POSSIBLE CLIMATIC EFFECTS OF CONTRAILS AND ADDITIONAL WATER VAPOUR

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ABSTRACT

The importance of contrails in the upper troposphere and of additional water vapour in the lower stratosphere, both the result of aircraft emissions, for the radiation budget of the surface/atmosphere system is roughly assessed. The radiation flux density profiles with contrails and additional water vapour are compared to other greenhouse gas forcings. This leads to a very first order of magnitude estimate of the air traffic climate forcing potential: two percent contrail cover or air traffic induced natural cirrus may be as important for the planetary radiation budget as a 10 percent increase of present anthropogenic CO_2 forcing, equivalent to six years emission of 25 Gigatons CO_2 per year; additional water vapour in the lowest high northern latitude stratosphere is considerably contributing to the greenhouse effect of the atmosphere. If air traffic would cause a 10 percent increase in water vapour there this would be equivalent to up to 0.2 Wm^{-2} radiation budget change depending on surface temperature.

INTRODUCTION

Although the Club of Rome warned nearly two decades ago of a shortage of resources we are in the contrary now mainly discussing pollution problems. Here we have to ask whether air traffic is contributing considerably to the following major air pollution effects:

- increase of the greenhouse effect of the atmosphere provoking a global warming
- observed depletion of the stratospheric ozone layer leading to a thinning of the shield against ultraviolett radiation in the UV-B range from 0.28 to 0.32 micrometer wavelength

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- increased occurrence and severity of photochemical smog in the troposphere mainly caused by NO_x and hydrocarbon emissions increasing also average tropospheric ozone levels
- Widespread increased acidity of rain acidifying lakes and soils and causing corrosion of buildings
- eutrophication of marginal seas by wet and dry nitrate deposition, whereby the nitrate is the product of chemical reaction involving NO_x as precursor gas.

Since air traffic is a source of carbon dioxide (CO_2), nitrogen oxides ($NO_x = NO + NO_2$), carbon monoxide (CO), a variety of hydrocarbons (HC) and particles (often soot) it must contribute to all of them except ozone depletion in the upper stratosphere. However, this exception is only due to cruising levels mostly below 13 km, still too low for this effect (if also accounting for the general downward motion in the high latitude lower stratosphere). The main question is: How and where is the rather small air traffic contribution to total global emission enhanced? We have, in other words, to explain why water vapour emission by aircraft engines is a problem, although a lake of 150 km^2 evaporates roughly the same amount as is injected by the global fleet of aircraft.

The following pages will be restricted to the water vapour emission only. After a section 2 on the basic atmospheric temperature structure and water vapour abundance contrail formation as a function of pressure and temperature is introduced in section 3. The radiation flux density changes caused by thin cirrus (here taken as represen-tative for contrails, which may not be correct in all cases) are discussed in section 4 including a first order of magnitude estimate of contrail impact on the radiation budget. Section 5 then discusses water vapour in the lower stratosphere from the point of view of radiation flux density changes. A final section 6 concludes with a summary of findings and open questions.

ATMOSPHERIC STRUCTURE AND RESIDENCE TIME OF AN ADMIXTURE

The density of well mixed gases like oxygen (O_2) and carbon dioxide (CO_2) decreases like pressure exponentially with height halving the value approximately every 5.5 kilometers. Thus emission in 11 km at 250 hPa, a fourth of surface pressure, is for all substances a stronger disturbance than at lower levels even if accounting for a reduction in fuel consumption due to decreased air resistance. If the substance in question is falling off more rapidly with height than pressure, for instance water vapour, then aircraft emissions become more and more important, might even become dominant for the concentration of a trace substance from a certain height level upwards. This is illustrated in Table 1 and Figure 1. Temperature decreases typically by 0.6 K per 100 m ascent in the troposphere and water vapour saturation pressure is for T < 10°C at least halved by a 10 K temperature decrease. The result: water vapour is a trace gas in the parts per million by volume range at present subsonic jet engine cruising levels.

Table 1: Water vapour pressure at saturation.

