The Influence of the Greenhouse Effect and Ozone Depletion on Agricultural Production

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Abstract

Tropospheric temperature rises due to the greenhouse effect could be beneficial at high latitudes where the present climate is cold. However the greenhouse effect reduces stratospheric temperature, which could affect the stratospheric ozone depletion. There are two types of ozone depletion. In the first one originally proposed by Molina and Rowland all participating substances are in the gas phase (homogeneous chemistry), but in the second one corresponding to the ozone hole participating substances are in the gas and solid or liquid phases (heterogeneous chemistry). Stratospheric cooling suppresses the first one but enhances the second. The latest calculation shows that the latter effect is larger than the former and the greenhouse effect worsens stratospheric ozone depletion. The combined influence of the greenhouse effect and stratospheric ozone depletion on rice production in Northern Japan, which is known to be climate-sensitive, is investigated. At present, the benefits of the greenhouse effect are much greater than the detriments of ozone depletion, though in the future the detriments might prevail, because the heterogeneous processes are also initiated by stratospheric sulphate aerosols, which have recently been increasing at an alarming rate. Therefore the argument that the greenhouse effect could be beneficial at high latitudes should be viewed with caution.

Key words: temperature, ozone, rice, aerosols.

1. Different types of ozone depletion and their temperature dependencies

There are two types of ozone depletion. The first one was proposed by Molina and Rowland (1974), in which chlorofluorocarbons (CFCs) rise to the stratosphere and are photolysed to release Cl to decompose O_3 . All participating substances are in the gas phase and the processes are based on homogeneous chemistry. However, theories based on this assumption completely failed to predict the dramatic appearance of the Antarctic ozone hole.

In winter temperatures of the Antarctic stratosphere cool down to as low as $-80^{\circ}C$. Aerosols called polar stratospheric cloud (PSC) are formed, CFCs are adsorbed by them and are decomposed yielding Cl molecules in the dark. When spring comes and the sun rises, the Cl molecules are photolysed to Cl atoms which destroy O_3 . These substances are in the mixed phase (Cl and O_3 are gases, and PSC is solid.) and the processes are based on heterogeneous chemistry. This hypothesis succeeds in explaining the ozone hole.

The important point is that the temperature dependencies of these two types of ozone depletion are completely opposite. In the homogeneous type, at low temperatures ozone destroying reactions are suppressed and ozone producing reactions are enhanced and hence ozone depletion is suppressed. In the heterogeneous type, PSC formation rate becomes higher at lower temperatures, which enhances ozone depletion.

This difference is very important in relation to the greenhouse effect, which reduces temperatures in the stratosphere (e.g. Stouffer et al. 1989).

When stratospheric temperature falls, ozone depletion is suppressed in the homogeneous type but is enhanced in the heterogeneous type. The former has been well known and many related papers have been published (e.g. Brasseur et al. 1988). However, the latter has not been discussed properly, although brief comments were made occasionally in several papers.

Recently, though, a detailed investigation has appeared (Brasseur et al. 1990). Their results show that, when only homogeneous processes are considered, ozone depletion between 1960 and 2010 is very small at $\leq 30^\circ$, and at $\geq 40^\circ$ almost zero or even negative (Ozone increases). The global ozone reduction is only 0.22%. However when heterogeneous processes on PSC are added ozone decreases at all latitudes. The global reduction is 3.6%, which is 16 times as large as that with homogeneous processes.

However in the lower stratosphere there exist aerosols of solutions of sulphuric acid in water at all latitudes, and on their surfaces the heterogeneous processes could occur. The effects of these stratospheric aerosols (abbreviated hereafter as STA) are small in the southern hemisphere, though in the northern hemisphere the ozone depletion becomes almost twice as large as the case of PSC only, and the global ozone reduction is 5.7%, which is indeed 26 times as large as that with homogeneous processes.

These results show not only the importance of heterogeneous processes with PSC, but also those with STA. The latter is of concern from the global viewpoint. If heterogeneous processes were initiated only by PSC, their effects would be confined mainly near the polar regions, because PSC is formed only in these regions as its name shows. However if they were also initiated by STA, their effects could spread over the entire globe, and even if the amount of STA were constant, the expected increase of chlorine compounds (Cl_x) from CFCs would enhance ozone depletion. Unfortunately, however, the amount of STA is reported to be increasing at the alarming rate of 5%/y (ten times as great as that of CO_2) due probably to an increase in jet air traffic (Hofmann 1991), which might give rise to serious ozone depletion on a global scale in the future. (This point is discussed briefly at the end.)

2. Influence on rice production in Northern Japan

The influence of these synergistic effects is investigated for rice production in Northern Japan (Tohoku and Hokkaido districts), since in these regions the rice yield is sensitive to summer temperatures and cold episodes inflict severe damage. Greenhouse warming will reduce the frequency of cold episodes, and combined with yield increases due to photosynthesis stimulation by CO_2 increase (CO_2 fertilization) rice production in Northern Japan would enjoy benefits of the greenhouse warming. However if the detriments of ozone depletion were great, this argument might not apply.

In the present calculation concentrations of greenhouse gases assumed by Brasseur et al. (1990) are used, and those other than CO_2 are converted to CO_2 corresponding to the same temperature rise using values of global warming potentials (Fisher et al. 1990) and are added to CO_2 concentration to obtain the CO_2 equivalent concentration (denoted as $\rho_{\text{eq.}}$), which is calculated from 1960 to 2010. Results can be expressed by an exponential function with an exponent α of 0.75%/y.

