United States. Both CFC-11, called Freon-11, and Freon-12 were rapidly produced in hundreds of thousands of tons. So, by the 70s, these were being released into the atmosphere in large amounts.

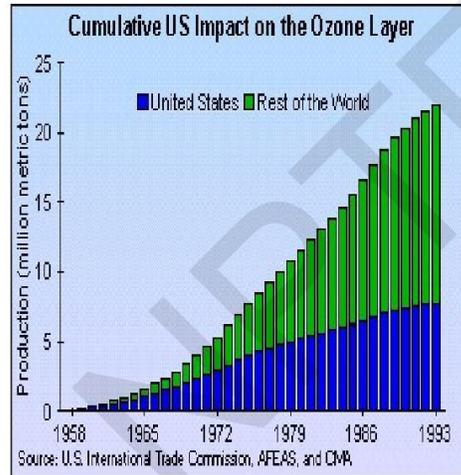


Now, this happened because these chemicals were used not only in refrigerators and air conditioners—they were used for sterilization in medical applications, in foam products, and as aerosols in containers, which all of us use.



And for firefighting, halons are used as a way to control fire, as well as in solvent cleaning products. So, you can see that a number of the so-called harmless chemicals were used in the 30s, 40s, and onwards. They were non-toxic, non-flammable, did not have an odor, and were non-reactive, so they thought they were safe. But these accumulate in the atmosphere because they have a long lifetime. The long lifetime is what you should remember. Any new chemical you put in the Earth's atmosphere that has a long lifetime has the potential to damage the Earth's climate and chemistry.

CFC Production

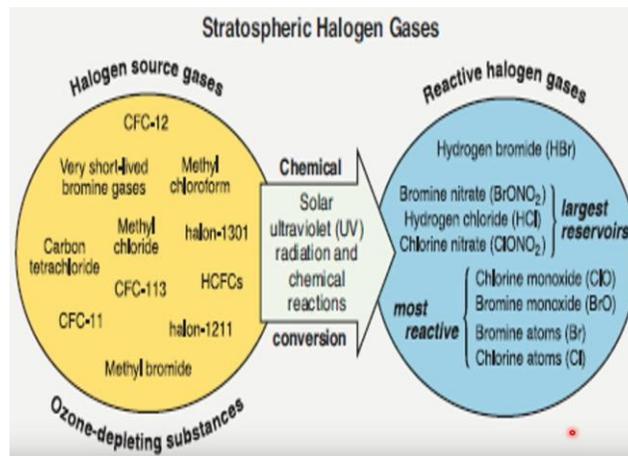


Freon 11 is fluorodichloromethane and has a structure of



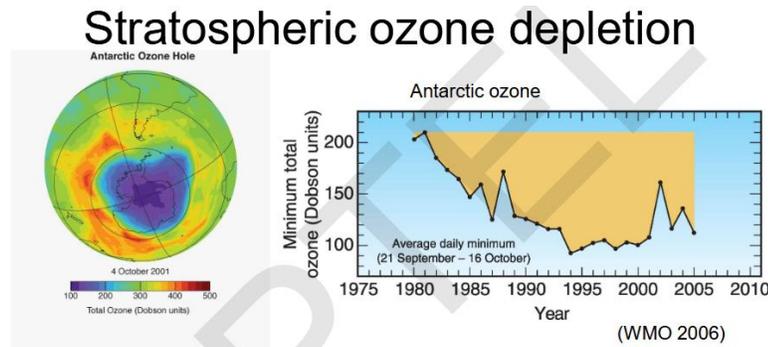
Carbon tetrachloride, methyl bromide and methyl chloroform and other halons also destroy the ozone layer

This graph shows the increase in production of Freon-11 beyond 1958, ultimately reaching 20 million metric tons. From hundreds of thousands of tons, we went on generating more and more. So, by 1993, when the ozone hole problem became very severe, we were producing 20 million metric tons. So, the Montreal Protocol had to take drastic measures to bring down this huge production, which was around 20 million metric tonnes, to almost zero by 2010. This was a major achievement for which you have to give credit to all the countries in the world that realized the serious mistake they had made. And within a matter of 20 years, they brought it down to zero.



The above figure is an example of various chemicals which were produced—ozone-depleting substances—and some of the most reactive were chlorine monoxide, bromine monoxide, bromine atoms, and chlorine atoms, which came out of these chemicals. These chemicals were non-reactive in the beginning, but when they went to the stratosphere, the high-energy ultraviolet photon broke these bonds and created all these chemicals—chlorine oxide, bromine oxide, and so on.

