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Abstract

This work examines changes in cirrus cloud cover in possible association with aviation activities at congested air corridors. The analysis is based on the latest version of the International Satellite Cloud Climatology Project D2 data set and covers the period 1984- 1998. Over areas with heavy air traffic, the effect of large-scale modes of natural climate variability such as ENSO, QBO and NAO as well as the possible influence of the tropopause variability, were first removed from the cloud data set in order to calculate long-term changes of observed cirrus cloudiness. The results show increasing trends in cirrus cloud coverage, between 1984 and 1998, over the high air traffic corridors of North America, North Atlantic and Europe, which in the summertime only over the North Atlantic are statistically significant at the 99.5% confidence level (2.6% per decade). In wintertime however, statistically significant changes at the 95% confidence level are found over North America, amounting to +2.1% per decade. Statistically significant increases at the 95% confidence level are also found for the annual mean cirrus cloud coverage over the North Atlantic air corridor (1.2% per decade). Over adjacent locations with lower air traffic, the calculated trends are statistically insignificant and in most cases negative both during winter and summer in regions studied. Moreover, it is shown that the longitudinal distribution of decadal changes in cirrus cloudiness along the latitude belt centered at the North Atlantic air corridor, parallels the spatial distribution of fuel consumption from highflying air traffic, providing an independent test of possible impact of aviation on contrail cirrus formation. Results from this study are compared with other studies and different periods of records and it appears as evidenced in this and in earlier studies that there exists general agreement on the aviation effect on high cloud trends.

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1. Introduction

Cirrus clouds are the most common form of high-level clouds forming in the vicinity of the tropopause. In the tropics, their formation is mainly triggered by deep convection (Jensen et al., 1996); in the northern middle latitudes, they are associated to the existence of large ice supersaturated regions in the upper troposphere (Gierens et al., 2000). Cirrus cloud formation depends strongly on the existence of small particles that provide the surface on which ice crystals nucleate (Jensen and Toon, 1997). Cirrus clouds have alternately two opposite effects; an IR greenhouse effect and a solar albedo effect. Which effect dominates, depends strongly on optical properties. Thin cirrus clouds usually produce a positive radiative forcing (RF) at the top of the atmosphere; thick cirrus clouds may cause cooling (Stephens and Webster, 1983; Fu and Liou, 1993; Fahey and Schumann, 1999).

Contrails are visible line-shaped clouds that form in the wake of aircraft, when the relative humidity in the plume of exhaust gases mixing with ambient air temporarily reaches liquid saturation, so that liquid droplets form on cloud condensation nuclei and soon freeze to ice particles (Schumann, 2002). Parameters determining contrail formation and persistence are analytically described in Schumann (1996). Contrails may evaporate quickly when the ambient air is dry, or persist for hours when the ambient air is substantially supersaturated with respect to ice (Jensen et al., 1998). Ice supersaturated regions in the upper troposphere of the northern middle latitudes are very common (Gierens et al., 1999; Jensen et al., 2001). These regions and the number of aircraft flights in these regions control the area of the Earth covered by persistent contrails (Fahey and Schumann, 1999).

The influence of contrails on the radiation budget depends mainly on their coverage and optical depth (Meyer et al., 2002; Schumann, 2002). Like thin layers of cirrus clouds, contrails usually produce a small heating at the top of the atmosphere. Regional and global estimates of contrail RF can be found in numerous studies (Meerkoetter et al., 1999; Minnis et al., 1999; Marquart and Mayer 2002; Meyer et al., 2002;

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Ponater et al., 2002). IPCC follows Fahey and Schumann (1999) and retains a range of 5 to 60 mW/m^2 for the present day contrail RF, around the best estimate of 20 mW/m^2 (IPCC, 2001).

Contrail occurrence and coverage have been observed using satellite and ground-based observations. The mean coverage of line-shaped contrails is greatest over the USA, over Europe and over the North Atlantic (Fahey and Schumann, 1999). Surface observations of contrail occurrence from 17 bases across the continental USA indicated that contrail occurrence varies substantially with location and season. Most contrails prevailed in winter and least during the summer with a pronounced minimum in September (Minnis et al., 2003). Bakan et al. (1994), using NOAA/AVHRR infrared images, found a mean contrail cover of 0.5% over the eastern Atlantic/western Europe and showed that the highest contrail coverage (>2%) lies along the North Atlantic air routes during the summertime. Sausen et al. (1998) calculated a global contrail cover value of 0.09%, with maximum values exceeding 5% over certain regions in USA. Over the USA and Europe, larger values occurred in winter than in summer. Calculations of the seasonal variability in contrail coverage over the US by Ponater et al. (2002) were found to be in agreement with previous studies (Minnis et al., 1997; Sausen et al., 1998). Over eastern Atlantic/western Europe they simulated a higher peak value in the summer compared to the winter, which was consistent to the results by Bakan et al. (1994) but in contradiction to the findings of Meyer et al. (2002) and of Sausen et al. (1998).

