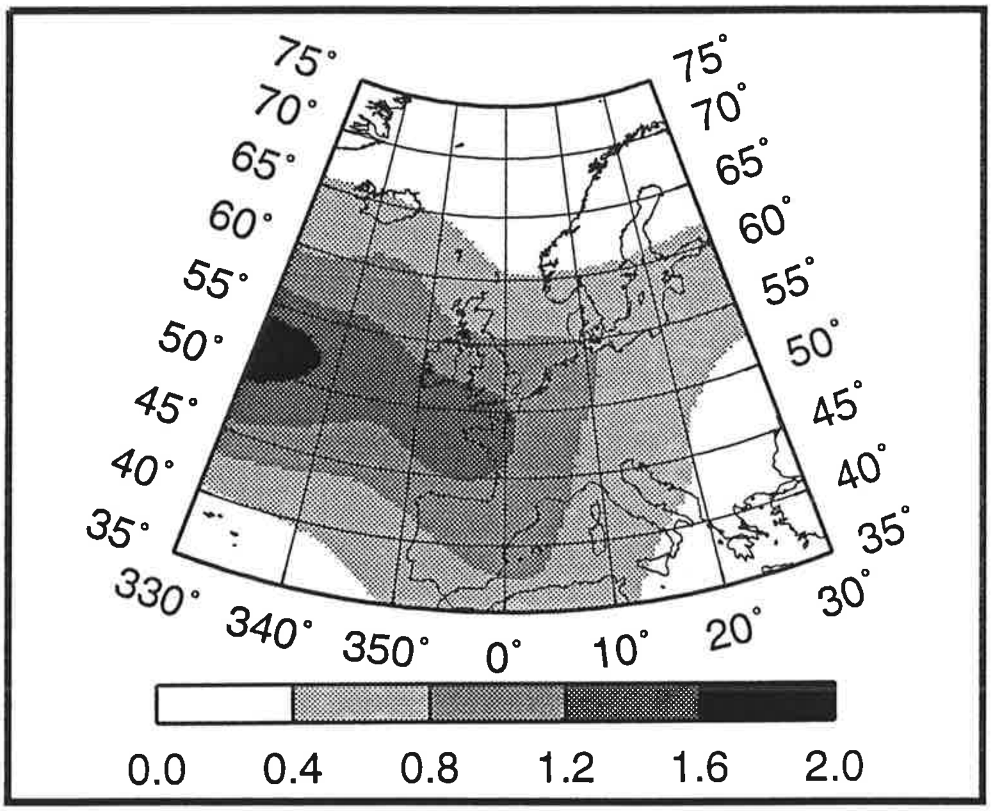
Max-Planck-Institut für Meteorologie

REPORT No. 118



TOWARDS A CONTRAIL CLIMATOLOGY FROM NOAA-SATELLITE IMAGES OVER EUROPE

by

STEPHAN BAKAN · MARGARITA BETANCOR
VERONIKA GAYLER · HARTMUT GRASSL

HAMBURG, NOVEMBER 1993

AUTHORS:

Stephan Bakan Hartmut Graßl	Max-Planck-Institut für Meteorologie
Margarita Betancor Veronika Gayler Hartmut Graßl	Universität Hamburg Meteorologisches Institut Bundesstraße 55 D-20146 Hamburg FRG

MAX-PLANCK-INSTITUT
FÜR METEOROLOGIE
BUNDESSTRASSE 55
D-20146 Hamburg
F.R. GERMANY

Tel.: +49-(0)40-4 11 73-0
Telemail: MPI.METEOROLOGY
Telefax: +49-(0)40-4 11 73-298

REPb 118

Towards a Contrail Climatology
from NOAA-Satellite Images over Europe

S.Bakan[2], *M.Betancor*[1], *V.Gayler*[1], *H.Graßl*[1,2]

1 Institut für Meteorologie. Universität Hamburg. 20146 Hamburg. Germany
2 Max-Planck-Institut für Meteorologie, 20146 Hamburg. Germany

ISSN 0937-1060

Abstract

Contrail cloudiness over Europe and the eastern part of the North Atlantic Ocean was analyzed for the two periods Sept. 1979-Dec. 1981 and Sept. 1989-Aug. 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^oN (of almost 2%) and over western Europe resulting in 0.5% contrail cloudiness on the 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 of one decade separation there is a significant decrease in contrail cloudiness over western Europe and a significant increase over the North Atlantic observable between March and July. Contrail cloud cover during daytime is about twice as high as during nighttime. Contrails are preferably found in larger fields of 1000 km diameter which last usually for more than one day. Causes, possible errors and consequences are discussed.

