AIAA-92-5071

The Impact of the Spacecraft System SÄNGER on the Composition of the Middle Atmosphere

C. Brühl & P. Crutzen,
Max Planck Institute for Chemistry,
Mainz, Germany
H. Graßl,
Max Planck Institute for Meteorology,
Hamburg, Germany
D. Kley,
Forschungszentrum Jülich, Germany

AIAA FOURTH INTERNATIONAL AEROSPACE PLANES CONFERENCE
1 - 4 DECEMBER 1992/ORLANDO, FL

THE IMPACT OF THE SPACECRAFT SYSTEM SÄNGER ON THE COMPOSITION OF THE MIDDLE ATMOSPHERE

C. Brühl and P. J. Crutzen
Max Planck Institute for Chemistry
Mainz, Germany

H. Graßl
Max Planck Institute for Meteorology
Hamburg, Germany

D. Kley
Forschungszentrum Jülich, Germany

Abstract. A two-dimensional chemical model and physical considerations are used to estimate the impact of the spacecraft system SÄNGER on stratospheric and mesospheric ozone in relation to other spacecraft and other anthropogenic perturbations. Perturbations of middle atmospheric NO_y, H_2O and H_2 concentrations, and their impact on the radiative balance of the atmosphere, including contrail formation, are discussed. It is found, that in case of about 24 launches per year the perturbations due to SÄNGER are about negligible on a global scale. However, if a SÄNGER version would be used for a hypersonic fleet of commercial aircraft a serious ozone depletion is predicted.

THE SPACECRAFT SYSTEM SÄNGER

The concept of the spacecraft system SÄNGER is, that it can take off and land like an aeroplane. It consists of a lower and upper stage. In contrast to existing spacecraft systems the engines of the lower stage use ambient air for combustion like conventional airplanes. The fuel is liquid hydrogen. The spacecraft system has no solid fuel boosters. The mission of the lower stage can be divided in 5 typical phases: take off at airbases in Europe and ascent to lower stratosphere in turbojet mode; ascent from 19.6 km to 26 km in ramjet mode; cruise at 26 km to about 20° latitude in ramjet mode; further ascent to 34.6 km and acceleration to Mach 6.5 with release of the upper stage to orbit; return cruise to Europe in ramjet-mode at about 26 km altitude. The typical flight patterns are given in Fig. 1. The engine of the upper stage is fueled by liquid hydrogen and oxygen. It has a thrust of 1400 kN and burns from 34.6 km to 70 km altitude, the perigeum of its first orbit. After reentry, the upper stage returns to the surface in a similar way as the space shuttle.

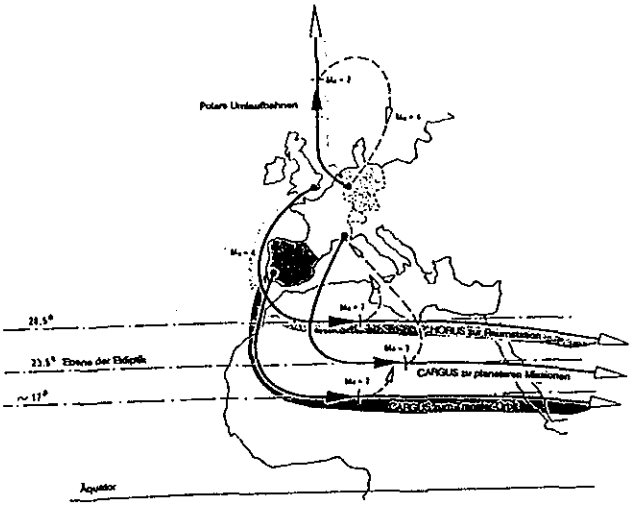

Fig. 1: Typical flight patterns of the SÄNGER lower stage

In contrast to the space shuttle or other existing systems, the only emissions of environmental significance are water vapor, nitrogen oxides and molecular hydrogen. Most critical are the nitrogen oxide emissions at the cruise altitude of 26 km since they affect the ozone layer.

A typical scenario considers two launches per month. This is compared with the hypothetical case, that the lower stage of the spacecraft were to be used as a hypersonic transport, assuming a fleet of 500 crafts.