Temperature	saturation pressure over water	saturation pressure over ice
30°C	42.42 hPa (*)	
20	23.94	
10	12.27	
0	6.10	6.10
- 0	2.86	2.59
- 20	1.25	1.01
- 30	0.50	0.37
- 40	0.19 *	0.12
- 50		0.039
- 60		0.010
- 70		0.0026
- 80		0.00054
- 90		0.00009
- 100		0.00001

* Supercooled water droplets often exist down to -40°C.
(*) Volume mixing ratios are calculated by dividing by total pressure in the level of observation.

Another basic feature of our atmosphere, which is of relevance here, is the higher tropopause over warm surfaces. Therefore, nearly all present subsonic aircraft never reach the tropical stratosphere, experience coldest temperatures during advection of subtropical air, when the tropopause is roughly at 13 km.

The potential atmospheric residence time of an admixture "jumps" from a few weeks for the upper troposphere to typically a year or more in the lower stratosphere. Residence time is meant as the time a molecule or particle - if not undergoing chemical transformation - typically resides in the respective part of the atmosphere before entering another part or being mixed down to the surface where it is eventually deposited.

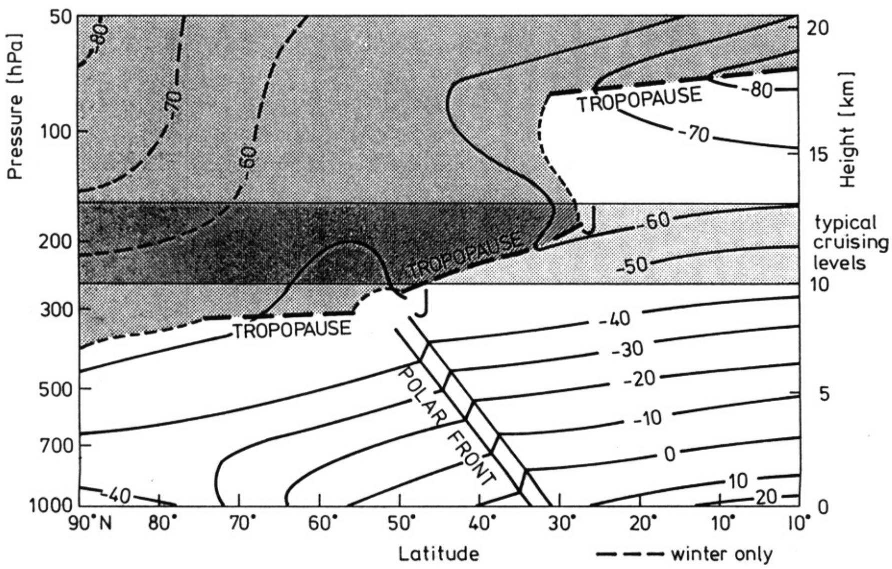

Fig. 1: Temperature structure of the Northern Hemisphere winter atmosphere, shown in a latitude-height isoline plot (°C) with indication of mean tropopause level and typical subsonic jet aircraft cruising levels. Dashed lines in the stratosphere show minimum temperatures rather than averages.

CONTRAIL FORMATION

Contrails (condensation trails) may form in the exhaust plume of a jet engine if a volume of air is supersaturated with respect to a plane water or ice surface. Supersaturation in this case is reached by mixing of two unsaturated air volumes of different temperatures, here by cooling the engine exhaust containing the additional water vapour and many condensation nuclei through dilution with ambient air. Since the saturation vapour pressures (see also table 1) is lower over ice, the contrail, starting as a water cloud in the still warm exhaust air stream, is after a short time easily transformed into an ice cloud because the temperatures are low enough (below -40°C) for icing of any cloud, even without any ice nuclei. Thus contrails lasting for more than a few seconds show a spectral transmission typical for ice clouds (Grassl, 1970). Already in 1953 Appleman has calculated the temperature and pressure values leading to contrail formation if kerosene is burnt. Fig. 2 repeats the basic features and indicates, by including an observed and a mean temperature profile, that present cruising levels very often tend to optimize inadvertently contrail formation. Roughly speaking flying in 12 km at -60°C has to cause a contrail, whose lifetime is proportional to the distance between actual temperature and the 0% relative humidity line in Fig. 2, hence under these conditions the aircraft emitts enough water vapour to cause an ice cloud even in a dry atmosphere. The contrail lifetime is also dependent on lateral and vertical diffusion which is not only influenced by the dynamical and thermal structure of the atmosphere but also by aircraft and engine design. Despite