For calculating the temperature rise ΔT Stouffer et al.'s calculation (1989) is most appropriate because (1) The calculation assumes a gradual CO_2

increase and includes effects of the deep ocean and one of the most realistic calculations at present. (2) The first year of calculation is 1958, which is close to that of Brasseur et al., 1960. (3) The increase of ρ_{eq} is also exponential, although their α is 1%/y.

Values of ΔT are read from their Fig. 1 for 40°N and 43°N, and results are regarded as ΔT of Tohoku and Hokkaido, respectively. To take account of the difference in values of α , their results are shifted by a factor of $1/0.75 = 4/3$. (For instance 15y in their figure is regarded as 20y.) Values of ΔT increase almost linearly by year both for Tohoku and Hokkaido.

The yield increase of rice due to temperature rises, $\Delta Y(T)$, is calculated using the following formula (Yoshino et al. 1987).

$$\Delta Y(T) = \{1.2035 - 0.04803(T_{7.8} - 22.5)^2\} - 1 \quad (\text{Hokkaido}) \quad (1)$$

$$= \{1.1207 - 0.03147(T_{7.8} - 24.5)^2\} - 1 \quad (\text{Tohoku}) \quad (2)$$

where $T_{7.8}$ is the average temperature in July and August.

The coefficient of variation, CV, which is a measure of yield variability is also calculated using the following formula.

$$CV = 275.19 - 19.933T_{7.8} + 0.376T_{7.8}^2 \quad (3)$$

Smaller CV means a smaller yield variability and a more stable production.

For yield increases due to CO₂ fertilization, the following formula used in simulation of future American agricultural production (Okamoto et al. 1991) is again used here.

$$\Delta Y(\text{CO}_2) = C\{1 - \exp(-\lambda \Delta \rho / C)\} \quad (4)$$

where $\Delta \rho$ is the CO₂ increase, and C and λ are parameters for simulation. Asymptotic behaviours of eq.(4) for small and large $\Delta \rho$ are given by

$$\Delta Y(\text{CO}_2) \rightarrow \lambda \Delta \rho \quad \text{as } \Delta \rho \rightarrow 0 \quad (5)$$

$$\Delta Y(\text{CO}_2) \rightarrow C \quad \text{as } \Delta \rho \rightarrow \infty \quad (6)$$

The total yield increase, ΔY_+ , is defined by

$$\Delta Y_+ = \{1 + \Delta Y(T)\}\{1 + \Delta Y(\text{CO}_2)\} - 1 \quad (7)$$

The ozone depletion is read from Fig. 1c of Brasseur et al. (1990). Since it is impossible to differentiate Tohoku and Hokkaido in this figure, values of 40°N are used for both. The ozone depletion between May and October is relevant to rice production and the decrease between 1960 and 2010 averaged over these months is about 1.5%.

For the yield change due to ozone depletion, $\Delta Y(\text{O}_3)$, data on cultivars in the Phillippines, which are suitable for comparison with Japan, show decreases in leaves, stems, roots and panicles (Teramura et al. 1991). Among them, data on panicles are most appropriate for yield, which shows decreases of 25 ~ 55% by irradiation of UV corresponding to an ozone depletion by 20%. Therefore the yield decrease by ozone depletion of 1.5% assumed above would be about 2 ~ 4%. If homogeneous processes only are considered, it would be only 0.1 ~ 0.3%, which shows the importance of heterogeneous processes.

Table 1 Changes in rice production in Northern Japan between 1960 and 2010 by the greenhouse effect and the ozone depletion (Arakawa and Itoh 1992)

	ΔT	$\Delta \rho (\text{CO}_2)$	$\Delta \rho_{eq}$	$\Delta Y(T)$	$\Delta Y(\text{CO}_2)$	ΔY_+	$\Delta Y(\text{O}_3)$
Tohoku	1.54°C	65ppm	140.8ppm	11.6%	10.5%	23.3%	-2 ~ -4%*
Hokkaido	1.64	"	"	19.5	"	32.0	"

* Original values are -4~-5%, but these were revised by the present author.

In Table 1, the results are summarized. Although not shown, the CV of eq.(3) decreases by about 20%, showing that the yield becomes more stable.

3. Discussion

One might feel that the positive effects are much greater than the negative ones, though since ozone depletion increases with latitude, at higher latitudes than Tohoku or Hokkaido the negative effects could become considerable. Moreover, as can be seen from eqs.(1), (2) and (4), positive effects will either saturate or decrease, though the negative effect will probably continue to increase and in the distant future the negative effect might prevail. As already cited, the increase of STA is now 5%/y (Hofmann 1991) and the increase of the surface area of STA is $(1.05)^{2/3} = 1.033$, or 3.3%/y. If this trend continues and if the rates of homogeneous processes are proportional to the surface area of STA, in 2010 (after 18 years from now) they would increase by 80% and -2 ~ -4% in Table 1 could become -3.6 ~ -7.2%, the higher one of which would cancel 1/3 of ΔY_+ of Tohoku. Moreover the UV increase on the surface by the decrease of the O_3 column would increase O_3 on the surface, which would, not only be toxic by itself, but would also act synergistically with UV, and the actual yield decrease could be larger than these estimates. In the longer term this trend would become stronger, and ozone depletion associated with the greenhouse effect might become quite serious at high latitudes and the simple argument that greenhouse warming would be beneficial at high latitudes should be viewed with caution.

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