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Impact of air traffic on cirrus coverage

Claudia J. Stubenrauch¹ and Ulrich Schumann²

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[1] TOVS Path-B satellite data provide information on effective high cloud amount and relative humidity for the period 1987 to 1995. Differences in trends of seasonal mean effective high cloud amount between situations favorable for contrails and for cirrus are analyzed in regions with high and low air traffic density. In regions with especially high air traffic density, a significantly stronger increase of effective high cloud amount is found for situations with sufficiently cold and humid air masses favorable for contrails than for all situations in general or for situations favorable for cirrus. Situations of potential contrails occur in about 5 to 10% of all situations, and their seasonal effective high cloud amount averages lie between about 7% and 22%. Indicators of cirrus increase due to air traffic corresponding to the difference in trends of effective high cloud amount between potential contrail situations and cirrus or all situations are about 2.8%–3.5% and 1.6%–4.7% per decade over Europe and the North Atlantic flight corridor, respectively. Weighted by frequency of potential contrail occurrence, the overall increase amounts to at least 0.20%–0.25% and 0.08%–0.24% per decade over regions with very high air traffic (Europe and the North Atlantic flight corridor, respectively). **Citation:** Stubenrauch, C. J., and U. Schumann (2005), Impact of air traffic on cirrus coverage, *Geophys. Res. Lett.*, 32, L14813, doi:10.1029/2005GL022707.

1. Introduction

[2] The increase of air traffic during the 20th century has led to numerous theoretical and observational investigations of its impact on the formation of cirrus clouds. Condensation trails (contrails) form when the hot and humid exhaust gases from the combustion of fuels by an aircraft mix with the ambient, cold atmosphere [Schumann, 1996]. Their persistence depends on upper tropospheric relative humidity [Sausen *et al.*, 1998]. Contrails trigger the formation of additional clouds from natural water vapor present in the atmosphere. Since the 1980's, satellite observations give continuous information on atmospheric temperature, humidity and cloud properties on Earth [Rossow and Schiffer, 1999; Scott *et al.*, 1999]. Recently, several attempts have been made to relate trends in cirrus coverage to zones with heavy air traffic [Boucher, 1999; Zerefos *et al.*, 2003; Minnis *et al.*, 2004; Stordal *et al.*, 2004]. However, the attribution of the observed cirrus trends to aviation was not direct, since these studies have investigated trends in

general, but contrails only form under specific conditions. By comparing trends in cirrus coverage in situations favorable for contrail formation to trends in general and to those favorable for cirrus, separately over regions with heavy air traffic and with low air traffic, it is possible to relate an increase in cirrus coverage to air traffic.

2. Method

[3] This analysis consists of determining trends in effective high cloud amount ϵN (emissivity ϵ of clouds with pressure smaller than 440 hPa weighted by their coverage N within a grid of 1° latitude \times 1° longitude) [Stubenrauch *et al.*, 1999] in regions of high and low air traffic, distinguishing situations cold and humid enough for contrail formation and subsequent triggering of additional cirrus clouds and situations without contrails. Cirrus evolves without contrail triggering when the upper tropospheric relative humidity with respect to ice exceeds the saturation humidity over ice, while contrails form already when the relative humidity is below this value but exceeds a critical value depending on temperature and a parameter depending on the fuel used by the aircraft: the ratio G of rates in change of vapor pressure and temperature in the expanding aircraft exhaust plume [Schumann, 1996]. For Kerosene and $p = 230$ hPa, $G = 1.5$ Pa/K, leading to a maximum temperature of contrail formation of about 233 K.

2.1. Data

[4] The data needed for this analysis are provided by the TOVS (TIROS-N Operational Vertical Sounder) Path-B satellite climatology [Scott *et al.*, 1999] for the period of June 1987 to May 1995 (thereafter, we do not yet have established the required calibration data): precipitable water column W , integrated from 300 hPa to 100 hPa, and atmospheric temperature $T(p)$ in pressure steps of about 25 hPa, for situations of clear sky or thin cirrus. The latter are defined as high clouds with ϵN less than 0.5. The instrumental cloud detection threshold is about 0.1 in visible optical thickness [Wylie *et al.*, 1995], and due to its relatively coarse spatial resolution very thin and small-scale cirrus clouds may be missed. In the following study, however, we do not require directly the presence of cirrus but use relative humidity and ϵN . The average ϵN of all these situations is about 13% to 17%, depending on the region (see section 2.2).

[5] Due to the relatively coarse resolution of the channels sensitive to water vapor, the TOVS instruments only provide water vapor integrated over a relatively large height interval [Chaboureau *et al.*, 1998], and therefore we are obliged to estimate the relative humidity as well as its critical value for contrail formation integrated over this height interval (between about 9 km and 15 km).