Few studies have examined trends in cirrus cloudiness. Wylie and Menzel (1999), showed evidence of a gradual increase in the occurrence of high clouds in the northern middle latitudes (0.5% yr^{-1}), while the change in the southern middle latitudes was considered insignificant due to the very small cloud coverage. Boucher (1999) calculated seasonal and annual mean global and regional trends in cirrus occurrence over land and ocean for the period 1982–1991. The highest increases in annual mean cirrus occurrence were observed over the main air flight corridors (i.e. 13.3% per decade over the northeastern USA and 7.1% per decade over the North Atlantic air corridor).

These trends were attributed to condensation trail formation by aircraft exhaust gases, excluding the contribution of other possible causes such as the effects of the El Chichon and Mount Pinatubo volcanic aerosols, or long-term changes in relative humidity and climate variations related to the North Atlantic Oscillation. Minnis et al. (2001), calculated trends in high cloud cover over air traffic and non-air traffic regions and found a statistically significant increase in high cloud coverage over areas where air traffic was heaviest relative to other regions, concluding that air traffic could cause an increase in cloud cover. Trends in cirrus-high level clouds over regions with contrail coverage greater than or less than 0.5% were summarized in Fahey and Schumann (1999) (their Table 3-5). Both satellite data and surface observations showed larger increases in cirrus-high level cloudiness in regions where contrails were expected to occur more frequently than in all other areas.

Although satellite and surface-based observations of seasonal and decadal changes in cirrus frequency of occurrence over main air traffic regions suggested a possible relationship between air traffic and cirrus formation, Fahey and Schumann (1999) stressed the difficulty to attribute observed changes in cirrus coverage to aircraft emissions. The aim of the present work is to study changes in cirrus cloud cover over locations near and remote from air corridors and to compare them with earlier results with respect to evidence of effects from aviation.

2. Data sources and methodology

The cloud dataset analyzed in this study is produced by the International Satellite Cloud Climatology Project (ISCCP) (Rossow et al., 1996). The data set contains detailed information on the distribution of cloud radiative properties and their diurnal and seasonal variations, as well as information on the vertical distribution of temperature and humidity in the troposphere. The data are based on observations from the suite of operational geostationary and polar orbiting satellites. Visible radiances are used to retrieve the optical thickness of clouds and infrared radiances to retrieve cloud top temperature

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and pressure. The revised (D2) version of the data set used in this study has a spatial resolution of 280 km (2.5° at the equator) and provides monthly averages of cloud properties and their diurnal variation. For each map grid-box, both the mean properties of the cloud field and the properties of fifteen different cloud types are provided. The cloud types are derived based on radiometric definitions that rely on cloud optical thickness and cloud top pressure. Cirrus clouds are defined as those with optical thickness less than 3.6 and cloud top pressure less than 440 mb.

The air traffic density over the globe is examined using the aviation fuel consumption inventory (civil and military) as determined by the Deutsches Zentrum für Luft- und Raumfahrt (DLR). The method used by DLR to produce this dataset has been described by Schmitt and Brunner (1997) and has been used in national and international work programs, such as the IPCC report, where it was noted that among other global inventories of civil and military aircraft fuel emissions, DLR fuel consumption inventory is suitable for calculating the effects of aircraft emissions on the atmosphere (Henderson and Wickrama, 1999). The emission data are monthly mean values for the year 1992 in kg, distributed over the world's airspace by altitude, latitude and longitude. Data for every set of altitude, latitude and longitude are reported in an equal-area map grid with a 2.8° latitude $\times 2.8°$ longitude horizontal resolution and 1 km vertical resolution. There are totally 17 altitude levels. The major air traffic corridors are found in the northern middle latitudes at cruising altitudes between 10–11 km.

