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Contrail frequency over Europe from NOAA-satellite images

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Abstract. Contrail cloudiness over Europe and the eastern part of the North Atlantic Ocean was analyzed for the two periods September 1979–December 1981 and September 1989–August 1992 by visual inspection of quicklook photographic prints of NOAA/AVHRR infrared images. The averaged contrail cover exhibits maximum values along the transatlantic flight corridor around 50°N (of almost 2%) and over western Europe resulting in 0.5% contrail cloudiness on average. A strong yearly cycle appears with a maximum (<2%) in spring and summer over the Atlantic and a smaller maximum (<1%) in winter over southwestern Europe. Comparing the two time periods, which are separated by one decade, shows there is a significant decrease in contrail cloudiness over western Europe and a significant increase over the North Atlantic between March and July. Contrail cloud cover during daytime is about twice as high as during nighttime. Contrails are found preferentially in larger fields of 1000 km diameter which usually last for more than a day. Causes, possible errors and consequences are discussed.

1 Introduction

The worldwide demand for air transportation has grown considerably and is expected to double from 1988 to 2000 (Nüßer and Schmidt, 1990; Reichow, 1990). During the last decade increasing concern about the possible long-term impact of man-made activities on the global atmosphere has also led to a growing interest in the effects of global air traffic on climate. These effects are potentially important, as air traffic is the dominant source for pollution in the upper troposphere/lower stratosphere.

Contrails are a manifestation of high-flying subsonic air traffic. They mostly appear at environmental temperatures below about −45 °C (Applemann, 1953) in the upper troposphere. Their residence time depends strongly on ambient relative humidity as well as on the amount of mixing with the environment (Schumann, 1993). Contrails, as man-made ice clouds, can trigger additional ice clouds (Wendling and Schumann, 1990).

It is known that thin natural cirrus clouds in the upper troposphere can contribute to a warming of the atmosphere by increasing the greenhouse effect (Liou, 1986; Liou *et al.* 1990). The climatic impact of contrails and of cirrus clouds that develop from contrails is due to their optical characteristics and to their areal coverage. However, there is insufficient knowledge today about the optical properties of contrails and their differences to natural cirrus clouds to allow reliable estimates of their influence on climate (Betancor and Graßl, 1993). The additional cloud cover due to high clouds or contrails was analysed in a few studies (Chagnon, 1981; Carleton and Lamb, 1988; Liou *et al.*, 1990; Wendling and Schumann, 1990; Roll, 1990). But none documented jet contrail occurrence on a large spatial scale for periods spanning a decade, as would be necessary for a rigorous evaluation of the contrail-cirrus climate relationship (Carleton and Lamb, 1988).

This paper reports an effort to derive a regional contrail cloud climatology. The regional and time-dependent variability of contrail cloud cover was analysed over Europe and the eastern part of the Atlantic Ocean poleward of 40°N, a region where most air traffic emissions take place (Kavanaugh, 1988). To assess long-term changes the analysis covers two periods of a few years' duration which are separated by one decade.

2 Data sources and processing

Satellite images are ideal for studying cloud occurrence because of their regular availability for large areas. Especially valuable for contrail studies are the data transmitted from the Advanced Very High Resolution Radiometer (AVHRR) onboard the NOAA-series of polar orbiting meteorological satellites. On the one hand this is due to their 1.1 km spatial resolution at the subsatellite point, which allows the detection of (older) contrails covering larger

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areas. On the other hand the wide swath of about 2000 km and the long visibility above a receiving station (resulting in about 4000 km length of the recorded subsatellite path) provides for the analysis of large areas within one image.

For the present study it was decided to analyse photographic image prints instead of original digital data. This was done in view of the considerable difficulties for image processing to automatically detect contrail areas and to distinguish these in a reliable manner from other structured cloud areas (e.g. cirrus fields). Also the immense data volumes (and the related handling, storing and financial effort) necessary to reach a climatologically meaningful time period forced this decision. Therefore, a large number of printed images was visually inspected in a manner that has already proven valuable in other cases (Bakan and Schwarz, 1992).