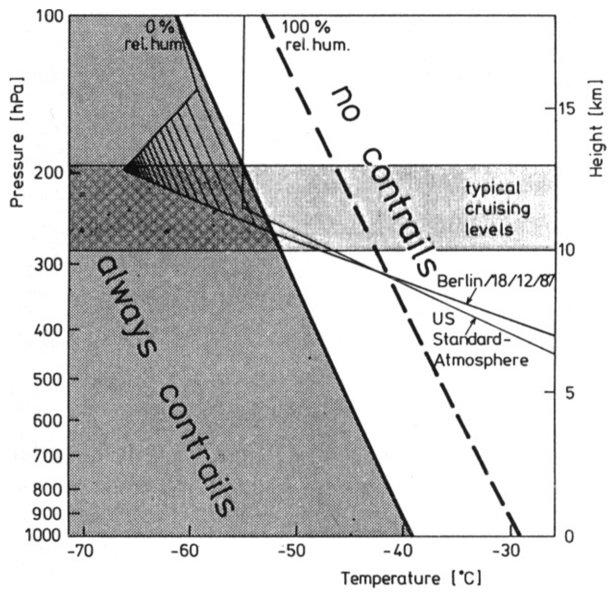

Fig. 2: Contrail formation depending on air pressure, air temperature and relative humidity, also indicating main cruising levels, a standard temperature profile as well as an individual one; modified after Appleman (1953).

these many influences Fig. 2 possibly points to a way for the assessment of the contrail abundance. Observation of the lifetime for several cases for a distinct aircraft could allow the extrapolation to all radiosoundings of a distinct station and might even lead to a contrail lifetime forecast for a distinct meteorological situation. The main drawback of this proposal is the poor quality of the water vapour measurement by radiosondes at temperatures below about -30°C.

A simple graphical representation of a simple calculation of the relative humidity increase by an airplane at cruising altitude should underline the importance of temperature (Fig. 3). Let us suppose we fly between 9 and 12 km height and the aircraft burns 1 ton kerosene per 100 km, i.e. emits 1.25 tons water vapour. This water vapour is diluted into a 1 km wide and 150 m thick exhaust channel. Then we would raise for example relative humidity and thus water vapour concentration by 6 percent at 10.5 km and -60°C.

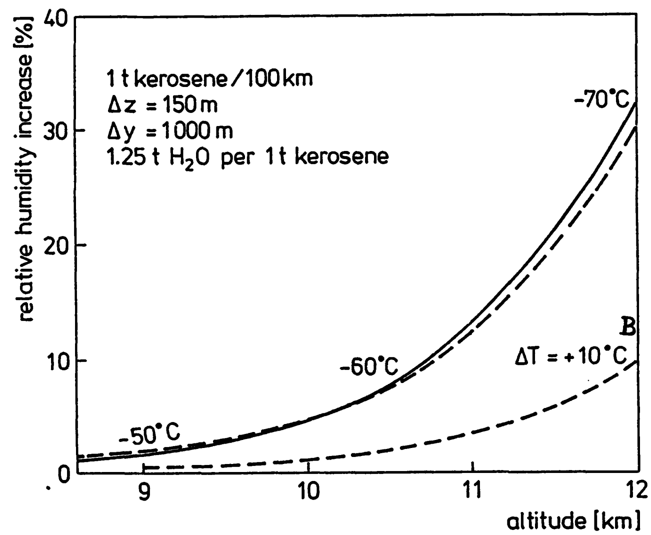

Fig. 3: Relative humidity increase as a function of altitude and corresponding temperature; the dashed line includes increased efficiency at higher cruising altitudes. The lower dashed curve is valid for higher temperature (+ 10 K).

The temperature height curve assumed is quite realistic as indicated by the Berlin radiosonde profile in Fig. 2, where temperature drops by 15K from 10 to 12 km. The corresponding maximum relative humidity increase at 12 km is plotted as B in Fig. 3.