METEOROLOGICAL CONDITIONS AND ATMOSPHERIC CHEMISTRY

Lower stage

The region, in which most of the emissions of the lower stage of SÄNGER occur, the altitude region around 25 km at a latitude range between 45° and 17° N, is an area with weak diabatic meridional circulation and small meteorological variability. It is the transition region between the lower stratosphere which is dynamically influenced by the tropospheric disturbances and the part of the stratosphere that is dominated by the circulation from the warm summerpole to the cold winterpole in the upper stratosphere. Another characteristic feature there are small vertical diffusion coefficients. In this region there is the potential for accumulation of Sänger exhaust in a similar way as clearly observed after the nuclear bomb tests in 1962 from the decay of Sr-90, C-14 (e.g. List and Telegadas [1], Telegadas [2]) and other radioactive decay products. Transport of material to the troposphere occurs intermittently at the extratropical tropopause causing a typical lifetime of about 1 to 3 years for material ejected near 25 km altitude. However, a significant fraction of this material is distributed with the mean circulation throughout the whole stratosphere.

A perturbation in water vapor or ozone around 25 km affects the radiation budget much less than the same perturbation near the tropopause which is mostly a consequence of the temperature distribution. With regard to the greenhouse effect, therefore, the typical flight patterns of SÄNGER are optimized to some extent. Fig. 2 shows the effect of a change in H_2O mixing ratio on the net flux at the tropopause compared to the same change in CO_2. At about 15 km a H_2O change is about 180 times more effective than a CO_2 change. At 25 km this ratio per molecule decreases to 30. Because of transport processes also other regions are effected by H_2O emission so that it might be misleading, just to look at one altitude.

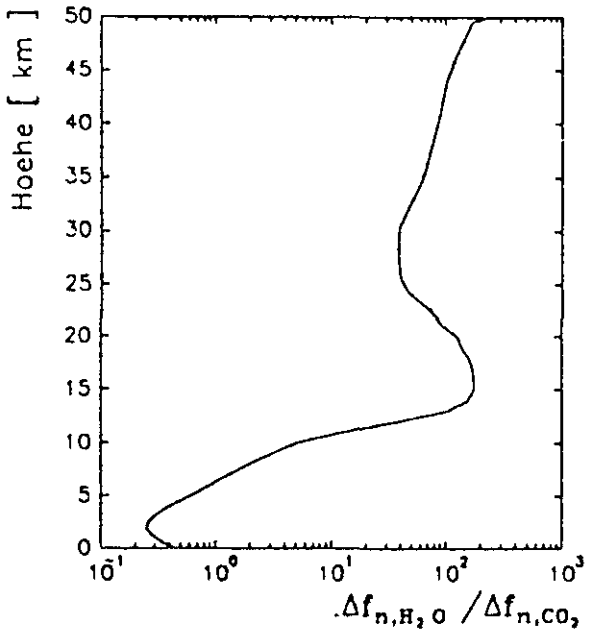

Fig. 2: The altitude dependence of the ratio of net radiative flux change at the tropopause (10 km) due to equal changes of the volume mixing ratios of H_2O and CO_2. $(\Delta f_{nH_2O}/\Delta\mu_{H_2O}(z))/(\Delta f_{nCO_2}/\Delta\mu_{CO_2}(z))$.

Above about 20 km stratospheric ozone is perturbed mostly by the emisions of nitrogen oxides which destroy ozone in the gas phase catalytically by the set of reactions

$$\begin{array}{lcl} NO + O_3 & \rightarrow & NO_2 + O_2 \\ O_3 + h\nu & \rightarrow & O_2 + O \\ O + NO_2 & \rightarrow & O_2 + NO \\ \hline \text{net: } 2O_3 & \rightarrow & 3O_2 \end{array} \qquad (1)$$

In the lowest part of the stratosphere ozone changes due to NO_x increases are small because of low atomic oxygen concntrations, while at the same time NO_x short circuits the ozone destruction cycle involving OH and H_2O:

$$\begin{array}{lcl} O_3 + OH & \rightarrow & HO_2 + O_2 \\ HO_2 + O_3 & \rightarrow & OH + 2O_2 \\ \hline \text{net: } 2O_3 & \rightarrow & 3\,O_2 \end{array} \qquad (2)$$

into

$$\begin{array}{lcl} O_3 + OH & \rightarrow & HO_2 + O_2 \\ HO_2 + NO & \rightarrow & OH + NO_2 \\ NO_2 + h\nu & \rightarrow & NO + O \\ O + O_2 + M & \rightarrow & O_3 + M \\ \hline \text{no net chemical effect} \end{array} \qquad (3)$$