The NOAA-satellite image archive at the University of Dundee was used for several reasons. This receiving station has been archiving and distributing NOAA/AVHRR data since 1978. The area covered most of continental Europe and the eastern North Atlantic, containing the very busy European and North Atlantic air traffic regions. The scenes are available for inspection as high quality quicklook prints of the IR channel 4 (10.5 μm) and VIS channel 2 (0.8 μm) with constant print quality throughout the years. The reduced spatial resolution of 20 km per mm of the photographic images still permits a good identification of aged contrails. Only the IR image was analysed as this is known to be most valuable for the detection and analysis of jet contrails, since cirrus-level features (cold and bright in the IR) can easily be discriminated from lower-tropospheric and surface phenomena. The use of visible imagery for contrail detection is particularly dangerous over the ocean, where similar-looking features that are related to ships can occur in stratocumulus and stratus decks (Fett, 1979; Carleton and Lamb, 1988). Also, meaningful observations are only available for noon-images, and even then varying solar height with changing image brightness and contrast is disturbing.

The quicklooks enclose the region 30°W–30°E; 35°N–75°N. Due to the satellite orbital period, the satellite field of view is displaced eastward from day to day. After a time period of 8–11 days the subsatellite track which can be received again lies westward from Dundee. Thus only a core region around 0° longitude is displayed daily. Figure 1 shows on how many days (as a percentage)