RADIATIVE FLUX DENSITY CHANGES BY THIN ICE CLOUDS

High clouds have generally a strong impact on thermal radiation transfer in the atmosphere (Liou, 1986), since they absorb heat radiation from the warm surface in otherwise transparent spectral intervals of a cloudless atmosphere and reradiate far less upward as well as downward, dictated by their low temperatures. Hence, they effectively shield the planet from a higher heat loss to space. This shielding may be offset during daytime by reflecting back to space solar radiation. The thermal radiation change is best understood by discussing the radiation flux density profiles for different thin ice clouds. Fig. 4 clearly points to the drastic reduction of radiation to space (here only shown up to 20 km height) by optically thin cirrus. Approximately 100 Wm^{-2} less heat radiation is emitted to space if an ice cloud with an optical depth of 1.8 (this would be a very strong contrail) interferes. The crystal size distribution assumed has been proposed for cirrostratus clouds. Since the thermal net flux density F_{net} is strongly decreasing with increasing height in the lower portion of the cirrus layer this

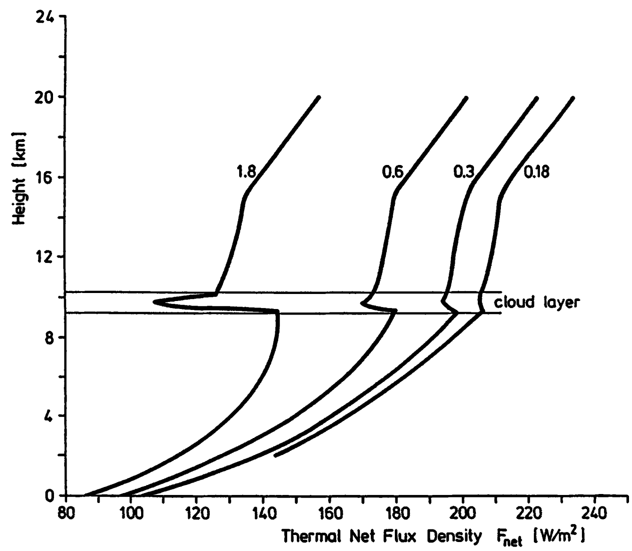

Fig. 4: Thermal net radiation flux density profiles for different thin ice clouds of 750 m vertical extent but varying optical depth as indicated; modified after Manschke, 1985.

layer is heated through absorption of radiation from below. Only the upper portion with a strong increase of F_{net} with height shows a cooling. One can imagine that radiation processes acting long enough in this way tend to destabilize the temperature profile causing turbulent mixing and a contrail cross section change. This radiation forced vertical mixing is well known to all of us as the bumpiness when flying near to a cloud top. Vertical net flux density gradients may be converted into instantaneous heating rates by

$$\frac{\partial T}{\partial t} = -\frac{1}{\rho c_p} \frac{\partial F_{net}}{\partial z}$$

with ρ = air density, c_p = specific heat of air at constant pressure.

At 250 hPa with air density ρ of roughly 0.35 kg m^{-3} and 20 Wm^{-2} net flux difference within 300 m cooling or heating depending on the sign of the difference already amounts to ~1K per hour. Most important for the following discussion of possible contrail effects is the F_{net} change for very thin ice clouds. A cloud with an optical depth δ = 0.1 already reduces net thermal radiation to space by about 10 Wm^{-2}, depending on height and temperature as well as microphysical properties of ice clouds. This exceptionally strong radiation budget change is due to the following physical facts:

- very low temperatures near the tropopause lowering emission of an absorber
- strong absorption by ice crystals in the entire thermal infrared
- crystal sizes large enough to cause a relative extinction efficiency of approximately 2, but still small enough to lead to high optical depth

  $$\delta = 2 \int \Pi r^2 \, n(r) \, dr$$

  with r = cross section equivalent radius of a cirrus crystal,
  n(r) = crystals per volume per radius unit.
  It has been shown by Kinne (1982) that the cross section equivalent radius is a better approximation than surface or volume equivalent radius.

Thin cirrus clouds therefore are most effective in shielding the Earth from a heat loss.