To what extent the ozone concentration is changed by nitrogenoxide emissions is also dependent on the scenario of atmospheric chlorine released from CFCs since there are titration reactions between the two ozone depleters which convert these into $ClNO_3$ and HCl, which do not react with ozone:

$$NO_2 + ClO \xrightarrow{M} ClNO_3 \qquad (4)$$

$$NO + ClO \rightarrow NO_2 + Cl \qquad (5a)$$

$$Cl + CH_4 \rightarrow HCl + CH_3 \qquad (5b)$$

Since most of the emissions occur in the stratospheric sulfate aerosol layer between the tropopause and about 28 km, also the heterogeneous reaction

$$N_2O_5 + H_2O_S \rightarrow 2HNO_3 \qquad (6)$$

on sulfate particles has to be considered which proceeds quite fast with a sticking coefficient of 0.1. Reaction (6) mitigates direct ozone destruction by (1) but increases the shares of the odd hydrogen and odd chlorine ozone destruction, because of less removal by OH by the reaction set

$$\begin{array}{lcl} OH + NO_2 & \xrightarrow{M} & HNO_3 \\ HNO_3 + OH & \rightarrow & H_2O + NO_3 \\ NO_3 + h\nu & \rightarrow & NO_2 + O \\ \hline 2OH & \rightarrow & H_2O + O \end{array}$$

less conversion of ClO_x to $ClNO_3$ and HCl by reactions 4, 5a and 5b, and enhanced formation of ClOx via $HCl + OH \rightarrow H_2O + Cl$.

Emissions of H_2O perturb the OH concentrations, however, their effect on ozone is relatively small in the lower atmosphere.

From the chemical point of view H_2 is the least important species despite substantial concentration changes. Its main importance lies in the fact that it is oxidized to H_2O which takes place on time scales of the order of years.

Upper stage

Here the H_2 and H_2O emissions in the mesosphere are most important. In the mesosphere the circulation is very different in summer and winter. In summer at middle to higher latitudes air rises with a typical speed of some centimeters per second to the very cold mesopause. At the winter pole there is subsidence. The meridional wind forced by these motions towards the winter pole reaches 10 m/s at the mesopause at about 30° latitude. This circulation pattern has the consequence, that emissions in the subtropical mesosphere are normally transported to the winterpole and then downward to the stratosphere where they may accumulate. Some of the emitted water vapor may reach the cold summerpole mesopause region enhancing the probability for noctilucent clouds formation.

Typical vertical fluxes of water vapor and molecular hydrogen at 60 km and 60°N latitude are a downward flux of 2×10^{10} molecules $cm^{-2}s^{-1}$ H_2O and 10×10^{9} molecules $cm^{-2}s^{-1}$ H_2 in January and an upward flux of 1×10^{10} molecules $cm^{-2}s^{-1}$ H_2O and 4×10^{9} molecules $cm^{-2}s^{-1}$ H_2 in July (Le Texier et al [4]). As a result one SÄNGER launch emits only

so little H_2O into the mesosphere, as is supplied by natural transport during 3 minutes in summer.

The H_2O emissions of the upper stage perturb upper stratospheric and mesospheric ozone by enhancing the catalytic ozone destruction cycles involving odd hydrogen:

$$\begin{array}{lcl} H + O_3 & \rightarrow & O_2 + OH \\ OH + O & \rightarrow & O_2 + H \\ O_3 + h\nu & \rightarrow & O + O_2 \\ \hline 2O_3 & \rightarrow & 3O_2 \end{array}$$

and

$$\begin{array}{lcl} OH + O_3 & \rightarrow & O_2 + HO_2 \\ HO_2 + O & \rightarrow & O_2 + OH \\ O_3 + h\nu & \rightarrow & O + O_2 \\ \hline 2O_3 & \rightarrow & 3O_2 \end{array}$$

Near the stratopause the NO_x formation in the shockwave during re-entry contributes in comparable amounts to the odd nitrogen as the NO_x from the emissions of the lower stage of SÄNGER transported upward from the lower stratosphere.

THE EMISSIONS IN RELATION TO OTHER PERTURBATIONS

The emissions of H_2O, H_2 and NO_x during the different phases of the SÄNGER flight are given in Table 1.

To assess the perturbation caused by these emisions, it is not sufficient, to compare them only with the total burden or local concentrations of the trace gases of interest. The emissions must also be intercompared with the perturbations caused by other anthropogenic activities like CH_4 and N_2O increases. This is done in Table 2. For 24 SÄNGER-launches per year for example the additional amount of water vapor produced in the stratosphere by the oxidation of methane growing by 1 % per year is about 2 orders of magnitude larger than the contribution of 24 SÄNGER starts.