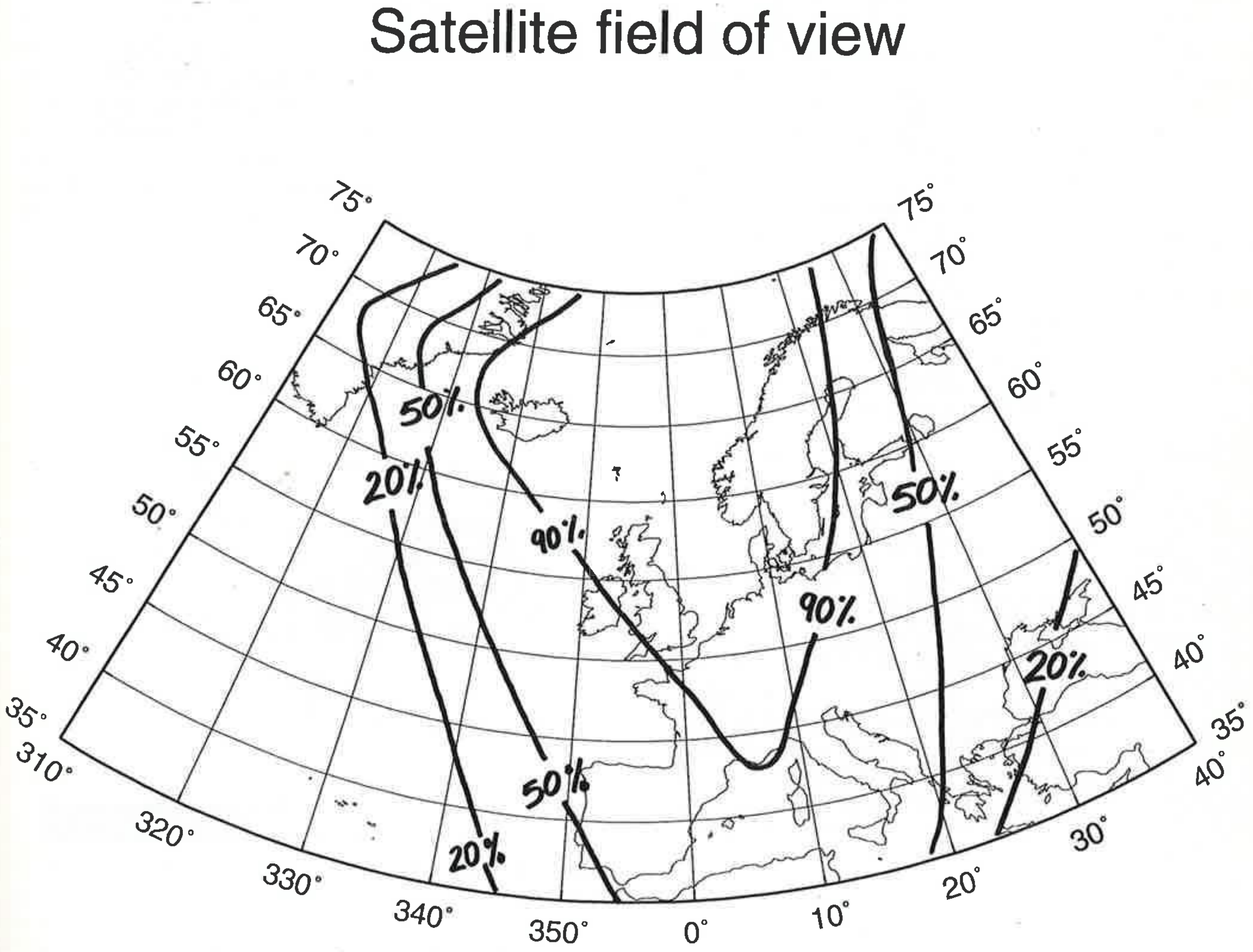

Fig. 1. Visibility frequency of a certain geographic area during the 6 years analysed

of the analysed period of a certain area was covered. Quicklooks of the early afternoon pass for nearly 6 years, separated over two time periods, September 1979–December 1981 and September 1989–August 1992, were processed. For the derivation of the following statistics only those regions that are covered on more than 30% of the days are included. For the assessment of the daily cycle and the life cycle of contrails a small additional dataset of two months (August 1984 and September 1985) with 4 passes per day (close to 400, 800, 1400, 1800 UT) was available for further inspection.

Cold clouds with a pronounced linear structure could either be contrails or cirrus filaments. Experience shows that contrails are frequently observed in groups being spread out over an area of hundred kilometers' diameter. Correct classification is possible, especially when they are not aligned in parallel but intersect one another, due to different plane flight directions. Very old contrails often cannot easily be distinguished from natural cirrus clouds and are therefore not included. A training phase on about 100 images proceded the real evaluation. This was done in order to establish a consistent feeling for what exactly should be labeled a "contrail", or, if grouped together as usual, a "contrail area" (Fig. 2 is an example of analysed NOAA-AVHRR images).

For each contrail region, an image overlay was used to read center geographic coordinates, region size, contrail number, and mean length and width, respectively. These quantities were used to estimate the contrail cloudiness for areas of 10° longitude and 5° latitude. We are well aware of the problems with this procedure – as contrail length and width are only roughly estimated – which could cause some systematic error in the derived cloudiness values. However temporal and spatial variations should be reliably documented by our procedure, and comparisons mentioned in Section 4 show that even the absolute cloudiness values are grossly consistent with such values from other studies.

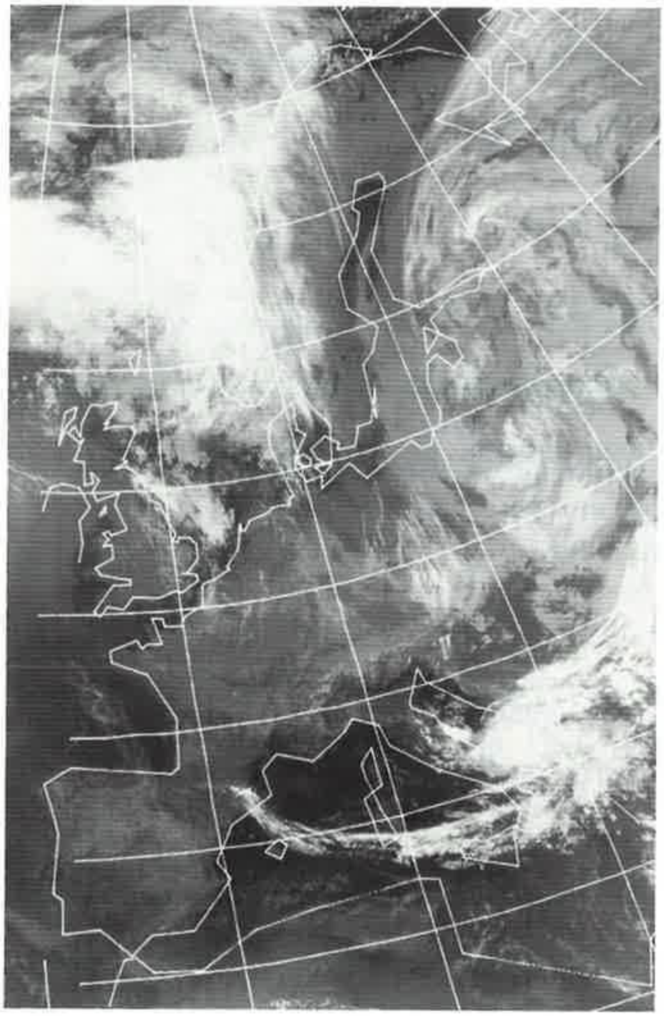

Fig. 2. Example of a photographic quicklook as used in the study. (NOAA-8/AVHRR channel 4 image of 13 October 1985, 7:40 UT as recorded at the University of Dundee). The region enclosed between 55°N–45°N and 10°W–10°E shows many linear cloud formations recognized as contrail areas