The depletion in stratospheric ozone is shown below from 1980 rapidly to 1995. It was increasing very rapidly, you can see. Even after the Montreal Protocol was signed, the ozone amount did not increase. It remained very low. That is because this phenomenon—the Earth's atmosphere—has a long-time scale.

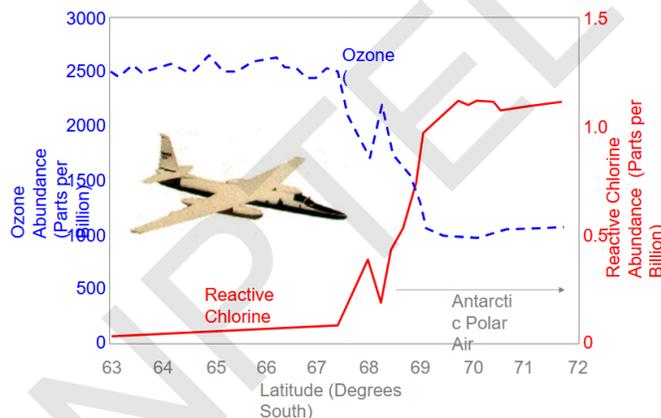


- Anthropogenic CFC emissions cause Antarctica stratospheric ozone depletion
- 40%-50% of the Antarctic ozone layer destroyed
- corresponds to a modeled global mean depletion between 14.1 and 28.6 Dobson Units

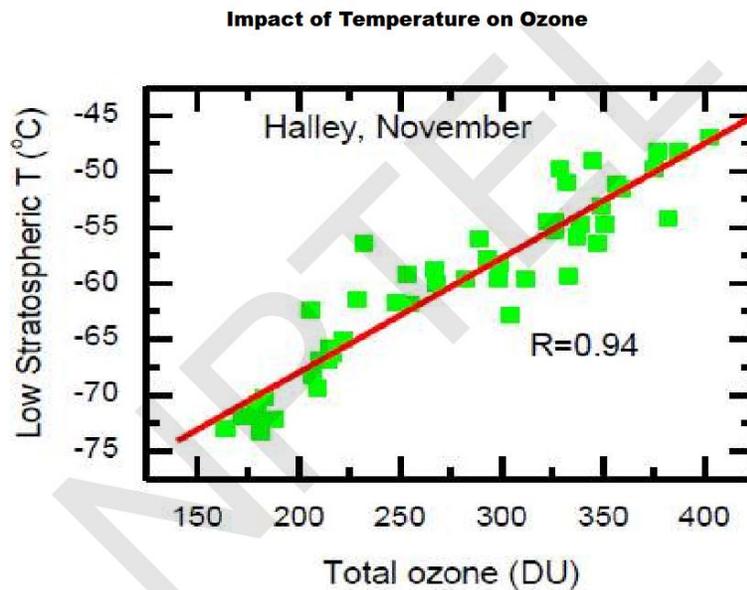
You start producing ozone today, you stop producing these chemicals today, but it will not immediately control ozone depletion. Because the chemicals released last year, 10 years ago, or 20 years ago are still around and they go and attack the ozone layer. So, it took a long time. We are still not completely out of the woods. We have stopped the further release of all these chemicals, but the ozone has not been restored to the value which was there in 1980 yet. It will take some more time.

So, the role of chlorine was demonstrated very nicely when the aircraft was taken to Antarctica.

Measurements of Ozone and Reactive Chlorine from a Flight Into the Antarctic Ozone Hole, 1987



The aircraft showed clearly that when the amount of reactive chlorine increased rapidly with latitude, as you approached the Antarctic region, the ozone layer depleted. This shows the clear link between ozone depletion and chlorine. Before that, people had certain doubts, but once this aircraft measurement showed clearly the connection between chlorine oxide and ozone depletion, the true mechanism that caused the large depletion of ozone was clear.



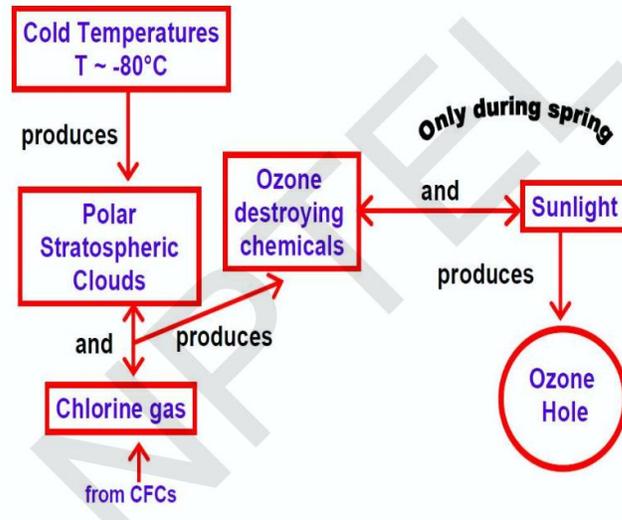
Now, you must remember that the low stratosphere and the Earth's atmosphere also control the amount of ozone in the stratosphere. When the stratosphere is very cold, there is very low ozone—about 150 Dobson units.