Similarly, the growth in stratospheric NO_x by the emissions of 24 SÄNGER starts per year would be

Table 1. The emissions of the two stages of the SÄNGER spacecraft system in molecules (E30 = $\times 10^{30}$) for 1 launch.

Altitude, km	H_2O	H_2	NO
Lower stage			
10.0 - 19.6	5.9 E30	-	4.1 E28
19.6 - 26.0	2.0 E30	1.2 E29	9.0 E27
26.0	2.8 E30	5.0 E27	5.7 E28
26.0 - 34.6	5.8 E30	3.0 E30	1.8 E28
34.6 - 26.0	1.2 E30	-	1.8 E28
Upper stage (with re-entry)			
34.6 - 60	1.1 E30	9.6 E28	5.4 E27
60 - 70	1.3 E30	1.1 E29	2.6 E27

Table 2. Emissions of 24 SÄNGER-launches per year compared to those resulting from the oxidation of growing concentrations of CH4 (≈ 1% /yr) and N_2O (≈ 0.3 % /yr), and their effects on the concentrations at 50 hPa (NO_y = NO_x + HNO_3, NO_x = NO + NO_2 counted as NO_2).

	CH_4	N_2O	lower stage of SÄNGER	upper stage of SÄNGER	
	increase/year kt/yr	kt/yr	kt/yr	kt/yr	
H_2O	1000	-	12.5	1.7	
NO_x	-	4.1	0.29	0.014	
	pert. in 15 yrs %		%		conc. ppm
H_2O	5	-	0.005	0.0005	4.0
NO_y	-	3	0.015	0.0003	0.007
H_2	1.5	-	0.005	0.0001	0.56

5 - 8 % of that resulting from the grouth in N_2O. An important difference however is, that the sources from CH_4 and N_2O have to be seen cummulative so that over a time span, say 15 years, the relative contribution of SÄNGER to the perturbation of ambient concentration gets much smaller (see Table 2).

CHANGES IN ATMOSPHERIC COMPOSITION

Model and scenario

To estimate the vertical and meridional distribution of changes in the atmospheric composition due to SÄNGER, the Mainz two-dimensional chemical transport model (based on Gidel et al [5]; but with diabetic circulation) was integrated for 15 years beginning in 2010 with a scenario in compliance with the Montreal Protocol (London version) regarding CFC emissions. The model extends from the surface to about 60 km with a vertical resolution of about 2 km and a 10° latitude grid. For the present, the model results are in fair agreement with observations (Brühl et al [6]; WMO [3]). It was assumed, that during the integration period 24000 SÄNGER-launches per year would take place. The upward scaling by a factor of 1000 was chosen to raise the signal clearly above numerical noise and is appropriate for resulting ozone changes of less than about 5%, as calculated.

The calculations were carried out considering the effects of both stages and the lower stage only. The percentage changes for NO_y, H_2O, H_2 and O_3 compared to the scenario without SÄNGER are given in Figs. 3 - 6 for the northern hemispheric winterseason.

Changes in precursors of ozone destroying species.

The most significant changes occur in the total odd nitrogen (Fig. 3) and especially in NO_x = NO + NO_2. Here, changes up to about 20 % (0.02 % without scaling) at 16 km altitude and 45° latitude due to the ascent in the turbojet phase and about 15 % near the cruise altitude of 26 km are calculated. The NO_x formation in the shockwave during reentry of the upper stage about doubles the perturbation in the upper stratosphere that is caused by transport of NO_x produced in the lower stage.