After Mount Pinatubo eruption in June 1991, ISCCP detected a significant decrease of thin cirrus clouds, particularly over the ocean, accompanied by a comparable increase of altocumulus and cumulus clouds. In contrast, results from the split-window observations and 3I data, did not show any significant change in thin cirrus associated with the volcanic eruption over both ocean and land (Luo et al., 2002). The apparent large decrease of thin cirrus in the ISCCP data set was reported as a satellite artifact due to the additional visible reflection by volcanic aerosols hanging around in the stratosphere (Rossow and Schiffer, 1999). Because of the contamination of the satellite signal by the Mt. Pinatubo eruption, cirrus cloud data taken between January 1991

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and June 1993 were not used in our analysis.

The effect of natural phenomena on cirrus clouds, such as ENSO, QBO and the NAO, is examined in detail in Zerefos et al. (2003). It was found that over certain latitudinal belts, a significant part of the cirrus cloud variability could be attributed to ENSO and NAO fluctuations. While ENSO and QBO effects were found to be insignificant over the northern middle latitudes, the North Atlantic Oscillation perturbs directly cirrus cloudiness over the North Atlantic Ocean and Europe, since it affects the frequency and the intensity of baroclinic storms from which cirrus clouds mainly form in these regions (Tselioudis and Jakob, 2002). Therefore, it was necessary to isolate and remove from the data set the effect of these large-scale modes of natural climate variability, in order to search for other possible impacts on cirrus cloud long-term changes (i.e. from aviation). These effects were removed by applying cross-correlation function analysis at each individual grid box. Cirrus cloud changes could also be related to dynamical variability seen for example trends in tropopause temperatures. The possible effect of the tropopause variability on cirrus cloud changes over examined regions with high and lower air traffic was also removed from the data set based on regression analysis, accordingly. This tropopause temperature was taken from the independently produced NCEP/NCAR reanalysis data set for the same period.

The ISCCP cloud properties have been tested extensively both against other satellite cloud retrievals and against surface cloud observations (Rossow and Schiffer, 1999). In the latest (D-series) version of the ISCCP dataset, changes in the retrieval thresholds and the inclusion of an ice microphysics model for retrieval of optical thicknesses and top temperatures of cold clouds, have improved the agreement of cirrus cloud amounts with both surface observations (Rossow and Schiffer, 1999) and an analysis of High-Resolution Infrared Sounder (HIRS) data (Stubenrauch et al., 1999). A small underestimate of ISCCP cirrus cloud amounts (~5% at middle northern latitudes) compared to the HIRS results is caused by missed detection of very thin clouds (Stubenrauch et al., 1999; Rossow and Schiffer, 1999). The cloud analysis in this study is done in a way that attempts to minimize potential systematic errors in the cirrus trends. Adjacent regions observed by the same satellite are chosen for comparison, in order to avoid trends introduced by satellite calibration and to minimize differences due to illumination geometry. This provides confidence that, even with the uncertainty in retrieving cirrus cloud properties from satellite observations, the trends derived in the study reflect a real change in the amount of the cloud type defined as cirrus by the ISCCP retrieval process. These trends have been evaluated as to their statistical significance by applying the t-test of each trend against the null hypothesis of no-trend for the appropriate number of degrees of freedom (Wonnacot and Wonnacot, 1982).

3. Results and discussion

To examine the spatial distribution of fuel consumption from highflying aircrafts, Fig. 1 shows the geographical distribution of total fuel burned (in kg) at 10–11 km height as calculated in four months (December, January, February, March) of 1992. From Fig. 1 it appears that the most congested air traffic areas are found over the northern middle latitude belt between 35° N–55° N (US, Europe and the North Atlantic air flight corridor). The seasonal dependence in aviation fuel consumption is quite large particularly in the North Atlantic air corridor with a maximum in the boreal summer and a minimum during winter (Henderson and Wickrama, 1999). Over higher and lower latitudes of the northern hemisphere, for example 5° N–25° N, fuel consumption is much lower.

Table 1 summarizes decadal long-term changes in cirrus cloudiness calculated for 6 regions of the northern hemisphere that correspond to different air traffic load. Two adjacent regions over North America, one with low air traffic and one with high air traffic, and similarly over the North Atlantic Ocean and over Europe, have been studied. Care was taken to select regions experiencing similar climatological characteristics since contrail occurrence is strongly governed by meteorological conditions (Minnis et al., 2003) and to avoid interference from different satellites between adjacent regions. By this way, calculated trends between adjacent locations do not include substantial differences in natural climate variability, such as for example different trends in annual mean

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upper tropospheric humidity, which could strongly affect contrail properties (Minnis et al., 2003) or trends introduced by satellite calibrations. Therefore, a contrail cirrus signal at these regions would be easier to detect. These regions are shown in Fig. 1 and are marked by black boxes. The long-term changes were estimated as the increase or decrease of cirrus cloud cover (%) during the 15 yr period of this study inferred from a linear fit to the data. The analysis was performed for each month and for each season of the year, as well as for different locations over the North Atlantic Ocean, accordingly. Time series of cirrus cloudiness for the summer is plotted in Fig. 2.