When the stratosphere is very hot, it is more like 400—a huge difference. So, if the stratosphere starts cooling, ozone will start depleting. If you just recall what I discussed in the last lecture: because of global warming, the stratosphere is cooling. Because of the increase in carbon dioxide, the stratosphere is cooling and the troposphere is warming. If the stratosphere is cooling, then ozone will get depleted.

Now you see the connection between ozone depletion and climate change. Climate change causes the cooling of the stratosphere, which will increase the ozone depletion. So, today you have to control the cooling of the stratosphere by reducing CO₂ emissions, because CO₂ increase in the stratosphere causes cooling, which leads to the depletion of the ozone.

You can see that when temperature is very, very low—like minus 75 degrees Celsius—the ozone amount is almost less than half of what it is when it is around minus 60. A 15-degree drop in temperature causes ozone to become half.

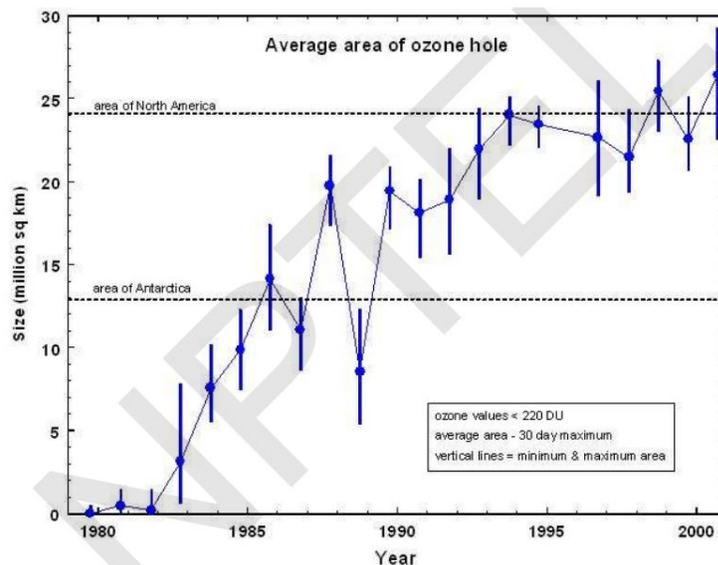
So, that is a very serious issue.



Remember that this depletion does not occur throughout the year because there is no sunlight in Antarctica during the Antarctic winter. So, for ozone depletion to occur, the Antarctic region must have sunlight, which means Antarctica must be in its summer period. And then sunlight has to be there and these ozone-depleting chemicals like chlorofluorocarbon must be there and should have created chlorine oxide. So, chlorine oxide and the presence of clouds in the stratosphere and the sunlight—three things are required.

You need sunlight to split the chlorofluorocarbon to create chlorine, and this chlorine will attack the ozone molecule. So, sunlight is required, and you need these clouds to accelerate the reaction. So, the combination of sunlight, the presence of clouds, and chlorine gas occurs only for a short period during the spring of the stratosphere—around September–October.

So, maximum depletion occurs in September–October. Then, once there is no sunlight in the stratosphere in its winter, then nothing will happen for the next six months. Then again, when the sunlight comes, there will be depletion of the ozone layer.



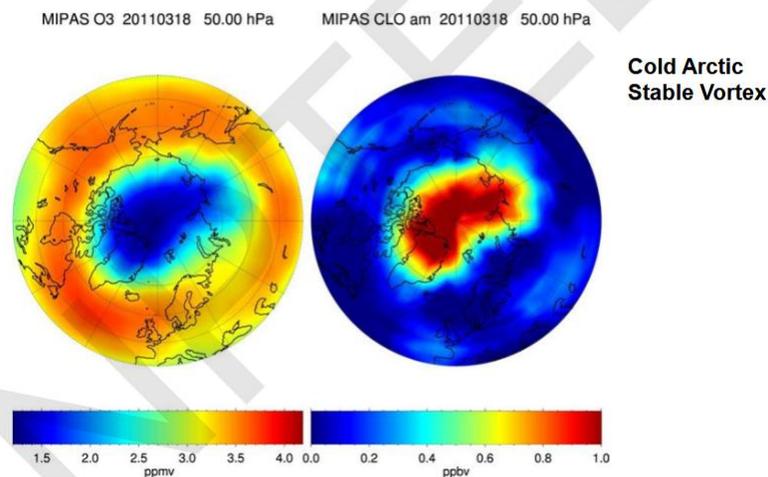
Now, although the Montreal Protocol was signed in 1987, you can see the size of the ozone hole defined by the region where the ozone amount is less than 220 Dobson units. The ozone hole has not decreased. It had a size of radius of 25 kilometers between 1993 and 2001. So, because of the presence of chlorofluorocarbon, the ozone hole continued to increase in size between 1993 and 2000.