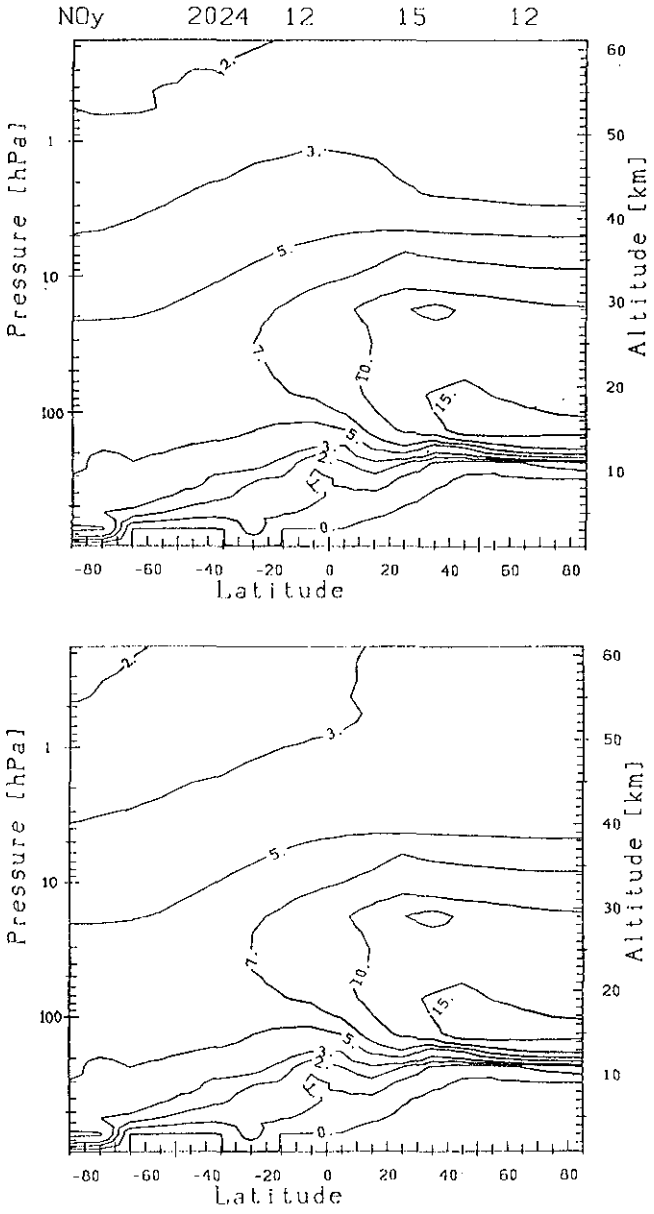

Fig. 3: Percentage changes of total nitrogen (NO_y = NO_x + HNO_3) due to 24000 SÄNGER launches per year with (lower panel) and without (upper panel) considering the upper stage as calculated by the Mainz 2D-model.

For water vapor (Fig. 4), increases of almost 10 % are calculated around 34 km altitude if both stages considered. The emission of the upper stage (here considered only below 60 km) enhances the changes in the upper stratosphere by about 50 %. Molecular hydrogen shows a similar pattern with slightly larger changes (Fig. 5). This substance, however, has only small effects on atmospheric chemistry.

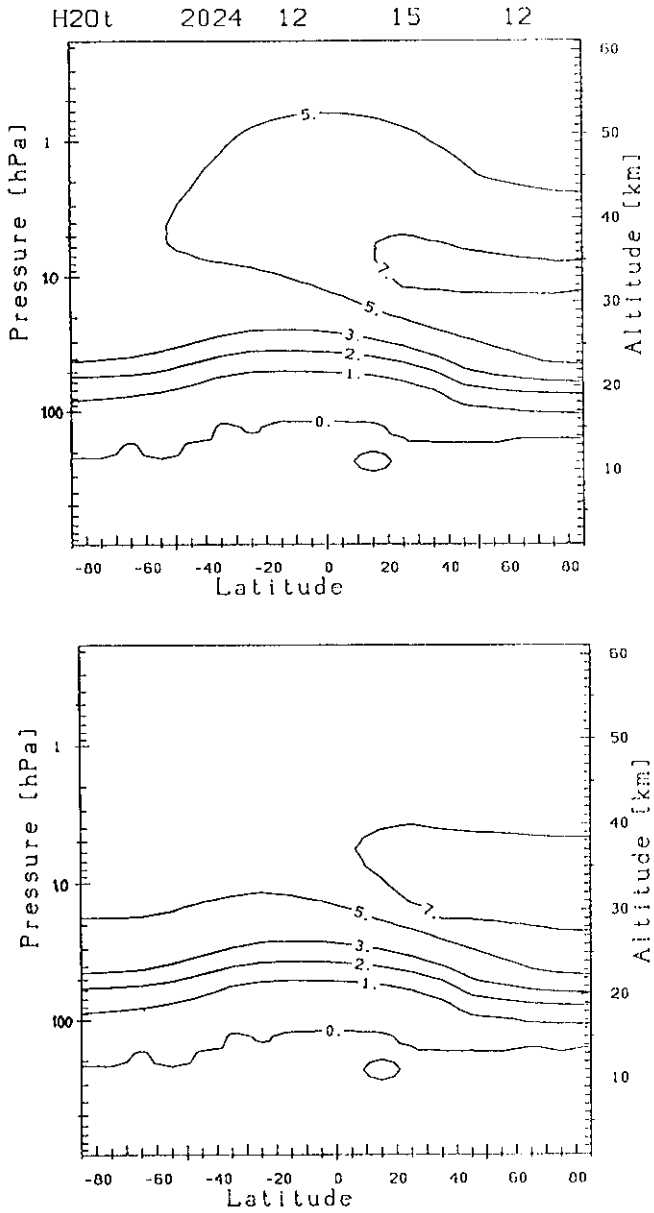

Fig. 4: As Fig 3 but for water vapor.