As can be seen from Table 1, long-term changes in cirrus cloud cover over examined regions with high air traffic, are higher in the summertime compared to the wintertime, except over North America, where higher increases are found during the wintertime. The largest increase is found along the North Atlantic air flight corridor in the summer, about 2.6% per decade and is statistically significant at the 99.5% confidence level. This is not a result of trends in tropopause temperatures because the statistically significant trend over the North Atlantic air corridor still remains significant after removing the tropopause variability together with all other natural perturbations. The corresponding trend over an adjacent lower air traffic location in the North Atlantic, which is viewed by the same satellite, is smaller (+1.2% per decade) and is not statistically significant. This is consistent with Boucher (1999) who found that cirrus frequency of occurrence increased significantly (97% confidence level) over the North Atlantic air corridor from 1982 to 1991 compared to the rest of the North Atlantic Ocean.

Part of the difference between the high and the lower air traffic regional long-term changes over the North Atlantic could be related to the fact that contrail coverage is maximum along the North Atlantic air flying routes during the summertime (Bakan et al., 1994), indicating possible impact from aviation on cirrus cloud formation. During winter, the calculated trend in cirrus cloud cover over the North Atlantic air flight corridor is not statistically significant. This is possibly due to the higher inter-annual natural variability in wintertime atmospheric synoptic systems, which may mask the impact of highflying air traffic on cirrus clouds.

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Increasing trends in cirrus cloudiness are also found over the heavy air traffic locations of North America and Europe in the summertime, which amount to about 0.5% and 1.3% per decade, respectively. Nevertheless, these trends are not statistically significant due to large variance in cirrus cloud cover over these areas (Figs. 2a and 2c). Over Europe, the calculated trend in cirrus cloud coverage during winter is 0.0% per decade. Over North America, the change in cirrus cloud cover is higher during winter (+2.1% per decade), when there is the highest contrail frequency of occurrence (Minnis et al., 1997; Sausen et al., 1998; Ponater et al., 2002; Minnis et al., 2003), compared to the summer and is statistically significant at the 95% confidence level. Lastly, the changes in annual mean cirrus cloud coverage over the high air traffic corridors of North America, North Atlantic and Europe, amount to +1.3%, +1.2% and +0.3% per decade, respectively, and are statistically significant only over the North Atlantic air corridor (95% confidence level). These trends are in agreement with the results given by Minnis et al. (2001), who calculated positive trends in mean annual high cloud cover over USA, Europe and the North Atlantic from surface-based and satellite observations (HIRS and ISCCP). Over the adjacent lower air traffic selected locations, the corresponding trends amount to −0.2%, +0.3% and −0.8% per decade, respectively and are not statistically significant.

Over regions where the main air routes exist, it was expected that a change in cirrus cloudiness within a decade could be related to air traffic density, concerning the large increase of transatlantic flights since the 80's and the transformation of persistent contrails to thin cirrus clouds. To investigate this assumption, decadal changes in cirrus cloud cover were computed after removing the effects of ENSO, QBO and NAO perturbations on cirrus clouds as well as the possible effect of the tropopause variability. Figure 3 shows the longitudinal distribution of the percentage change of cirrus cloud cover from 1984–1986 to 1994–1996 and of the total fuel consumption in 1992 during the wintertime (December, January, February, March). For comparison we present two figures: Fig. 3a shows cirrus cover change over high air traffic locations (35° N–55° N) and Fig. 3b shows cirrus cover change over low air traffic locations (5° N–25° N).

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From Fig. 3a it appears that the longitudinal distribution of cirrus cloudiness along the latitude belt centered at the North Atlantic air corridor, parallels the fuel consumption from highflying air traffic. The spatial distribution of the two variables has a significant positive correlation coefficient (R= +0.77). The correlation suggests that the apparent increase of thin cirrus clouds, about 20% over North America and about 9% over Europe, could be related to contrail cloudiness formed by aviation activities. Over East Asia however, the existence of complex circulation conditions in the area may mask this issue. This analysis was also performed for the summer months, where it was found that the largest increases in cirrus cloudiness are found over Europe (~12%) and the North Atlantic air corridor (~23%). At lower latitudes (5° N–25° N), the air traffic density is much lower and the correlation is insignificant (Fig. 3b).