The foregoing discussion did not account for backscattering of solar radiation by these clouds. If included, a more complicated picture emerges. Fig. 5, also like Fig. 4 taken from a master's thesis of a former student, demonstrates that optically thin ice clouds increase the greenhouse effect of the atmosphere in most cases, because the solar net flux density change $\Delta F_{net,\,s}$ at the top of the atmosphere is smaller than ΔF_{net} in the thermal infrared. Only for very low sun elevation $\Delta F_{net,\,s}$ surmounts ΔF_{net}. One should note, however, that all curves would at all sun elevations be lower for lower optical depth, typical for most contrails. Taking $\Delta F_{net,\,s}/\Delta F_{net}$ = 0.5 (no exaggeration, rather a conservative estimate) for δ = 0.1, we have to compare a 5 Wm^{-2} net radiative budget forcing with other anthropogenic forcings. Doubling CO_2 for example gives $\Delta F_{net} \cong$ - 3 Wm^{-2} at the top of the atmosphere at fixed other parameters, as also assumed for the calculations with thin ice clouds. If such a radiative forcing is applied to a radiative-convective equilibrium climate model the resulting forcing of the troposphere/surface system expressed in a net flux change at the tropopause is ΔF_{net} = 4 Wm^{-2}. Radiative-convective equilibrium in this context means that the radiation balance of the Earth has been reached again by heating of the lower atmosphere and the surface, thereby allowing for convection in the troposphere. Since industrialisation began, CO_2 content increased by 25 percent, the socalled CO_2-greenhouse forcing of the troposphere/surface system therefore $\cong$ - 1 Wm^{-2} at present. A two percent cover with such contrails would therefore be equivalent to 10 percent of the present CO_2 greenhouse forcing or to roughly 5 years of CO_2 emissions with presently 25 Gigatons CO_2 per year. This rough first estimate should not be misinterpreted, it is simply an indication that adding water vapour into very cold layers leading to contrails acts as a strong amplifier of radiation budget changes. While air traffic contribution to CO_2 emissions is in the 1-2% range, and emission height is irrelevant because of the long lifetime, high tropospheric water vapour injection strongly amplifies the environmental impact of air traffic. At the same time this underlines the difficulties climate modellers have in correctly describing the role of ice clouds in a warmer 2 x CO_2 climate.

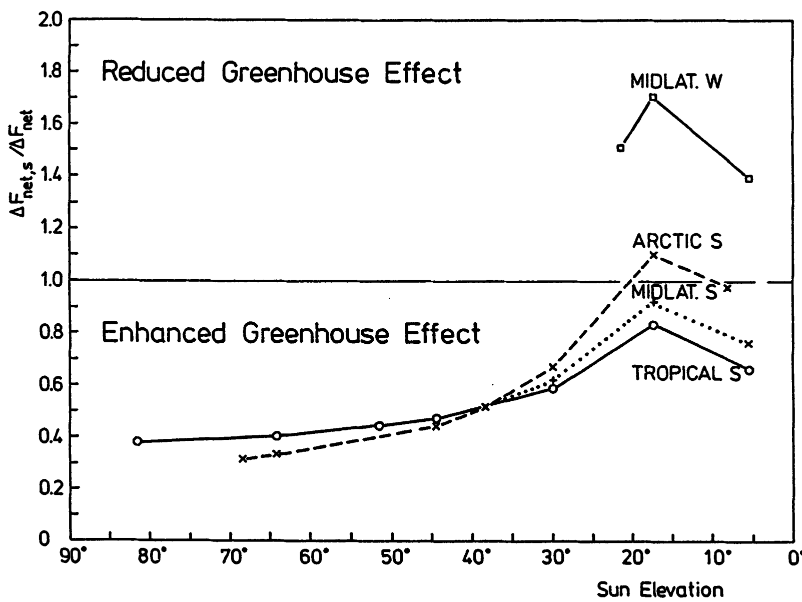

Fig. 5: Net effect of ice clouds (1 km cirrostratus with δ = 1) on the radiation budget shown as the ratio of solar radiation change to thermal radiation change ($\Delta F_{net,\,s} / \Delta F_{net}$) as a function of sun elevation; for four different standard atmo-spheres as indicated; modified after Kinne (1982).

Frequently the following argument is put forward: High level cirrus is of nearly no influence if above an optically thick lower cloud deck. With respect to contrails this would mean: only contrails in otherwise clear skies have a strong radiation budget change capacity. However, this is not true, since the backscattering of solar radiation is reduced by a thin cirrus above an optically thick water cloud (Bumke, 1984) and the shielding of thermal radiation is mainly a function of the temperature difference between lower cloud deck and cirrus clouds. Over low lying stratus decks contrail impact is thus enhanced if compared to a cloudfree condition.