Ozone changes

Calculated ozone changes considering gas phase chemistry and reactions on the background sulfate aerosol are shown in Fig. 6. The maximum ozone depletion is about 3 % (0.003 % without scaling) at 30 km altitude, mostly due to the NO_x emissions of the lower stage in the cruise phase.

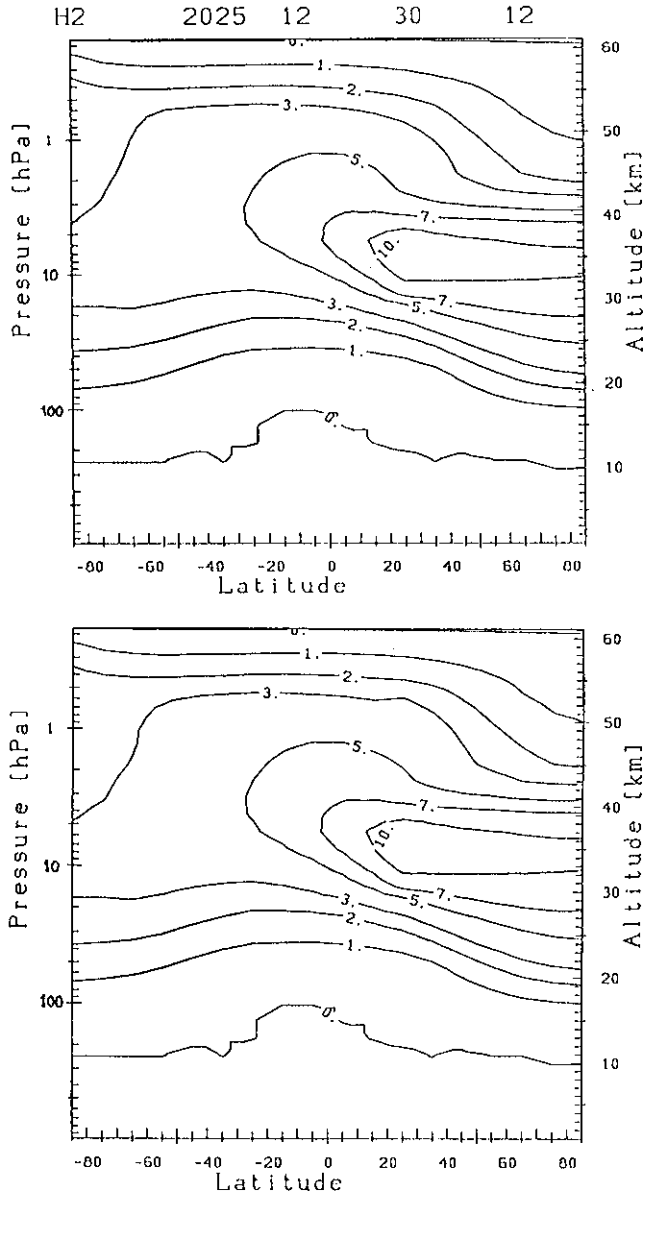

Fig. 5: As Fig. 3 but for molecular hydrogen (concentration fixed at upper boundary).

The upper stage causes additional ozone depletion of less than 1 %. Changes in total ozone are typically about 1% with a maximum exceeding 1.5 % in northern high latitude spring. For the normal operational mode without scaling this change of about 0.001 % is negligible. If SÄNGER were to be used as a public supersonic transport, however, calculated ozone changes exceed 10 % in northern midlatitudes in total and 25 % locally, values, which are clearly not acceptable.