1 Introduction

The worldwide demand for air transportation has grown considerably and it is expected to double from 1988 to the year 2000 (*Nüßer and Schmidt,*1990; *Reichow*, 1990). During the last decade increasing concern on the possible long-term impact of man-made activities on the global atmosphere led also 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 the visible manifestation of the high-flying subsonic air traffic. They mostly appear at environmental temperatures below about -45^oC (*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,* 1991). Contrails, as man-made ice clouds, can trigger additional ice clouds (*Schumann and Wendling,* 1990).

It is known that thin natural cirrus clouds with crystals bigger than $0.3\mu m$ in the upper troposphere at mid and low latitudes influence the radiation budget of the atmosphere by increasing the greenhouse effect (*Liou,* 1986; *Liou et al.*, 1990). The influence of contrails and cirrus clouds that developed out of contrails is due to their optical characteristics and to their areal coverage. An increase in contrail cloud cover would result in a similar effect (*Graßl,* 1988), in case, longlived contrails have similar optical properties as natural cirrus clouds. 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*).

In a few studies the additional cloud cover due to high clouds or contrails (*Chagnon,* 1981; *Carleton and Lamb,* 1988; *Liou et al.*, 1990; *Schuman and Wendling,* 1990; *Roll,* 1990) was analysed. But none was documenting jet contrail occurrence on a large spatial scale for periods spanning a decade, as it would be necessary for the rigorous evaluation of the contrail-cirrus climate relationship (*Carleton and Lamb,* 1988).

The present paper reports on 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^oN-latitude, a region where most of the air traffic emissions take place (*Kavanaugh,* 1988). To assess longterm 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 the ideal means of studying cloud occurrence due to their regular availability for large areas. Especially valuable for contrail studies are the data transmitted from the AVHRR(Advanced Very High Resolution Radiometer)- Radiometer 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 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 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 at a climatologically meaningful time period forced this decision. Therefore, a large amount of printed images was visually inspected by one of us (V.G.). Such a simple method has already been proved 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 is 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 and the VIS channel 2 with constant print quality throughout the years. The reduced spatial resolution of the photographic images still permits a good contrail identification. 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 dangereous over the ocean, where similar-looking features that are related to ships can occur in stratocumulus and stratus decks (*Fett,* 1979; *Carleton and Lamb,* 1986). Also, meaningful observations are only available for noon-images, and even for those varying solar height with changing image brightness and contrast is disturbing.

The quicklooks used enclose the region $30^oW - 30^oO; 35^oN - 75^oN$. Due to the satellite orbital period, the satellite field of view is displaced eastward from day to day. After a time period of 8 to 11 days the receivable subsatellite track lies again westward from Dundee. Thus only a core region around 0^o-longitude is displayed daily. Fig.1 shows on how many days (in percent) of the analysed period a certain area was covered. Quicklooks of the early afternoon pass of nearly six years separated into two time periods, September 1979-December 1981 and September 1989-August 1992, were processed. For the derivation of the following statistics only those regions are included that are covered on more than 30% of the days. For the assessment of the daily cycle and of the life cycle of contrails a small additional dataset of two months (Aug. 1984, Sept. 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 were identified as contrails. Their alignment parallel to flight corridors with different directions, thus frequently showing crossovers is used to distinguish them from natural cirrus clouds, that follow the upper tropospheric air flow. Old contrails with a shape similar to natural cirrus cannot easily be distinguished from natural cirrus clouds and are, therefore, not included. A training phase on about 100 images preceeded the real evaluation. This was done in order to establish a consistent feeling for what should exactly be labeled as a "contrail", or, if grouped together as usual, as a "contrail area" (Fig. 2 is an example for the analyzed 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 degrees longitude and 5 degrees 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 Ch.4 show, that even the absolute cloudiness values are grossly consistent with such values from other studies.

3 Results

3.1 Additional Cloudiness due to Contrails

Fig.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 observed, while the average value for the whole scene is 0.5%.

Fig.4 documents the strong yearly cycle of contrail cloudiness. 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 to the north in summer but remains south of $60^{\circ}N$ in winter. On the other hand few contrails are observed south of $40^{\circ}N$ except for the winter time.