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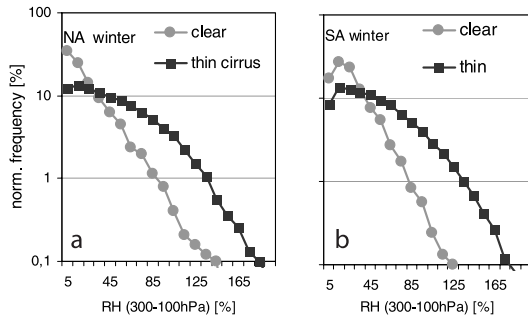


Figure 1. Normalized frequency distribution of upper tropospheric relative humidity with respect to ice during winter, separately for clear sky and thin cirrus, (a) over NA and (b) over SA. Data are from TOVS observations from 1987 to 1995, with about 12000 clear sky scenes and about 45000 thin cirrus scenes.

[6] In a first step, we determine the upper tropospheric relative humidity with respect to ice as:

$$U^{ice}(\Delta p) = \frac{g\rho W}{0.622 \int_{100-300 \text{ hPa}} dp e_{sat}^{ice}(T(p)) / [p - (1 - 0.622)e_{sat}^{ice}(T(p))]} \quad (1)$$

with gravity g , density ρ and saturated partial water vapor pressure e_{sat}^{ice} with respect to ice [Sonntag, 1990], which is determined from the temperature profile within the height interval. Figures 1a and 1b present normalized frequency distributions of this relative humidity over the North Atlantic (NA, 30°N–60°N and 0°–60°W) and over the South Atlantic (SA, 30°S–60°S and 0°–60°W) during winter, separately for clear sky scenes and for thin cirrus. One observes that clear sky distributions are slightly narrower than those of thin cirrus, but few clear sky scenes are also ice saturated, in agreement with other observations [Gierens et al., 1999]. The shapes of the distributions of NA and SA are similar.

[7] In a second step, we determine the critical relative humidity for the formation of contrails, by integrating over the same height interval, as:

$$U^*(\Delta p) = \frac{\int_{100-300 \text{ hPa}} [G(T - T_{max}^{liq}) + e_{sat}^{liq}(T_{max}^{liq})] dp}{\int_{100-300 \text{ hPa}} e_{sat}^{liq}(T) dp} \quad (2)$$

with $T_{max}^{liq} = 230.8$ K and $e_{sat}^{liq}(T_{max}^{liq}) = 20.6$ Pa [Schumann, 1996]. The index *liq* refers to saturation over liquid water.

[8] Since contrails and even most cirrus are geometrically much thinner than the height interval covered by TOVS, we have to adjust threshold values $U^{ice}(\Delta p)$ and $U^*(\Delta p)$ for cirrus and for contrails by a scaling factor less than 1. The threshold values separate three situations: 1) cirrus with $U^{ice}(\Delta p) > 0.7$, 2) possible contrail occurrence with $U^{ice}(\Delta p) < 0.7$ and $U^{liq}(\Delta p) > 0.4$ $U^*(\Delta p)$ and 3) clear sky with $U^{ice}(\Delta p) < 0.7$ and $U^{liq}(\Delta p) < 0.4$ $U^*(\Delta p)$. Scene type 2 covers non-persistent and persistent contrails (those for which a very thin atmospheric layer within Δp is

saturated with respect to ice). Thicker persistent contrails are also part of scene type 1. The scaling factors of 0.7 and 0.4 have been obtained iteratively by considering the occurrence frequency and εN of these three scene types. These factors should depend slightly on the atmospheric profiles. Therefore, we study in the following only regions with similar distributions in upper tropospheric relative humidity.

[9] The TOVS data used are from NOAA-10 and NOAA-12, with observation times of 7:30 am and 7:30 pm.

2.2. Trend Analysis

[10] We compare trends in εN for all situations (clear sky and thin cirrus, corresponding to the sum of scene types 1, 2 and 3), for situations favorable for contrail formation but without any cirrus yet (scene type 2) and for situations favorable for cirrus (scene type 1). Four geographical regions are considered: Europe (40°N–60°N and 0°–40°E), North Atlantic flight corridor (NAF, 50°N–60°N and 0°–60°W) where air traffic density according to [Schmitt and Brunner, 1997] is high, as well as the larger NA and SA regions described in Section 2.1. An analysis of the fuel consumption data [Schmitt and Brunner, 1997] in these regions for February 1992, indicates fuel consumption between 8 and 13 km altitude of 559 Mt over Europe, 388 Mt over the NA and only 7 Mt over the SA.