Although we had reduced the release of chlorofluorocarbon, because these substances have a long lifetime in the Earth's atmosphere—thousands of years—just because you stop releasing these chemicals, their amount will not be reduced. They will take time. So, only in the last 10 years have we seen a depletion in the chlorofluorocarbon, and it will take a long time for the ozone to reach the level that was there before 1980.

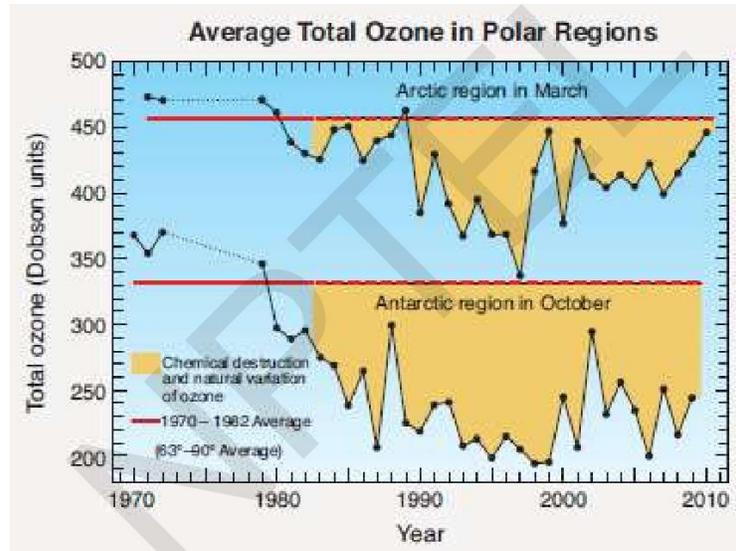
Now, just to point out: the hole in the Antarctic ozone layer was dramatic, but there is also ozone depletion in the Arctic. But it is much smaller and it is not as extensive as that in Antarctica, because the ozone in the Arctic when it is depleted is able to mix with ozone from other regions, and that ozone mixes with the ozone from Antarctica and alters the amount of ozone in the Arctic.

So, the Arctic has the benefit of interacting with the surrounding atmosphere, which is not the case in the Antarctic because of the closed vortex.

2011 March Arctic Ozone Hole



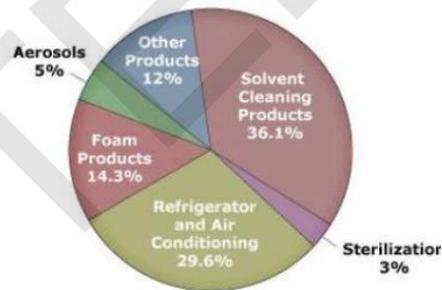
Now, what this above graph shows is ozone on the left and chlorine oxide on the right. Wherever chlorine oxide is present, ozone is depleted. So, it is a very clear demonstration of the connection between chlorine oxide and ozone.



And this is shown again in the graph as the depletion of ozone in Antarctica in October and in the Arctic in March. Remember, March is spring in the Arctic. That is why the combination of sunlight, chlorine oxide, and temperature causes the destruction of ozone. So, the ozone destruction occurs in different months in the Arctic and Antarctic because it needs sunlight and chlorine oxide for this to occur.

COMMON USES OF ODS

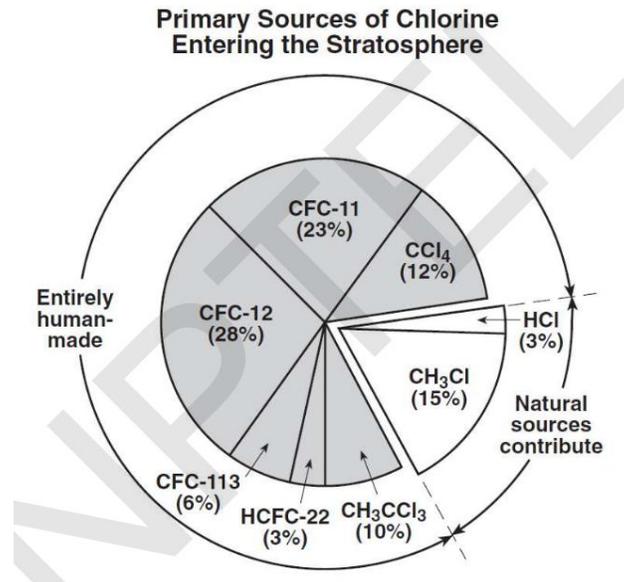
- Refrigerants
- Blowing agent for foams
- Cleaning solvent
- Propellants for aerosols
- Fire extinguishers
- Fumigants
- Chemical synthesis feedstocks
- Sterilants for health care products
- Laboratory uses