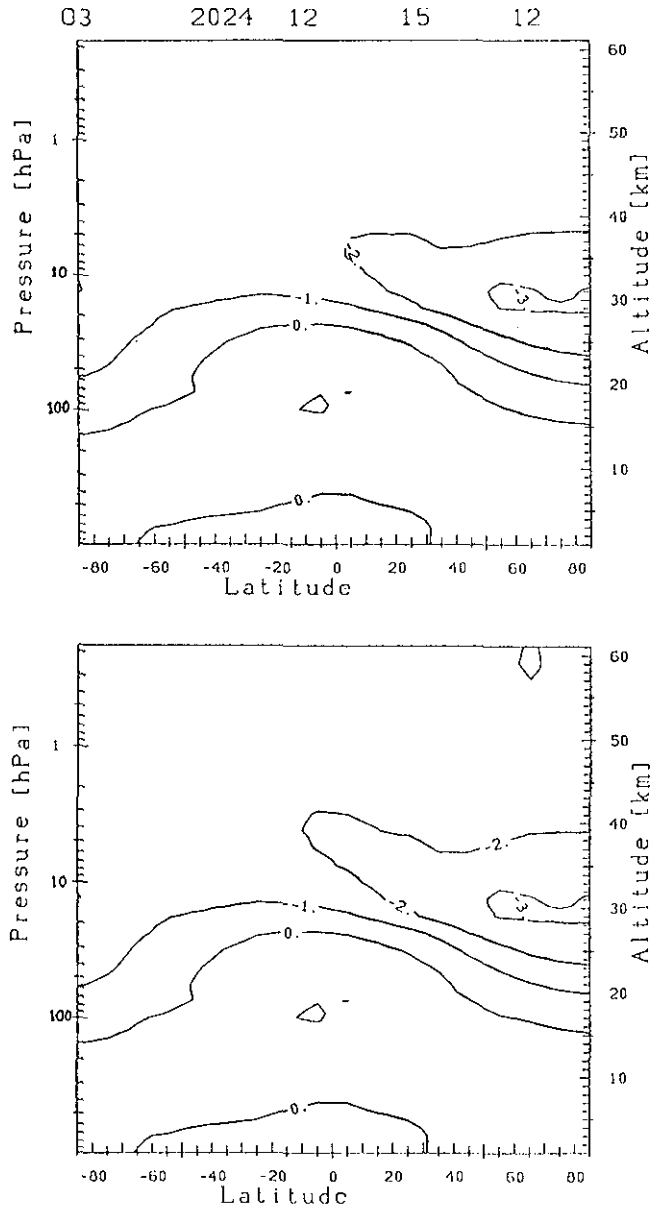

Fig. 6: As Fig. 3 but for ozone.

IMPACT ON STRATOSPHERIC AND MESOSPHERIC CLOUD FORMATION

Polar stratospheric clouds

The calculated increase in the abundance of H_2O and NO_y, which is in high latitude winter essentially nitric acid, may increase the probability of the formation of polar stratospheric clouds (Peter et al [7]), allowing their formation at higher temperatures than in the unperturbed stratosphere. The emissions of 24000 SÄNGER-launches may cause a rise of nitric acid tri-hydrate nucleation temperatures by 0.3 K. Fig. 7 shows the consequence of this for the PSC-formation probability as a function of season and longitude at the 50 hPa level at 70° N based on a 25 years statistics of observed temperatures. Without

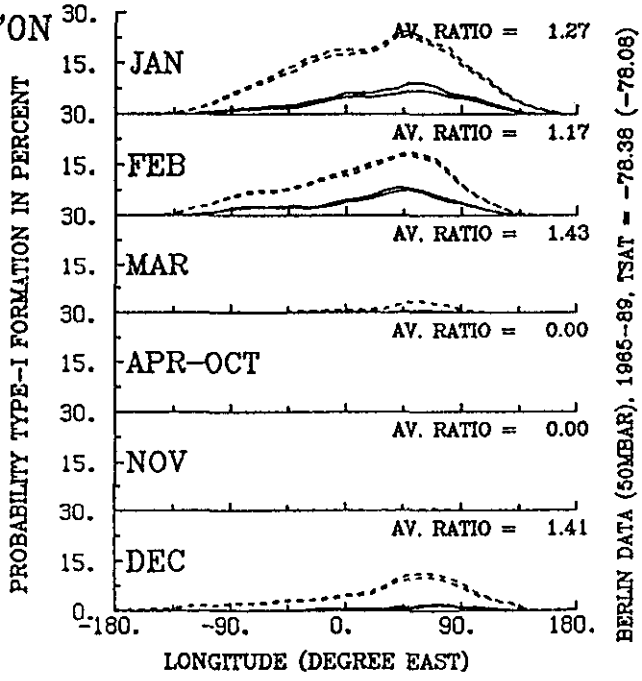

Fig. 7: Probability for PSC-formation at 70° N and 50 hPa as as function of longitude and season with (upper solid line) and without (lower solid line) 24000 SÄNGER-flights per year. Dashed lines show the probability for T below the saturation temperature for nitric acid trihydrate.

scaling, the increase in PSC-probability in 0.03 % at maximum, again a negligible process. The impact of the CH_4 and N_2O increase is much more important. For the large fleet of SÄNGER-like supersonic transport, however, the probability of PSCs may more than triple with potentially serious consequences for stratospheric ozone.