[11] Figure 2 presents the time series of seasonal averages of effective high cloud amount (above) as well as the residuals between these values and the eight-year mean seasonal averages (below) over Europe, separately for all scene types and for scene type 2 alone. Statistical errors even for occurrence of scene type 2 are small for all four regions, with about 800 to 2000 retrievals per season over Europe, 400 to 1000 retrievals per season over NAF and 1000 to 3000 retrievals per season over NA and SA. The statistical errors of the eight-year seasonal averages of εN are about 0.5%. εN exhibits a seasonal cycle with larger values in winter (14%) than in summer (9%), and this cycle is more pronounced for situations of potential contrails (18% compared to 7%). After having taken out the eight-year mean seasonal cycle we fit linear tendencies to the data to look for a first indication of an increase of εN in the case

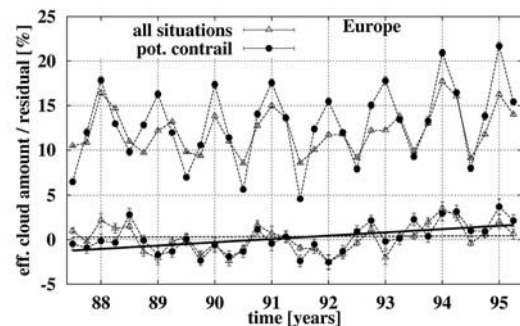


Figure 2. Time series of seasonal εN (above) and residuals from eight-year seasonal averages (below) over Europe. Linear fits take into account statistical errors: no trend (—) for all situations (clear sky and thin cirrus) and a slight increase (---) for situations favorable for contrail formation.

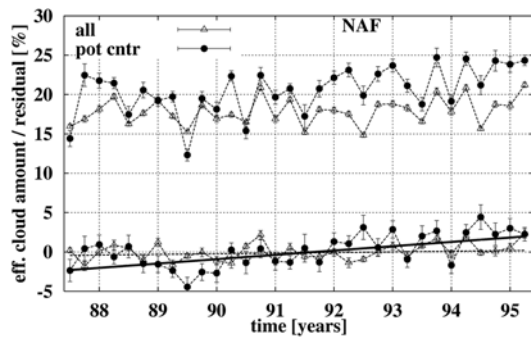


Figure 3. Time series of seasonal ϵN (above) and residuals from eight-year seasonal averages (below) over North Atlantic flight corridor. Linear fits take into account statistical errors: no trend (—) for all situations (clear sky and thin cirrus) and a slight increase (—) for situations favorable for contrail formation.

of situations in which contrail may form. Whereas the general slope of ϵN within this time period is only 0.2% per decade, it is 3.7% per decade in situations favorable for contrail formation. Within the statistical errors, the confidence levels of the fits are larger than 99%. As in the analyses cited in section 1, retrieval errors have not been taken into account. Therefore, for a further estimation of the uncertainty of these slope values, we have fitted the data again, after taking out the last year and the first year, respectively. In all three periods the increase of ϵN in situations favorable for contrail formation is considerably larger than in general and than for cirrus, shown as differences between trends in Table 1. This means that by isolating situations in which contrail may form the larger increase in ϵN can presumably be linked to air traffic. A similar conclusion can be drawn from analyzing the NAF: the difference in trends between situations of potential contrails and all situations is 4.7% per decade. Figure 3 exhibits a seasonal cycle similar to the one over Europe with ϵN larger in winter (19% and 22%) than in summer (16% and 17%), for all situations and for situations favorable for potential contrails respectively. Over this region, cirrus also increase strongly, but still the difference in slopes between situations of potential contrails and cirrus is positive: 1.6% per decade. Therefore, the most conservative indicator for an increase of ϵN due to air traffic is the difference in trend between situations of potential contrails and cirrus. An

additional uncertainty estimation is given by changing the scene type thresholds described in section 2.1 from 0.7/0.4 $U^*(\Delta p)$ to 0.8/0.4 $U^*(\Delta p)$ (i8w4) and to 0.8/0.5 $U^*(\Delta p)$ (i8w5), also presented in Table 1. All thresholds lead to similar results. The overall uncertainty can be estimated to about 1.5% per decade. In general, slope differences between potential contrail and cirrus are smaller than those between potential cirrus and all situations, probably because on one hand a general increase in cirrus is also partly reflected in situations which have been labeled as favorable for contrail formation and on the other hand the scene type cirrus can also contain thicker persistent contrails.

[12] As shown in Figure 1, the relative humidity distributions of NA and SA look quite similar, and therefore we use these two regions to contrast cirrus behavior under high air traffic density (NA) and low air traffic density (SA). Columns 3 and 4 of Table 1 show the linear trends obtained from the time series of the seasonal residuals of ϵN over NA and over SA, separately for all scene types, for scene type 2 and for scene type 1. Table 1 shows that the trend difference between potential contrails and all situations is always negative or negligible over SA as well as over NA. However the values are always slightly more positive over NA than over SA. The comparison between SA and NA becomes more conclusive by considering the difference in trends between potential contrails and cirrus, because it is always positive over NA whereas it is always negative over SA. The comparison between NA and SA indicates that an analysis of trends in general, without considering situations favorable for contrail formation, makes it difficult to link a trend to air traffic, as the increase of cirrus over SA is larger than over NA. The analysis also shows that one has to focus on a region with a very high air traffic density (like NAF or Europe) and on situations favorable for contrail formation in order to extract a significant signal using the TOVS Path-B data.