3 Results

3.1 Additional cloudiness due to contrails

Figure 3 shows the averaged cloudiness due to contrails for the entire analysis period. Contrails are primarily observed over western Europe and the eastern North Atlantic along the main transatlantic flight route. There, a maximum contrail cloudiness of almost 2% is found, while the average value for the whole scene is 0.5%. A considerable interannual variability of the scene averaged contrail cloudiness is observed, resulting in an rms-value of the same size as the yearly averaged value itself.

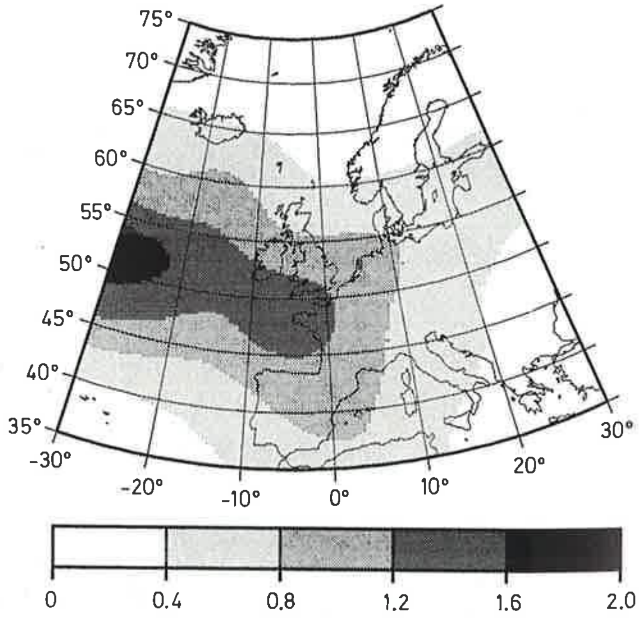

Fig. 3. Yearly averaged contrail cloudiness (in percent) over Europe and the eastern part of the Atlantic Ocean for the total analysis period September 1979–December 1982; September 1989–August 1992

3.2 Seasonal cycle

Figure 4 documents the strong seasonal cycle of contrail cloudiness as derived from the complete dataset available. During spring and summer a maximum around 2% is found over the Atlantic. During autumn and winter, however, contrail cloudiness is smaller, reaching maximum values <1% over western Europe and very moderate values over the Atlantic. Over south-western Europe maximum contrail cloudiness around 1% is found during winter and spring, being considerably smaller in summer and autumn.

Over the Atlantic the northern limit of contrail observations moves northward in summer but remains south of 60°N in winter. This variation is in phase with the seasonal motion of the polar jet stream. On the other hand few contrails are observed south of 40°N (except in winter), which corresponds to reduced air traffic south of the main transatlantic flight route.

3.3 Long-term trends

The long-term trend was studied by a separate evaluation and comparison of the two analysis periods 1979–1981 and 1989–1992. Figure 5 shows considerably less cloudiness over central Europe during the early summer months (March–July) of the second time period than the first. At the same time the average cloudiness over the Atlantic flight corridor increased. Both of these changes turn out to