Of course, there is a considerable interannual variability of the scene averaged contrail cloudiness, resulting in an rms-value of the same size as the yearly averaged value itself.

3.2 Longterm Trends

The long term trend was studied by separate evaluation and comparison of the two analysis periods 1979-1981 and 1989-1992. Fig.5 shows a considerably smaller cloudiness over central Europe during the early summer months (March through July) of the latter time period as compared to the former. At the same time the average cloudiness over the Atlantic flight corridor increased. Both of these changes turn out to be significant ($> 95\%$), when a t-test is applied. No significant changes are found for the winter time.

3.3 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 are for the daily average values two months (August 1984 and September 1985) were analysed in addition, for which four IR-Quicklooks per day were available (around 400,800,1400,1800 UT). Fig.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 the night time by roughly a factor of 2. This corresponds to the variation of air transport activity troughout the day over Europe.

3.4 Contrail Life Cycle

The mentioned two month set of images was also used to get a hint at the life cycle of contrails. It is important to note that single contrails are rarely observed but normally larger groups of contrails appear. These contrail regions have a typical diameter of 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 on 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 hours. On the other hand, 62% of the contrail areas could be followed for more than one day and 24% even for more than two days.

4 Discussion

4.1 Accuracy considerations

Although the chosen method to analyze contrail occurrence in satellite images from quick-look photographs is somewhat subjective, it allowed to process a rather large - and thus climatologically meaningful - data set. To our knowledge, there is no proven automated method for contrail detection from digital satellite data available at the moment, that could allow results of the same quantity and quality as an image inspection by human eye. As discussed in Chapter 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 single person analyzed all the images without any change of the procedure. Using only infrared images allows to detect contrails preferably 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 may often be 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 too many comparable evaluations are available, the values for the yearly averaged contrail cloud cover compare favourably to earlier reports. *Roll* (1990) showed for a smaller analysis region ($50^oN - 60^oN$, $20^oW - 10^oE$) near the North Atlantic flight route for a period of 1 year an averaged contrail cloud cover < 1%. *Schumann* (1991) reported a mean contrail area coverage of 0.4% for a fixed area of 300000 km^2 between Frankfurt and Genua derived from AVHRR digital data for 142 days between Oct. 1989 and Sept. 1990. Observed seasonal and daily variation of contrail occurrence are similar to those reported by *Roll* (1990), who found the maximum values also in summer and in the early afternoon.

4.2 Possible Causes for Longterm Trends

The increase in observed contrail cloudiness over the Atlantic corresponds to the fact that flight activities increased continously in the past, the observation of a reduction of contrail cloudiness over Europe is somewhat surprising. Of course, there is a small remaining chance of an artifact of our statistic, which has to be ruled out with further detailed analyses of the present or a related data set. Reasons for such a change could be a systematically changed flight level pattern in inner European air traffic or systematic changes in environmental conditions. The latter would be 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 appear rarely as isolated objects, but are usually observed in groups within areas of a few hundred kilometers diameter. These contrail fields last obviously 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 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*, 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) showed originally, 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 a statistics of contrail observations shows that the frequency of contrail occurrence correponds 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 consideration of a 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 discussed in 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 life time. Therefore, also moisture fields near the tropopause have to be well known for an interpretation of the observations. The importance of this parameter is 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 daily distributed 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. But average relative humidity was consistently larger in contrail cases than otherwise. In view of the small amount of cases (only 4) and the yet unsolved question of reliability of humidity measurements no details are given here.

4.4 Parameterization Proposal

Although the above considerations are somewhat preliminary a first rough proposal to parameterize contrail cloudiness in climate model studies may be suggested. According to the mentioned aspects cloudiness should primarily depend on the near tropopause values of air traffic intensity A, which may be given in flight kilometers per unit area and time. As the observed frequency of occurrence of contrails corresponds closely to *Appleman*'s prediction nomograms an expression for the probability for contrail appearance p_c may be derived from these. The vertical variation of *Appleman*'s critical temperature for contrails to appear even without any environmental moisture may be represented by $T_o(z) = -39 + 1.2z$, where the height z is in km and the temperature T in ^oC. The probability p_c depends primarily on the difference between environmental and critical temperature, at the tropopause height z_T:

$$p_c = \begin{cases} 0 & T(z_T) - T_o(z_T) < -5^oC \\ 1 & T(z_T) - To(z_T) > 15^oC \\ 0.75 - 0.05(T(z_T) - T_o(z_T)) & \text{otherwise} \end{cases}$$

The probability for a long lifetime of contrails is set proportional to the relative humidity r over ice, while all other potentially important parameters are ignored. The proposed simple parameterization expression for contrail cloudiness c is then given by

$$c = C\,A\,r\,p_c$$

The constant C represents the effective area covered by a contrail resulting from 1 flight-kilometer weighted by the average contrail lifetime. Unfortunately, we had no statistics of flight kilometer available, but rather a yearly inventory of NO_x-emissions, collected by *Schmitt* (1993). Using plausible estimates of fuel consumption and NO_x production results in $C = 1 km^2/(Flightkm)$.