[13] When such a trend is found, as in the case for Europe and NAF, it then has to be weighted by the frequency of occurrence of situations favorable for contrail formation in order to estimate their overall influence. In general the selected situations occur only about 5%, with a maximum of occurrence in winter over Europe of about 10%. Our estimates of the overall influence of air traffic increase over Europe and the NAF, computed as the difference in trends of ϵN between potential contrail situations and cirrus or all situations of 2.8%–3.5% and 1.6%–4.7% per decade weighted by frequency of potential contrail occurrence of

Table 1. Decadal Increase in ϵN Over Different Regions, Separately for All Situations (Clear Sky and Thin Cirrus), for Situations Favorable for Contrail Formation (pot. contrails) and for Cirrus^a

$\Delta \epsilon N / 10 \text{ yr}$ (%)	Europe	NAF	NA	SA
all 1987–1995	0.2	0.8	2.5	3.3
pot. contrails 1987–1995	3.7	5.5	2.3	2.4
cirrus 1987–1995	0.9	3.9	1.7	4.0
($\Delta \epsilon N / 10 \text{ yr}$) differences (%)	Europe	NAF	NA	SA
pc-all/pc-ci 1987–1995	3.5/2.8	4.7/1.6	−0.2/0.6	−0.9/−1.6
pc-all/pc-ci 1987–1994	3.4/2.8	3.8/0.9	−1.0/0.5	−1.2/−1.5
pc-all/pc-ci 1988–1995	3.3/4.5	6.2/3.3	0.0/1.1	−1.3/−2.3
pc-all/pc-ci i8w4	3.1/2.3	4.4/2.1	−0.6/0.6	−0.8/−1.4
pc-all/pc-ci i8w5	4.6/3.8	4.1/1.8	1.0/2.2	−0.1/−0.7

^aAs indicator for an increase due to air traffic are also shown the differences in trends between potential contrails and all situations (pc-all) and between potential contrails and cirrus (pc-ci), for three time periods and for different scene type thresholds.

7% and 5%, correspond to about 0.20%–0.25% and 0.08%–0.24% decadal cirrus increase respectively.

3. Conclusions

[14] The analysis of TOVS Path-B satellite data provided yet another link of cirrus increase to air traffic by comparing cirrus trends for meteorological situations favorable for contrail formation to those in general and those favorable for cirrus. Whereas in general no trend is observable over the eight-year data period over Europe and the NAF, the difference in trends of εN between potential contrail and all situations (clear sky and thin cirrus) mounts to 3.5% and 4.7% per decade. Comparing trends between potential contrail and cirrus situations leads to an indicator of change in εN due to air traffic of 2.8% and 1.6%, respectively. The average εN in these regions is about 13% to 17%. Contrasting larger regions having high air traffic (NA) and low air traffic (SA), without considering situations favorable for contrail formation, indicates that it is difficult to link a trend to air traffic, as the increase of cirrus over SA is larger than over NA. The analysis also shows that one has to focus on a region with a very high air traffic density (like NAF or Europe) and a comparison between situations favorable for contrail formation and all situations or those of cirrus in order to extract a significant signal. These findings extend studies of line-shaped contrails over Europe [Bakan et al., 1994; Meyer et al., 2002], with a coverage of about 0.5%, and provides objective support for trends of 1% to 3% deduced from other observations over Europe, NAF and United States [e.g., Boucher, 1999; Zerefos et al., 2003; Stordal et al., 2004; Minnis et al., 2004]. Those analyses studied cirrus trends in general, after having taken care of correlations related to different natural phenomena such as the North Atlantic Oscillation, tropopause variability and trends in humidity. Residual trends were then linked to air traffic increase.

[15] Situations favorable for contrail formation have been estimated to occur about 7% over Europe and 5% over the NAF which is slightly lower than from other observations, probably because of the coarse vertical resolution of the TOVS Path-B data. Hence, the overall effect linked to air traffic even over these regions is quite small: lower limits for the increase of effective high cloud amount are 0.20%–0.25% and 0.08%–0.24% per decade over Europe and the NAF, respectively. In conclusion, we find a weak but significant decadal increase of cirrus in regions where air traffic is very high for situations in which the air is cold and humid enough to let contrails form. To assess the radiative effects of such additional cloudiness, the optical thickness

and microphysical cirrus properties have to be taken into account.

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