Just to remind you again: ozone-depleting substances are used in a wide variety of applications by human beings—as refrigerants, as foams, as cleaning solvents, as propellants for aerosols, fire extinguishers, fumigants, chemical synthesis feedbacks, as sterilization for health products, and various laboratory uses. So, we have to now cut down all these applications and find new chemicals which do not harm the Earth's environment.

The primary sources of chlorine are mentioned in the figure below.

These are entirely human-made; they do not occur in nature.



Now, since there are many, many chemicals which are leading to ozone depletion, it is important to compare all these chemicals—some more, some less destructive. So, for that, the United Nations came up with a criteria called ozone depleting potential, which means the potential of a given chemical to deplete ozone when compared to Freon-11. Freon-11 is our reference gas—CFC-11, a chlorofluorocarbon—and we compare all the other molecules which cause ozone depletion with CFC-11. And this is the way these treaties operate.

OZONE DEPLETION POTENTIAL

Ozone depletion potentials (ODPs) provide a relative measure of the expected impact on stratospheric ozone per unit mass emission of a gas, as compared to that expected from the same mass emission of CFC-11 integrated over time. The concept of Global warming potential(GWP) was based on the concept of ODP developed earlier for Ozone

We have, for convenience, a reference gas, and we compare all the gases with the reference gas and then decide how to control these. So, this is the reason, because all CFCs are not equal. For example, if the ozone depleting potential of CFC-11 is defined as 1, because it is a reference gas, then HFCs—hydrofluorocarbons—have 0 ODP, because they do not contain chlorine. So, HFCs became very popular for use in refrigerators, because they do not cause ozone depletion because their ozone depleting potential is much lower than that of CFCs.

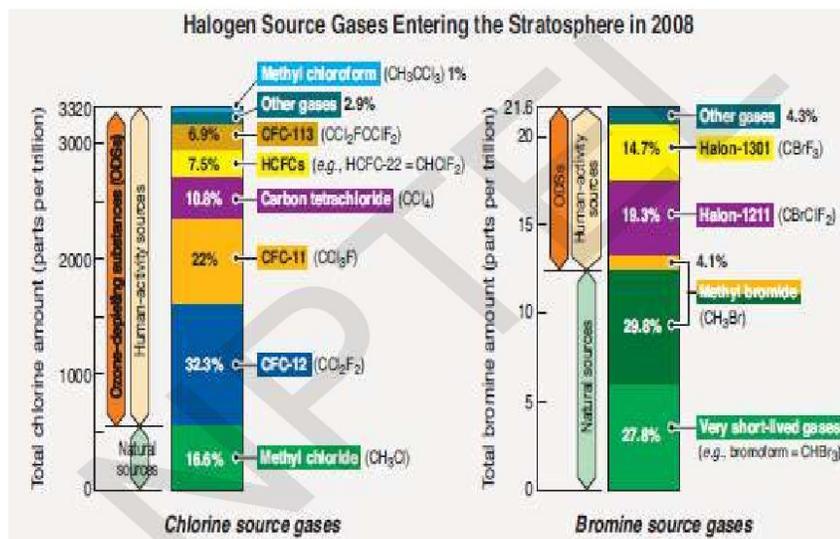
Ozone Depleting Potential

All CFCs are not created equal

- The ozone depleting potential (ODP) is the ratio of the impact on ozone of a chemical compared to the impact of a similar mass of CFC-11. Thus, the ODP of CFC-11 is defined to be 1.0. HFCs have zero ODP because they do not contain chlorine.
- Other CFCs and HCFCs have ODPs that range from 0.01 to 1.0. The halons have ODPs ranging up to 10. Carbon tetrachloride has an ODP of 1.2, and methyl chloroform's ODP is 0.11.