Contrails

Water vapor emitted by SÄNGER will cause even at the cruise altitude of 26 km, where the stratosphere is relatively warm (- 40° C typically), contrails of about 20 km length. When passing the (subtropical) tropopause region during ascent, contrails of a length even exceeding 100 km (or 10 minutes lifetime) are possible. Contrails may affect ozone through PSC-like heterogeneous reactions, especially if SÄNGER is used for polar orbits. Global climatic and chemical impacts of contrails are, however, negligible because of the low frequency of SÄNGER flights. Also in this case a large fleet could cause significant perturbations of ozone and temperature.

Noctilucent clouds

In summer thin ice clouds can form near the mesopause (at 82 km) at latitudes poleward of 50° and temperatures below 140 K. Recently, these clouds are observed often also at other times and latitudes, indicating an effect due to water vapor from rocket launches. If SÄNGER is launched towards high latitudes in summer, the water vapor emitted below 70 km will be transported by the mean circulation upwards to the mesopause and enhance the frequency noctilucent cloudformation. This would add to the enhanced probability of their formation due to the additional water vapor from oxidation of increasing methane (more than a doubling since pre-industrial times).

CONCLUSIONS (AND RECOMMENDATIONS)

If only 24 launches of the SÄNGER system per year take place, its global environmental impact is negligible. The system might be more critical if it is used as launcher for polar orbits. Compared to the existing systems 'Space Shuttle' or 'Ariane' the environmental impacts per launch are less severe since SÄNGER does not use solid fuel boosters which emit strongly ozone-depleting chlorine compounds. In the 'Space Shuttle' scenario (9 Shuttle launches + 6 Titan lauches per year) Prather et al [8] calculated the depletion in total ozone to be about 20 times larger than our results for SÄNGER. 'Ariane' causes about 10 times more ozone depletion per mass of payload if its 3 times higher effiency is taken into account. The use if the SÄNGER lower stage as supersonic transport for cruise at 25 km in a fleet of 500 crafts will cause serious ozone depletion exceeding 10 % in total column in midlatitudes even without considering the accompanying increase in the probability of polar stratospheric clouds, which are responsible for the 'ozone hole'.

Ackknowledgements: This paper is a summary of results obtained in a project on the environmental impact of SÄNGER funded by BMFT (German Ministry for Research and Technology).

REFERENCES

1 R. J. List, K. Telegadas, 1969: Using radioactive tracers to develop a model of the circulation of the stratosphere. J.Atm.Sci. 26, 1128-1136.

2 K. Telegadas, 1971: The seasonal atmospheric distribution and inventories of excess carbon-14 from March 1955 to July 1969. Rep. 243, Health and Safety Lab., U. S. Atomic Energy Comm., Washington.

3 WMO, 1991: Scientific Assessment of ozone Depletion: 1991. World Meteorological Organization global ozone research and monitoring project - report 25, Geneva / Washington.

4 H. Le Texier, S. Solomon, R. Garcia, 1988: The role of molecular hydrogen and methane oxidation in the water vapor budget of the stratosphere. Quart. J. Roy. Met. Soc. 114, 281-295.

5 L. T. Gidel, P. J. Crutzen, J. Fishman, 1983: A two dimensional photochemical model of the atmosphere. I: Chlorine emissions and their effect on stratospheric ozone. J. Geophys. Res. 88, 6622-6640.

6 C. Brühl, P. Crutzen, E. F. Danielsen, H. Graßl, H.-D. Hollweg, D. Kley, 1991: Umweltverträglichkeitsstudie für das Raumtransportsystem SÄNGER. Max Planck - Institute for Meteorology, Hamburg, Germany.

7 T. Peter, C. Brühl, P. J. Crutzen, 1991: Increase in the PSC-formation probability caused by high-flying aircraft. Geophys. Res. Lett. 18, 1465-1468.

8 M. J. Prather, M. M. Garcia, A. R. Douglas, C. H. Jackman, N. D. Sze, 1990: The Space shuttle's impact on the stratosphere. J. Geophys. Res. 95, 18583-18590.