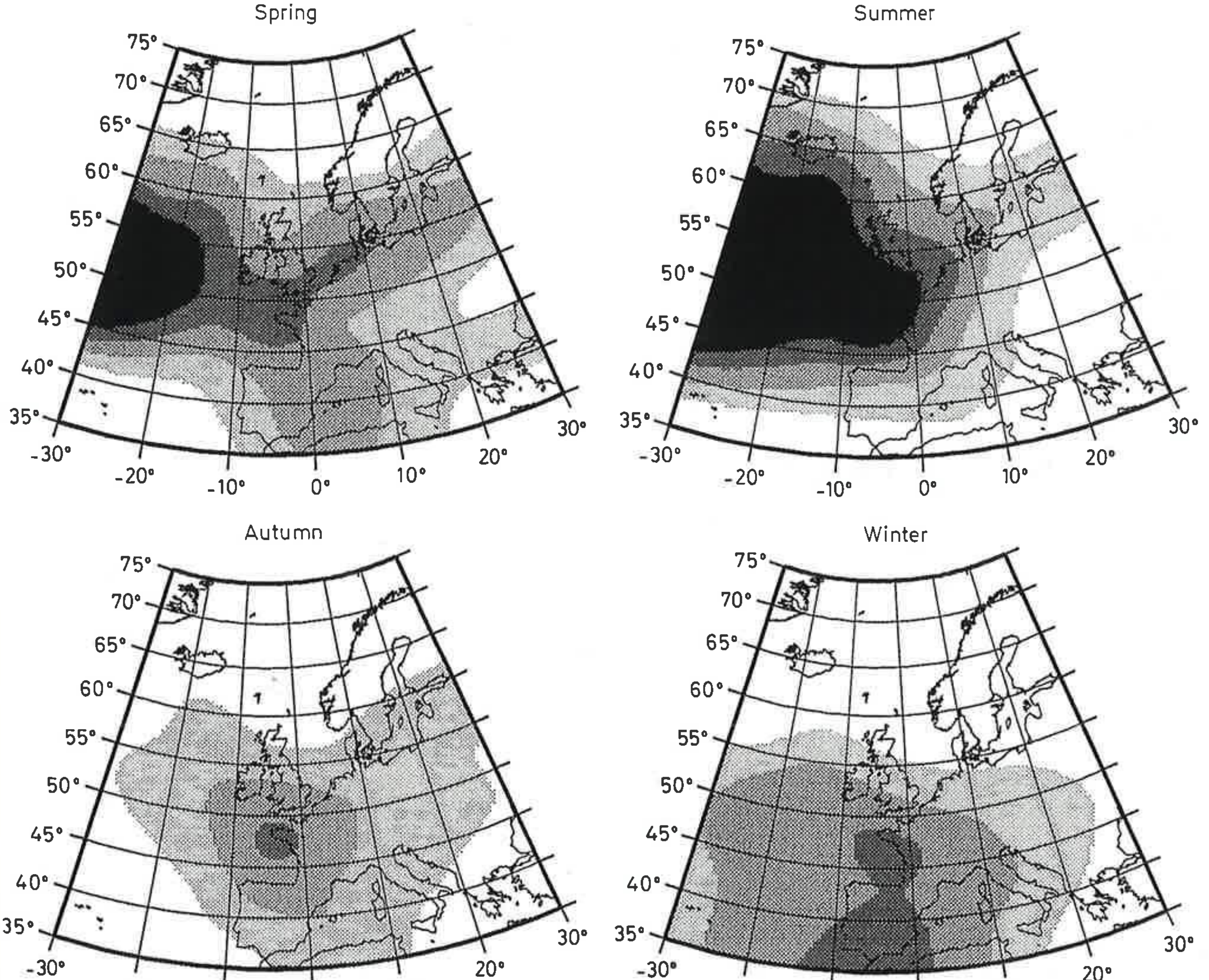

Fig. 4. Monthly averaged contrail cloudiness (in percent) in **a** spring, **b** summer, **c** fall and **d** winter for the same time period as in Fig. 3