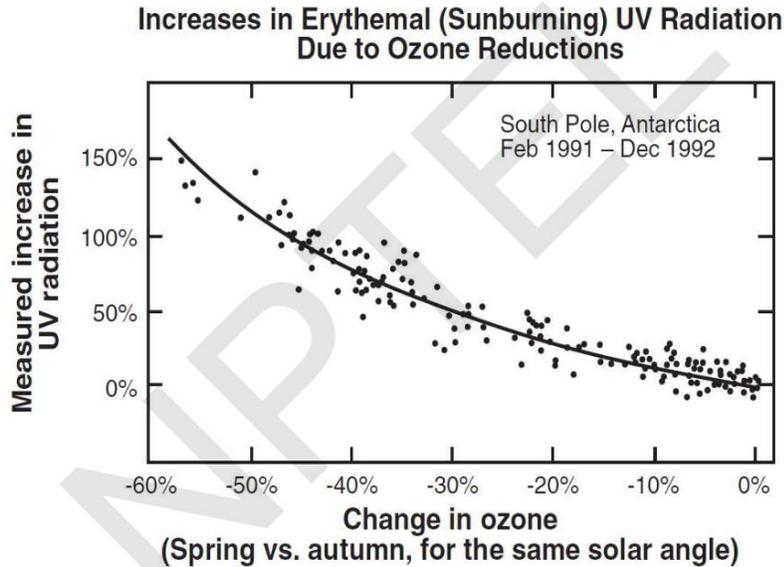
So, as far as ozone depletion is concerned, we want to choose a chemical whose ODP is below 0.1, and that is why the challenge is there.

Here is an example of chlorine and bromine gases used in Earth's atmosphere. And so, you can see that there are many, many sources for ozone depletion—both bromine and chlorine.



“To protect the ozone layer by taking precautionary measures to control equitably total global emissions of substances that deplete it with the ultimate objective of their elimination on the basis of developments in scientific knowledge”

They had to handle them to control the ozone layer. The ultimate objective of the Montreal Protocol was the elimination—on the basis of certain knowledge—of the chemicals which cause the ozone layer.



Now let me show you how the change in ozone increases the amount of ultraviolet radiation that is there in the South Pole of Antarctica. If there is no depletion of ozone, then there is no increase in UV. But as the ozone depletion occurs—moving from right to left—the ozone depletion goes up by 1.5 times. So, this shows the clear connection between ozone and the ultraviolet radiation which comes into Antarctica.

**Skin cancers, sunburn, eye damage, cataracts
estimated 10 % reduction
ozone layer → 25 % increase
non-melanoma skin cancer -
temperate latitudes by 2050
Suppress immune system
DNA mutation of existing
disease bacteria and viruses**

Skin cancer, sunburn, eye damage, cataracts will increase by 10 percent for a 25 percent increase in—can cause 25 percent increase in skin cancer if you reduce the ozone layer by 10 percent. Since the ozone layer affects the DNA of human beings, you need to be very careful about this particular gas.

Montreal Protocol.

Centerpiece of the regime.

50% cuts on 5 CFCs and 3 Halons by 2000.

10-year grace party for developing countries (Article 5).

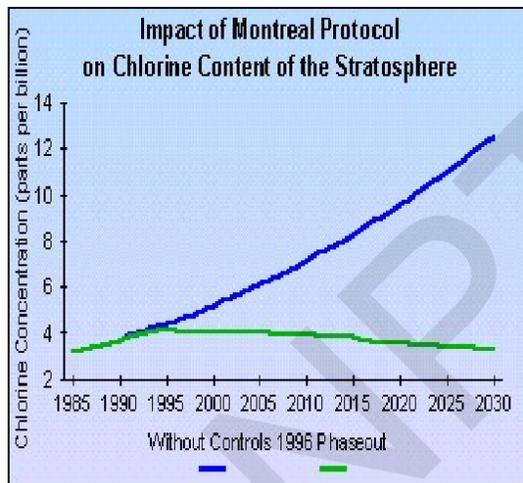
Assessment panels.

Amendment and adjustment procedures.

All countries have signed onto this as of 2009.

So, the Montreal Protocol said 50 percent cuts on these 5 chlorofluorocarbons and 3 halons by 2000, which was a very drastic measure because the protocol came into play only in 1990 or so. And within 10 to 20 years, they asked to reduce all these chemicals. So, as the discovery of more deadly chemicals was made, the Montreal Protocol went on changing the conditions imposed on the various chemicals. So, more and more chemicals were added, and more stringent measures were made to control these chemicals.