4. Comparison with previous studies

In order to validate the accuracy of our computed trend values we have reproduced and compared our results with previous studies examining long-term changes in high level cloudiness and their relationship to contrails. Two tables are shown: In Table 2, trends in cirrus cloud cover from this study are compared to corresponding trends in high level cloudiness over large air traffic and non-air traffic areas as defined by Minnis et al. (2001) and in Table 3, trends in cirrus cloud cover from this study are compared to trends in cirrus-high level cloudiness over regions categorized as having a mean value of contrail coverage less than or greater than 0.5% as given by Fahey and Schumann (1999).

Column A in Table 2, shows trends in annual mean high cloud coverage (cirrus (Ci) + cirrostratus (Cs) + deep convective (Cb)) from ISCCP 1984–1994 satellite observations as given by Minnis et al. (2001) and column B shows trends in annual mean cirrus cloud coverage (Ci) as calculated in this study. The trends were calculated based on monthly mean values, not annual, for the period July 1983–May 1991 and July 1993– August 1994, so the monthly trends were multiplied by 12 (Minnis, 2003, private communication). Column C shows more recent estimates of trends in annual mean Ci+Cs cloud coverage from ISCCP 1984–1996 satellite observations by Minnis (2003, private communication) and column D shows trends in annual mean cirrus cloud cover for the period 1984–1998 as calculated in this study. In order to be consistent with Minnis et al. (2001), trends in column D were calculated based on monthly mean values, so the monthly trends were multiplied by 12. This table provides a means for detecting and evaluating a trend movement in cirrus-high cloud coverage between successive time periods within the years 1984 and 1998.

As can be seen from Table 2, the calculated trend values from this study show consistent similarities to the corresponding values of Minnis et al. (2001) although some values are slightly different. In any case, any differences should be mainly attributed to the different data sets used in the two studies (high cloud data set in Minnis et al. (2001) and cirrus cloud dataset in this study). Analytically, for the period 1984–1994, our trend calculations over land air traffic regions are the following: over USA, we find a higher increase in cirrus cloud cover (5.8% per decade) compared to the result given by Minnis et al. (2001), which is statistically significant at the 99% confidence level. Over Western Europe (W. EUR), the trend in cirrus cloud cover of 3.0% per decade is statistically significant at the 99% confidence level and is slightly smaller than the value given by Minnis et al. (2001) (3.9% per decade). Over Western Asia (WA), the trend we calculate (0.7% per decade) is not statistically significant. Over the remaining land non-air traffic areas (NATR), we find a similar to Minnis et al. (2001) increasing trend in cirrus cloud cover by 1.4% per decade, which is statistically significant at the 99% confidence level. However, this trend includes all land regions (the ATR data were not removed from the result) (Minnis, 2003, private communication) and therefore it could be affected by contrail signals from land ATR regions. To investigate this assumption, we excluded land ATR regions from land NATR regions and we calculated a smaller trend, which was statistically insignificant. Over ocean air traffic regions, our calculated trend values are similar to those given by Minnis et al. (2001) and are statistically significant at the 99% confidence level. Over ocean non-air traffic regions, the trend we calculate is statistically significant at the 95% confidence level but as discussed previously, when excluding ocean ATR from ocean NATR regions, the corresponding trend is statistically insignificant.

More recent estimates of trends in annual mean Ci+Cs cloud cover by Minnis (private communication, 2003) for the period 1984–1996 (column C), show a general decrease in cloud cover relative to the period 1984–1994, over all land and ocean ATR and NATR areas. Similar trends in cirrus cloud cover are also observed during the period 1984–1998 (column D). Over USA, W. EUR and NA these trends amount to about +1.3%, +1.7% and +1.0% per decade, respectively and are statistically significant at the 99% confidence level. However, when using annual mean values to calculate trends instead of monthly mean values, the corresponding trend values are less statistically significant.