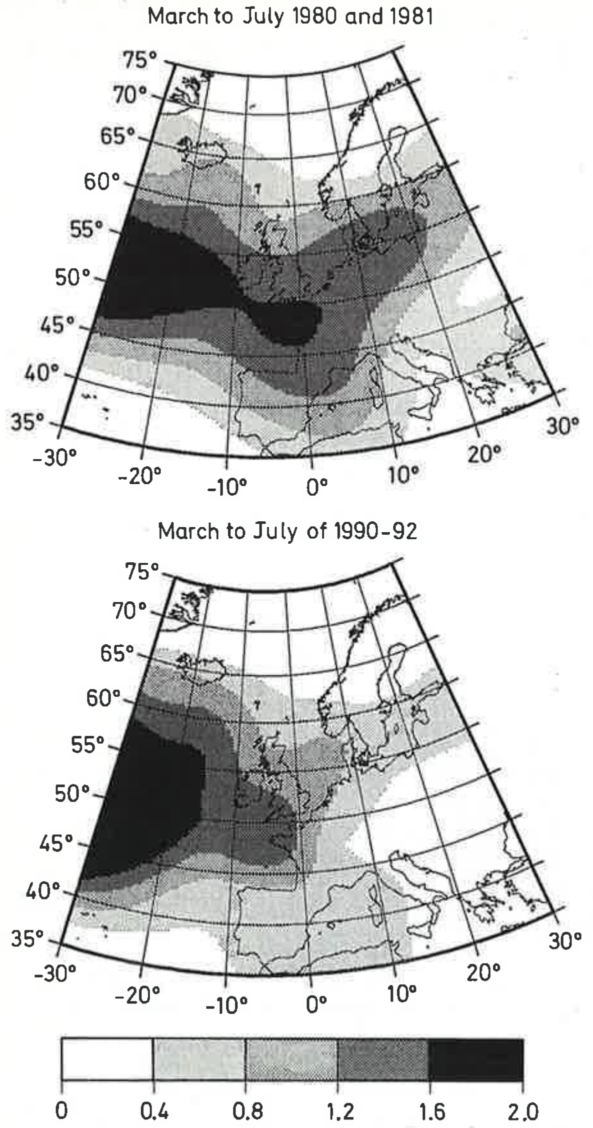

Fig. 5. Contrail cloudiness averaged for the months March to July exhibits significant differences between the two analysis periods (1980–1981 and 1990–1992)

be significant (>95%), when a Student's *t*-test is applied. No significant changes are found for the winter time.

3.4 Daily cycle

As mentioned before, only one image per day could be analysed for the whole period. In order to understand how representative these results were for the daily average values, 2 months (August 1984 and September 1985) were also analysed, for which four IR-Quicklooks per day were available (around 400, 800, 1400, 1800 UT). Figure 6 contains the contrail cloudiness values for these 53 days. First of all, the large scatter gives an idea of the general day-by-day scatter in the evaluated data. Nevertheless, a rather well-expressed daily cycle is observed with a reduction of cloudiness values during nighttime by roughly a factor of 2.

3.5 Contrail life cycle

The 2-month set of images was also used to get a hint of the life cycle of contrails. It is important to note that single contrails are rarely observed – normally larger groups of contrails appear. These contrail regions have a typical diameter of several 100 to 1000 km. While it turned out to be impossible to follow individual contrails from image to image, very often these larger areas could be followed through several scenes until they disappeared. The decision that a certain contrail region in a new scene is identical to a region on the previous one was based on a plausible assumption of the possible motion between two images.

Only 2% of the contrail areas appear in one single scene, which would correspond to a lifetime of less than about 6 h. On the other hand, 62% of the contrail areas could be followed for more than 1 day and 24% for more than 2 days.

4 Discussion

4.1 Accuracy considerations

Although the method of analyzing contrail occurrence in satellite images from quicklook photographs is somewhat subjective, it allowed us to process a large – and thus climatologically meaningful – data set. To our knowledge, there is no proven automated method for contrail detection from digital satellite data available that presently allows results of the same quantity and quality as an image inspection by human eye. As discussed in Section 1 errors due to our non-automated image analysis have been minimized by the combination of a careful training phase with an evaluation phase in which one person analysed all the images without any change in procedure. Using only infrared images allows us to detect contrails preferentially over cloud-free areas and over low-level clouds, but rarely in cases where they occur within or near natural cirrus. Also, due to the effective image pixel size, occasionally observable isolated or young contrails are often ignored, but contrail fields are mostly observed. The most probable error of the applied procedure is a systematic underestimation of contrail cloudiness, while relative variations (in space and time) should be more reliably reproduced.

Although not many comparable evaluations are available, the values for the yearly averaged contrail cloud cover compare favourably with earlier reports. Roll (1990) showed, for a smaller analysis region (50°N–60°N, 20°W–10°E) near the North Atlantic flight route for a period of 1 year, an averaged contrail cloud cover <1%. Schumann and Reinhardt (1991) reported a mean contrail area coverage of 0.4% for a fixed area of 300,000 km^2 between Frankfurt and Genua derived from AVHRR digital data for 142 days between October 1989 and September 1990. Observed seasonal and daily variations of contrail occurrence are similar to those reported by Roll (1990), who also found the maximum values in summer and in the early afternoon.