Montreal Protocol



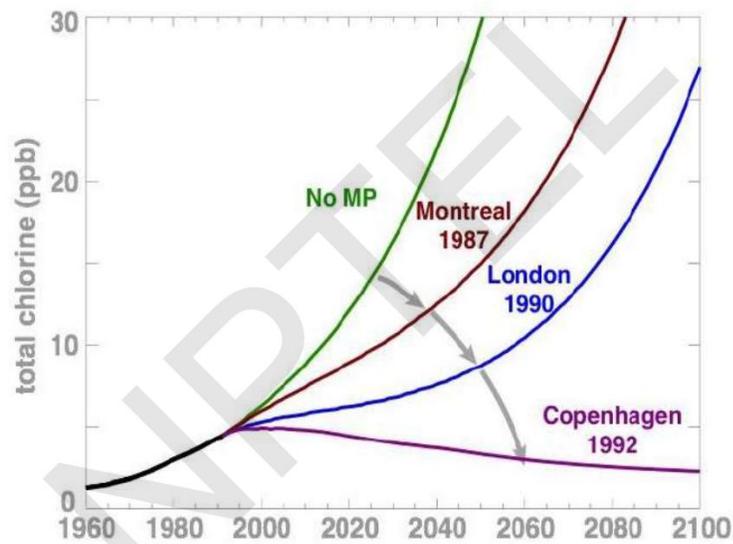
- 1989 Global Treaty to protect ozone layer
- Currently 140 countries are parties
- Timetable to reduce and end production and consumption of 8 major halocarbons
- Many governments committed to early phase outs

This figure shows how chlorine concentration would have continuously gone up from 1990 to 2030 by a factor of 3 or 4 if the phase-out had not been ordered in 1987.

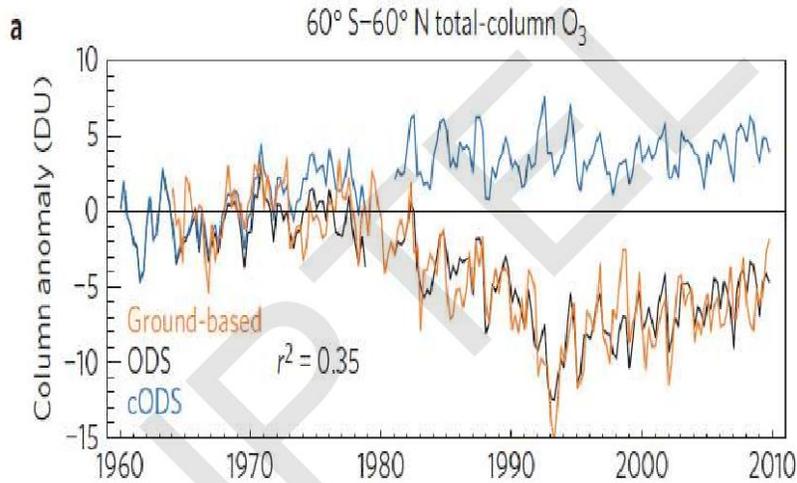
Because of the phase-out, we have reduced the chlorine concentration in the Antarctic region. But still remember—the ozone hole has not disappeared. It will take time. But the chlorine concentration has been brought down. To point out how tough these negotiations were—starting in 1987, a series of amendments were introduced into the Montreal Protocol in 1990, 1992, 1997, 1999, 2007, and 2016 to ensure that we bring down the ozone-depleting chemicals rapidly.

Agreement	Date of signature	Date of entry into force
Montreal Protocol - Full text (1987)	September 16, 1987	January 1, 1989
London Amendment - Full text	June 29, 1990	August 10, 1992.
Copenhagen Amendment - Full text	November 25, 1992	June 14, 1994
Montreal Amendment - Full text	September 17, 1997	November 10, 1999
Beijing Amendment - Full text	December 3, 1999	February 25, 2002
Beijing Adjustment - Full text	October 16, 2007	November 14, 2007
Kigali Amendment - Full text	October 15, 2016	January 1, 2019

As the science developed and more information came, more stringent regulations were imposed.



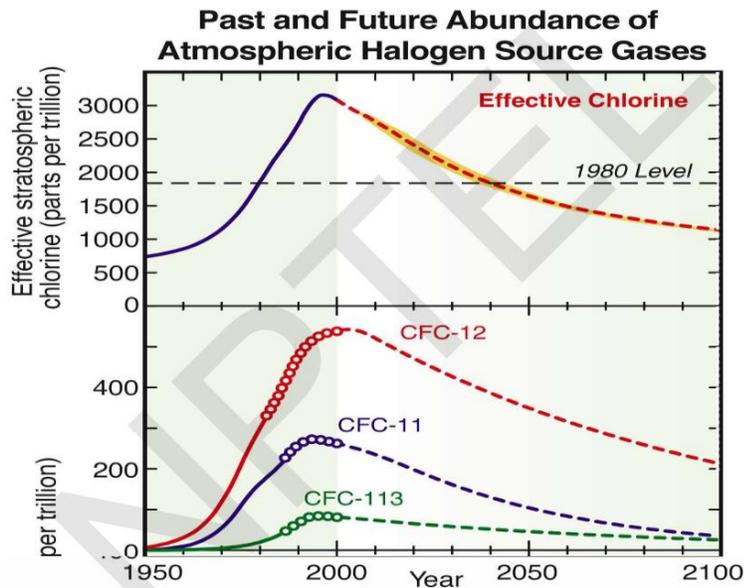
And this shows how the total chlorine has been brought down in Antarctica after the year 2000. It is going on this line, while it would have gone on along these lines if we had not done anything. If there were no Montreal Protocol, the amount of CFC would have gone up rapidly. The amount of chlorine in the stratosphere would have gone up rapidly to 30, which would have been very, very serious.