Table 3 shows the comparison between trends in cirrus-high cloud amounts as given by Fahey and Schumann (1999) and trends in cirrus cloud amount as calculated from this study. From Table 3 it appears that in spite of the differences, trends results from this study and their statistical significance show consistent similarities to the results given by Fahey and Schumann (1999). Analytically, for the period 1984–1990, the difference between trends in cirrus cloud cover over land contrail and non-contrail regions is 5.5% per decade and is statistically significant at the 99% confidence level. Over ocean, this trend difference is not statistically significant. Over both land and ocean (global ISCCP) the corresponding trend difference of 3.9% per decade is statistically significant at the 99% confidence level. During the period 1984–1998, there is a general decrease in cirrus cloud cover over all contrail and non-contrails regions. However, over regions with contrail coverage greater than 0.5% the trend values are positive while over regions with contrail coverage less than 0.5% the trend values are negative. The differential increases in cirrus cloud coverage over contrail regions relative to remaining non-contrail regions are statistically significant at the 99% confidence level for the land, ocean and global ISCCP 1984–1998 data.

5. Conclusions

This study examined changes in cirrus cloudiness over locations where contrail formation by aviation was expected to perturb the distribution of cirrus clouds and their long-term variability. Long-term changes in cirrus cloud cover were calculated for six regions of the northern middle latitudes categorized as having high and low air traffic for 1992 aircraft operations. Two adjacent regions over North America, one with low air traffic and one with high air traffic, and similarly over the North Atlantic Ocean and over Europe, have been studied. Care was taken to select regions experiencing similar climatological characteristics since contrail occurrence is strongly governed by meteorological conditions (Minnis et al., 2003) and to avoid interference from different satellites between adjacent regions. The main results of the present work can be summarized as follows:

Cirrus cloud cover increased significantly (99.5% confidence level), between 1984 and 1998, over the high air traffic corridors of the North Atlantic, amounting to about 2.6% per decade during the summertime. This was not a result of trends in tropopause temperatures because the statistically significant trend over the North Atlantic air corridor still remained significant after removing the tropopause variability together with all other natural perturbations. In wintertime however, statistically significant changes at the 95% confidence level were found over North America, amounting to about +2.1% per decade. Statistically significant increases at the 95% confidence level were also found for the annual mean cirrus cloud coverage over the North Atlantic air corridor (1.2% per decade). Over adjacent locations with lower air traffic the calculated trends in cirrus cloud cover were statistically insignificant and in most cases negative both during winter and summer in regions studied.

Moreover, it was found that the longitudinal distribution of decadal changes in cirrus cloudiness along the latitude belt centered at the North Atlantic air corridor parallels the spatial distribution of fuel consumption from highflying air traffic. The two variables were strongly correlated during the wintertime (R= +0.77), providing an independent

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test of possible impact of aviation on contrail cirrus formation. At latitudes with lower air traffic density, the observed changes in cirrus cloud coverage were not related to the spatial distribution of fuel consumption.

Trends in cirrus cloud coverage from this study were compared with other studies and different period of records (Fahey and Schumann, 1999; Minnis et al., 2001). As evidenced in this and in earlier studies in spite of the differences, there is a general agreement on the aviation effect on high cloud trends. However, the period under study is short for trend analyses and the results should be treated with caution as far as any aviation effects on cirrus cloud cover are considered. Other parameters that could possibly control contrail cover in these regions such as ambient air humidity, temperature and wind shear (Schumann, 2000) have not been studied as to their inter-annual variability and its relationship with cirrus cloud cover.

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Table 1. Seasonal and annual trends in cirrus cloud cover (% per decade) from ISCCP satellite cirrus cloud data set (1984–1998) for regions categorized as having high and low air traffic for 1992 aircraft operations. Values in brackets refer to statistical significance of each trend. Dashes in brackets indicate a confidence level less than 95%

Trend (%/dec)	Winter (DJFM)		Summer (JJAS)		Annual	
	HATR	LATR	HATR	LATR	HATR	LATR
North America	+2.1 (95%)	+0.9 (–)	+0.5 (–)	−1.4 (95%)	+1.3 (–)	−0.2 (–)
North Atlantic	−0.4 (–)	−0.7 (–)	+2.6 (99.5%)	+1.2 (–)	+1.2 (95%)	+0.3 (–)
Europe	0.0 (–)	−1.3 (–)	+1.3 (–)	−0.2 (–)	+0.3 (–)	−0.8 (–)

HATR: high air traffic region
LATR: adjacent lower air traffic region

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Table 2. Comparison between trends (% per decade) in annual mean high cloud cover as given by Minnis et al. (2001) and trends (% per decade) in annual mean cirrus cloud cover calculated over land and over ocean air traffic and non-air-traffic regions. Underlined are statistically significant at better than 95% confidence level