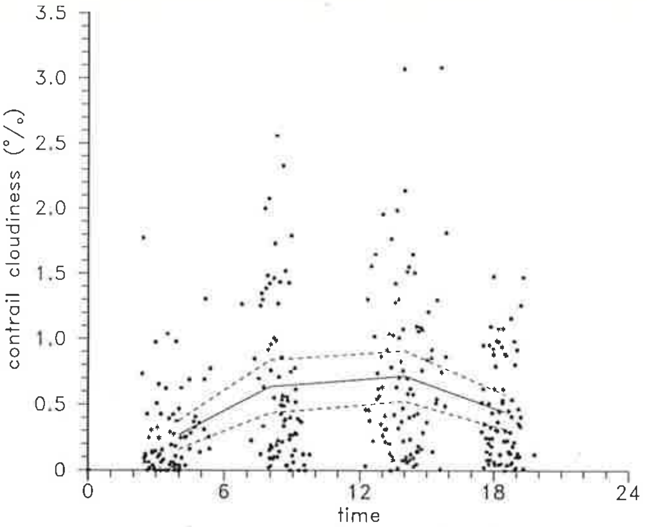

Fig. 6. Daily cycle of contrail cloudiness over Europe and the eastern part of the Atlantic Ocean for August 1984 and September 1985. *Solid line* shows the mean value, *dashed line* shows the 95%-confidence region for the mean value

4.2 Long-term trends

The increase in observed contrail cloudiness over the Atlantic corresponds to the fact that flight activities have continuously increased. But the observation of a reduction of contrail cloudiness over Europe is somewhat surprising. Of course, there is a small chance of an artifact of our statistics, which has yet to be ruled out by further detailed analyses of the present or a related data set. One reason for such a change could be a systematically changed flight level pattern in inner European air traffic. Even some influence of the political changes in Eastern Europe on all flight activities may not be ruled out completely. Other reasons could be found in systematic changes in environmental conditions due to secular changes in the atmospheric circulation pattern, probably caused by a general climate trend. This aspect has to be studied in much more depth before final conclusions may be drawn.

4.3 Contrail life cycle

Contrails on satellite images rarely appear as isolated objects, but are usually observed in groups within areas of a few hundred kilometers diameter. These contrail fields obviously last very long, most of them for more than one day. The interpretation of the observed spatial and temporal features necessitates the consideration of air traffic statistics as well as tropopause height, temperature and moisture statistics. None of these statistics is yet available with the required detail and accuracy. Therefore, no quantitative interpretation of our results is possible at the moment.

The average distribution of contrail cloudiness fits well with results about the distribution of NO_x emissions as a measure of traffic amount along the North Atlantic flight corridor (Schmitt, personal communication, 1993), as well as with preliminary results of 3D model calculations of such emissions (Schumann, 1993). Unfortunately, comparisons of monthly or at least seasonal values are impossible at the moment due to the lack of available data.

Of course, the appearance of contrails is also governed by the environmental conditions in the flight level. As Appleman (1953) originally showed, the actual temperature in flight level height has to be below a certain threshold value (depending somewhat on moisture) in order for contrails to appear. In fact, statistics of contrail observations show that the frequency of contrail occurrence corresponds closely to Appleman's critical temperature values (Pilié and Jiusto, 1956; HQ Air Weather Service, 1981). As the tropopause represents the coldest level between troposphere and stratosphere the statistics of height and temperature of that layer is also important.

While this temperature criterion provides a necessary condition for contrail appearance, it is probably not sufficient to explain the occasional long lifetime and wide spreading of contrails. Various processes have been described in the literature as important. While some of them are very difficult to assess (e.g. wind shear) environmental humidity should definitely be a key parameter for contrail lifetime. Therefore, moisture fields near the tropopause also have to be well-known for an interpretation of the observations. The importance of this parameter has been indicated by a preliminary and very limited analysis of radiosonde ascents in the vicinity of observed contrail areas. For one case per season, N-S cross sections of wind, temperature, and humidity have been constructed roughly along 0° longitude from radiosonde observations as reported in the European Weather Map, which is distributed daily by the German Weather Service. Each of these cases was compared to non-contrail situations of only a few days time distance. For assumed flight levels near the tropopause, no considerable difference in temperature and wind was found between contrail and non-contrail days. But average relative humidity was consistently larger in contrail cases than otherwise. In view of the small number of cases (only four), and the as yet unsolved question of the reliability of humidity measurements, no details of this analysis are given here.

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