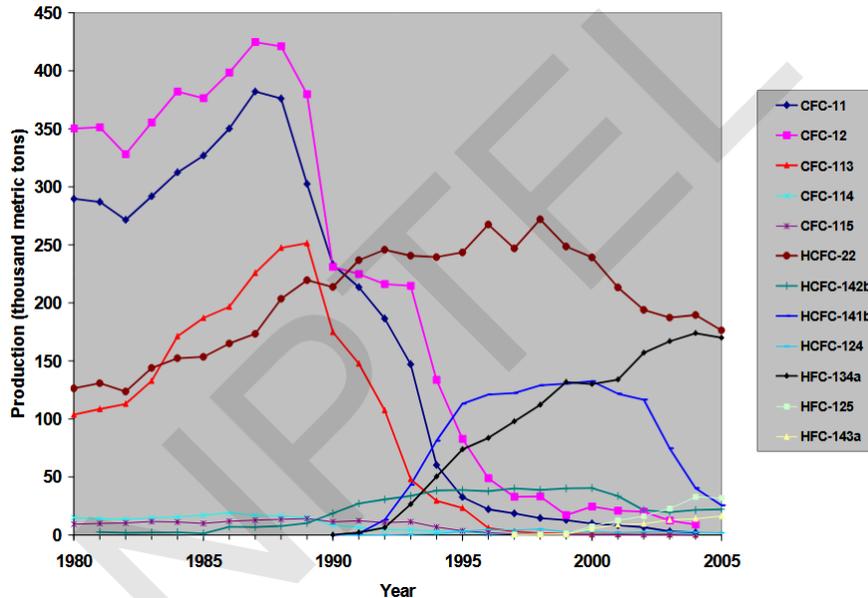
ozone anomalies relative to the 1964–1978 reference period for the model simulation with changing ozone-depleting substance (ODS) abundances (black), the model simulation with ODS abundances held constant at 1960s values (cODS, blue), and ground-based observations (orange), for different latitude bands. The model simulations are not plotted across the

So, this one shows a simulation that the Dobson units in the stratosphere of ozone would have gone down if we had not implemented the Montreal Protocol. Because of the protocol, we have been able to maintain the ozone-depleting substances reasonably constant. There are year-to-year variations due to natural factors, but we have prevented the loss that would have occurred by now.

Here is an example of how the chlorine level has gone down along with this reduction in the production of CFC-12, CFC-11, CFC-113—and these three agree with that.



That shows that this protocol has been successful in bringing down the chlorine in the stratosphere. And it will take some more time before we can totally control it. The three gases which are monitored—they are all now declining. Here is another example of how the various chemicals are declining. One chemical—HCFC—is not declining because at that time it was not realized that although HCFC is a good chemical for preventing ozone depletion, it happens to have an impact on global warming.



When this was realized, further changes were made to the Montreal Protocol to make sure that this chemical also starts declining. And this chemical should decline because of its impact on the greenhouse effect. So, in 1986, the share of the developing countries was only 5 percent.

In 1986, the share of developing countries in the total production of CFCs was around 5%. In 2002, it was 72%. For Halons it was around 6% in 1986 while it is 100% now.

By 2002, it had gone up to 72 percent. So, 12 countries were producing more and more CFCs. In the case of halons, used for fire protection, it went up to 100 percent. So, this clearly required new action. So, developing countries also had to join seriously the Montreal Protocol.

Annex A: Controlled substances

Group	Substance	Ozone-Depleting Potential*
<i>Group I</i>		
	CFCl ₃ (CFC-11)	1.0
	CF ₂ Cl ₂ (CFC-12)	1.0
	C ₂ F ₃ Cl ₃ (CFC-113)	0.8
	C ₂ F ₄ Cl ₂ (CFC-114)	1.0
	C ₂ F ₅ Cl (CFC-115)	0.6
<i>Group II</i>		
	CF ₂ BrCl (halon-1211)	3.0
	CF ₃ Br (halon-1301)	10.0
	C ₂ F ₄ Br ₂ (halon-2402)	6.0

So, this was done over the years. Now, in the next lecture, I will talk about ozone depleting potential and the new metric developed to decide how to control the various gases in the stratosphere. Thank you.