The above calculations of radiation flux density changes ΔF_{net} and $\Delta F_{net,\,s}$ applied measured crystal size spectra of cirrostratus, a natural ice cloud. These crystals are rather large (150 µm length, 30-40 µm width) and there are good arguments that crystals in contrails are far smaller owing to the evolution of contrails. They start as water clouds and are rapidly transformed into ice clouds. Since all known shortlived water cloud droplet size spectra peak in the 2 to 10 µm radius range, a better representation would be to use strongly smaller ice crystal sizes. However, this is only a physically plausible proposal not at all underlined by measurements, which do not exist, because sizing instruments typically stop at 50 µm diameter crystals. An additional argument for small crystal sizes is the increase in condensation nuclei numbers in the engine exhaust again leading to smaller typical droplet sizes freezing at -40°C the latest. An increase in crystal numbers at constant ice content in a contrail strengthens solar radiation back-scattering at a given ice content. Since we do not know the typical optical depths of long lived contrails the net effect in both radiation domains, solar and terrestrial, cannot be assessed more accurately. Two examples for a possible change: An increase of $\delta = 0.1$ to $\delta = 0.2$ would add to the greenhouse forcing, an increase from $\delta = 1$ to $\delta = 2$ would rather subtract.

WATER VAPOUR IN THE LOWER STRATOSPHERE

Water vapour is the most important radiatively active gas in the Earth's atmosphere and is responsible for more than two thirds of the greenhouse effect of the atmosphere. With its numerous absorption bands any concentration change in any layer affects the planetary radiation budget. As for other spatially varying gases changes in concentration are most effective at the tropopause level. Additionally accounting for the possibility of accumulation through increased residence time the lowest stratosphere is the most sensitive area for radiation flux density changes. In this context it is important to note that stratospheric water vapour content in undisturbed conditions is mainly controlled by two sources: Firstly, the source in anvils of tropical cumulonimbi penetrating a short distance into the stratosphere, where due to the very low temperatures around -80°C or even below the low water vapour volume mixing ratio of 2-3 ppm is determined; secondly, the source through oxidation of methane causing an increase in mixing ratio upwards and polewards from the tropical tropopause, to some-

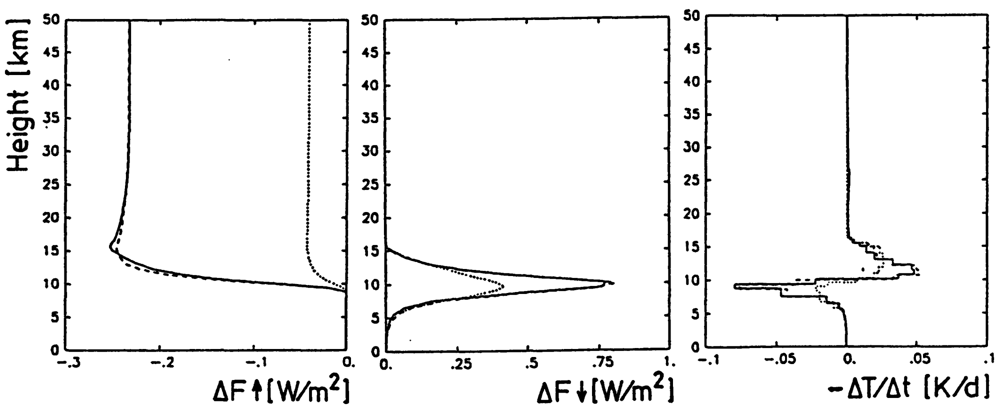

Fig. 6: Upward (a) and downward (b) thermal flux density change (ΔF↑, ΔF↓) caused by a 10 percent increase in water vapour density from 10-15 km for three atmospheres. Also changes in cooling rates (positive values mean stronger cooling) are shown in (c); (—) tropical atmosphere, (---) midlatitude summer atmosphere, (. . .) arctic winter atmosphere, after Hollweg (1990).

what higher values from 3-4 ppm on average. Again, like for contrails, air traffic is injecting water vapour into a rather sensitive area. In order to estimate the amount injected a simple calculation reveals: If from the yearly consumption of 120 million tons of fuel resulting in 150 million tons of water vapour 20 percent are injected into the stratosphere northward of 40°N (Lufthansa gave 15-17 percent for a test under summer conditions) this constitutes 15 percent of the typical water vapour content in the 10 to 13 km layer for the area north of 40°N. For this calculation a mixing ratio of 4 ppm has been assumed. Taking a residence time (here e-folding time) of one year a 5-6 percent increase in the 10-13 km layer would result. Higher flight levels would increase this percentage.