	Column A Minnis et al. (2001)	Column B This study	Column C Minnis (2003)*	Column D This study
Land	ISCCP (1984–1994) Ci+Cs+Cb	ISCCP (1984–1994) Ci	ISCCP (1984–1996) Ci+Cs	ISCCP (1984–1998) Ci
WA	+2.7	+0.7	−2.1	−3.1
W. EUR	+3.9	+3.0	+0.9	+1.3
USA	+4.9	+5.8	+2.3	+1.7
NATR	+1.7	+1.4	−0.6	−0.5
Ocean				
NA	+1.0	+2.0	+0.2	+1.0
NP	+1.7	+1.8	−0.4	−0.8
NATR	+1.4	+1.4	+0.1	−0.1

*Private communication (2003)

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Table 3. Comparison between trends (% per decade) in cirrus-high cloud amounts as given by Fahey and Schumann (1999) and trends (% per decade) in cirrus cloud amount calculated for regions categorized as having a mean value of contrail coverage less than or greater than 0.5%. Italics are trends in cirrus cloud amount for the period 1984–1998. Statistical significance refers to level of confidence in difference between trends for the two regions. Dashes indicate a confidence level less than 95%

	Period	Trend (% per decade) in regions with computed contrail cover < 0.5%	> 0.5%	Trend difference (% per decade)	Statistical Significance of difference (%)
Land from ISCCP Fahey and Schumann (1999) (Cirrus-high clouds)	1984–1990	1.2	4.7	3.5	95
Land from ISCCP This study (Cirrus clouds)	1984–1990	−0.1	5.4	5.5	99
Land from ISCCP This study (Cirrus clouds)	1984–1998	−1.1	1.3	2.4	99
Ocean from ISCCP Fahey and Schumann (1999) (Cirrus-high clouds)	1984–1990	4.3	5.9	1.6	–
Ocean from ISCCP This study (Cirrus clouds)	1984–1990	1.1	2.3	1.2	–

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Table 3. Continued

	Period	Trend (% per decade) in regions with computed contrail cover < 0.5%	> 0.5%	Trend difference (% per decade)	Statistical Significance of difference (%)
Ocean from ISCCP This study (Cirrus clouds)	1984–1998	−0.5	1.0	1.5	99
Global ISCCP Fahey and Schumann (1999) (Cirrus-high clouds)	1984–1990	3.2	5.2	1.9	99
Global ISCCP This study (Cirrus clouds)	1984–1990	0.5	4.4	3.9	99
Global ISCCP This study (Cirrus clouds)	1984–1998	−0.7	1.2	1.9	99

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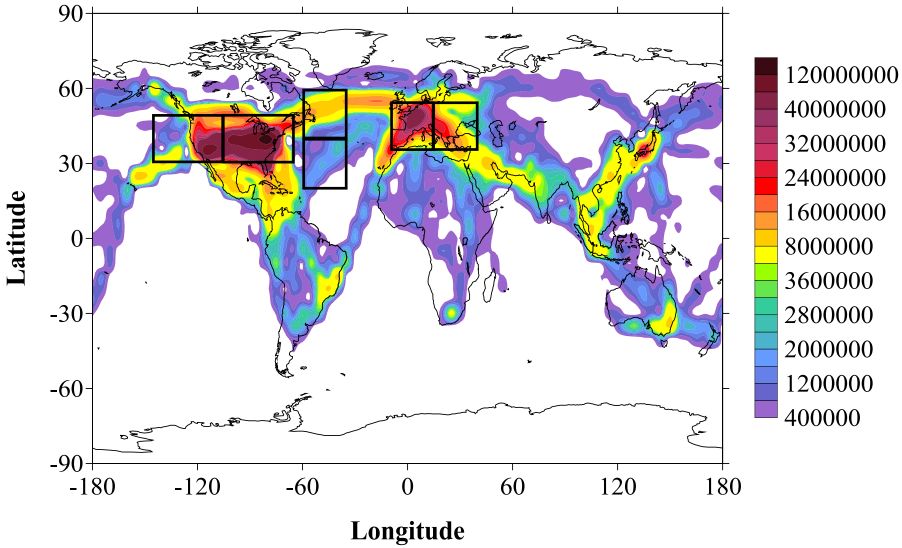

Fig. 1. Total fuel consumption from aviation (in kg) at 10–11 km height during the wintertime (DJFM). Rectangles correspond to regions with high and low air traffic in which cirrus cloud cover averages have been studied. North America: high air traffic region (30° N–50° N, 65° W–105° W), adjacent lower air traffic region (30° N–50° N, 105° W–145° W). North Atlantic: high air traffic region (40° N–60° N, 35° W–60° W), adjacent lower air traffic region (20° N–40° N, 35° W–60° W). Europe: high air traffic region (35° N–55° N, 10° W–15° E), adjacent lower air traffic region (35° N–55° N, 15° E–40° E).