Does this affect the radiation budget? The answer from radiative transfer calculations in our institute, using a code tested by a line-by-linde code, is (Hollweg, 1990): A 10 percent increase of water vapour in the 10-15 km layer reduces emission to space by up to 0.23 Wm^{-2} depending on geographical area. The biggest ΔF_{net} occurs over warm surfaces. However, since the tropical tropopause is at 15-17 km height, the calculations represented by the full curve in Fig. 6 are valid for a 10% increase in upper tropospheric water vapour amount. The dashed curve for a midlatitude summer atmosphere with a tropopause at 11 km height realistically describes the effect of a 10% water vapour increase at the tropopause and lower stratosphere. The small decrease of F_{net} in polar winter atmospheres (dotted curve) is due to the cold lower troposphere. Taking into account the surface area of the Earth ($\sim 5 \bullet 10^{14}$ m^2) this 10% water vapour increase from 10-15 km is in terms of heat trapped equivalent to up to $1.2 \bullet 10^{14}$ W, more than ten times global anthropogenic energy throughput. It is also over warm surfaces comparable to a tenth of present mean greenhouse forcing amounting to ~2 Wm^{-2}. Figure 6 additionally points to a redistribution of heating or cooling rates by this additional water vapour. More cooling in the lower stratosphere and less cooling below 10 km, giving a tendency for an upward shift of the tropopause.

These model results indicate that already a few percent increase of lower stratospheric water vapour concentration are of considerable importance for the planetary radiation budget and for the cooling rate profile. This statement is a mere consequence of injection of water vapour into layers of most effective greenhouse forcing in the atmosphere.

DISCUSSION

Water vapour, by far the most important greenhouse gas of the atmosphere, is also a product of burning of kerosene by aircraft (1.25 tons per tone kerosene) and due to its injection into very cold layers around the tropopause of considerable environmental impact. Especially two effects have to be discussed with respect to present civil air traffic:

- contrail formation in the upper troposphere
- additional water vapour in the lowest stratosphere of high latitudes.

Both enhance either under most conditions (contrails) or always the greenhouse effect of the atmosphere. Most effective is water vapour injection at very low temperratures since the optical depth of contrails will be low enough for a greenhouse forcing, their lifetime will be increased and shielding of radiation to space is most pronounced if the absorber (contrails or water vapour) is cold. In our latitudes these low temperatures are mainly observed in subtropical airmasses when the tropopause height is above average.

The relative contribution to atmospheric composition increases with injection height in a threefold manner:

- density falls off exponentially, approximately halved every 5.5 km height increase
- maximum possible residence time of an admixture increases from days over weeks and months to years if ascending up to 13 km
- water vapour and nitrogen oxide (NO_x) background mixing ratios show a minimum in the lower stratosphere.

All the statements in this paper are qualitative in the sense that we lack the proof of a considerable increase in cloudiness through contrails and of water vapour concentration in the lower stratosphere in high northern latitudes. Attempts to identify contrail impact on local climate parameters where either not finding a significant modification (Rotter, 1987) or if finding an impact have also looked to parameters in the solar spectral range, where the impact is smaller than in the thermal range (Changnon, 1981). A first objective contrail cover estimate over Central Europe (Schumann, this volume) points to frequent occurrence. However, the method used can only give a minimum cover.

If one would for example find a rather low contrail cover this is, however, by no means an argument not to continue search for an air traffic water vapour and cirrus cloud impact, because the increase in high tropospheric water vapour content even without the existence of longlived contrails will be the cause of earlier "natural" cirrus cloud formation lateron at favorable meteorological conditions. This effect might even be stronger than that caused directly by contrails. Also the question of changed stratospheric chemistry through additional water vapour has not been discussed as well as the possible impact of H_2O and NO_x on wintertime polar stratospheric clouds. We are only now - with forecasts of a dramatic increase in air traffic worldwide - starting research on the effect of a water vapour injection. What is most urgently needed is measurements around the tropopause.

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