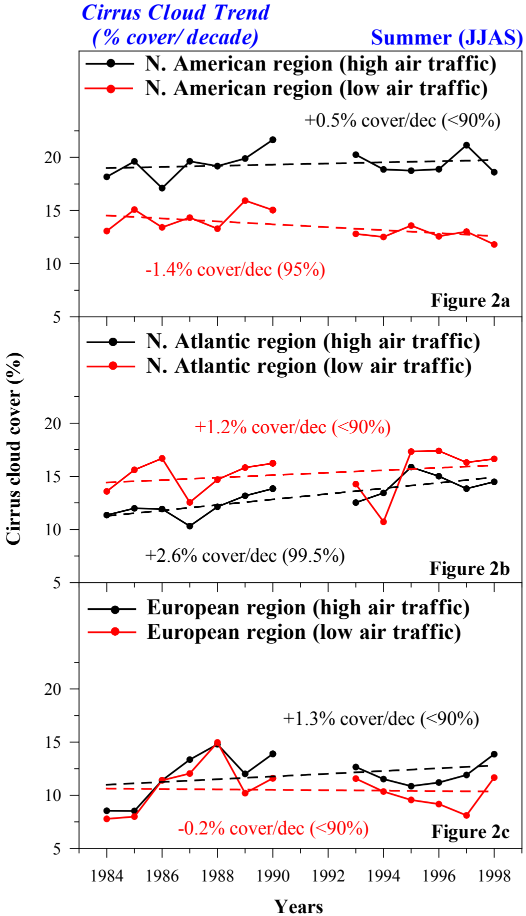

Fig. 2. **(a)** Trends in cirrus cloud cover (% per decade) during the summertime (June–July–August–September) at selected regions over North America with high and lower air traffic. **(b)** Same as (a) but for the North Atlantic. **(c)** Same as (a) but for Europe.

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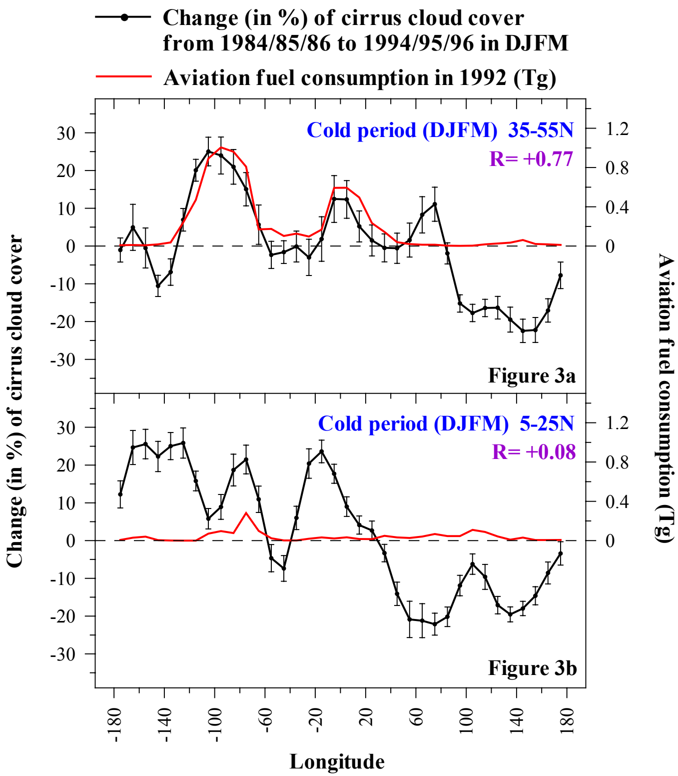

Fig. 3. **(a)** Longitudinal distribution of the percentage changes of cirrus cloud cover and their standard errors (black line) from 1984/1985/1986 to 1994/1995/1996 and of the total fuel consumption (red line) in 1992 during the wintertime (DJFM), over heavy air traffic locations (35° N–55° N). **(b)** Same as (a) but for low air traffic locations (5° N–25° N). Values on the abscissa correspond to 36 equal regions of 10° longitude, from west to east, on which cirrus cloud data have been averaged for the two latitudinal belts. R is the correlation coefficient between the two lines.

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