The validity of such an approach and the optimum value of the parameterization constant can only be proven after the availability of the mentioned fields. These fields could be taken together to construct the expected cloudiness distribution, which then has to be compared to our present contrail cloudiness observations.

5 References

Applemann, H. The formation of exhaust condensation trails by jet aircraft. Bull. Amer. Metorol. Soc., 34, 14-20, 1953

Bakan, S., E. Schwarz Cellular convection over the north-eastern Atlantic. Int. Journ. of Climat. 12, 353-367, 1992

Betancor ,M., H. Graßl Satellite remote sensing of the optical depth and mean crystal size of thin cirrus and contrails. Theoretical and Appl. Climatology, in press

Carleton, A., P. Lamb Jet contrails and cirrus clouds: A feasibility study employing high-resolution satellite imagery. Bull. Amer. Meteorol. Soc., 67, 301-309, 1988

Chagnon, S.A Midwestern cloud, sunshine and temperature trends since 1901: Possible evidence of jet contrail effects. J. Appl. Meteor., 20, 496-508, 1981

Fett, R.W. Navy tactical applications guide, Vol. II: Environmental phenomena and effects. Tactical Applications Department, Naval Environmental Prediction Research Facility, Monterey., 1979

Detwiler, A., R. Pratt Clear air seeding: opportunities and strategies. J. Weather Mod. 16, 46-60, 1984

Graßl, H. Wolkenbildung durch die Emissionen hochfliegender Flugzeuge. Tutzinger Materialien, No. 50. ISSN 0930-7850, 71-80, 1988

HQ Air Weather Service Forecasting aircraft condensation trails. Tecnical Report AWS/TR-81/001. Air Weather Service/DNTS. Scott AFB IL 62225, 1981

Kavanaugh, M. New estimates of NO_x from aircraft: 1975-2025. Proc. 81st Annual Meeting of APCA (Air Pollution Control Asociation), Dallas, Texas, June 14-19, paper 88-66.10, 15pp., 1988

Liou, K-N. Influence of cirrus clouds on weather and climate processes: A global perspective. Mon. Wea. Rev., 114, 1167-1199, 1986

Liou, K-N., S-C. Ou, G. Koenig An investigation of the climatic effect of contrail cirrus. In: U. Schumann (ed.): Air traffic and the environment. Lect. Notes in Engrg., Vol 60, Springer-V., Berlin, p.154-169, 1990

Nüßer, H-G, A. Schmitt The global distribution of air traffic at high altitudes, related fuel consumption and trends. In: U. Schumann (ed.): Air Traffic and the Environment. Lect. Notes in Engrg., Vol 60, Springer-V., Berlin, p.1-11, 1990

Pilié, R.J., J.E. Jiusto A laboratory study of contrails, J. of Met., 15, 149-154, 1956

Reichow, H-P. Fuel consumptions and emissions of air traffic. In: U. Schumann (ed.): Air Traffic aand the Environment. Lect. Notes in Engrg., Vol 60, Springer-V., Berlin, p.12-22, 1990

Roll, O. Kondensstreifen im Satellitenbild. Master Thesis, Univ. Cologne. Germany, 1991

Schmitt, A. Personal communication, 1993

Schumann, U. On the effect of emissions from aircraft engines on the state of the atmosphere. DLR .Report No.1. ISSN 0943-4771, 1993

Schumann, U., E. Reinhardt Studies on the effect of high-flying air-traffic on the atmosphere. 42nd Congress of the International Astronautical Federation. Oct. 5-11, 1991/Montreal, Canada. IAA-91-737, 1991

Wendling, P., U. Schumann Determination of contrails from satellite data and observational results. In: U. Schumann (ed.): Air Traffic aand the Environment. Lect. Notes in Engrg., Vol 60, Springer-V., Berlin, p.138-153, 1990

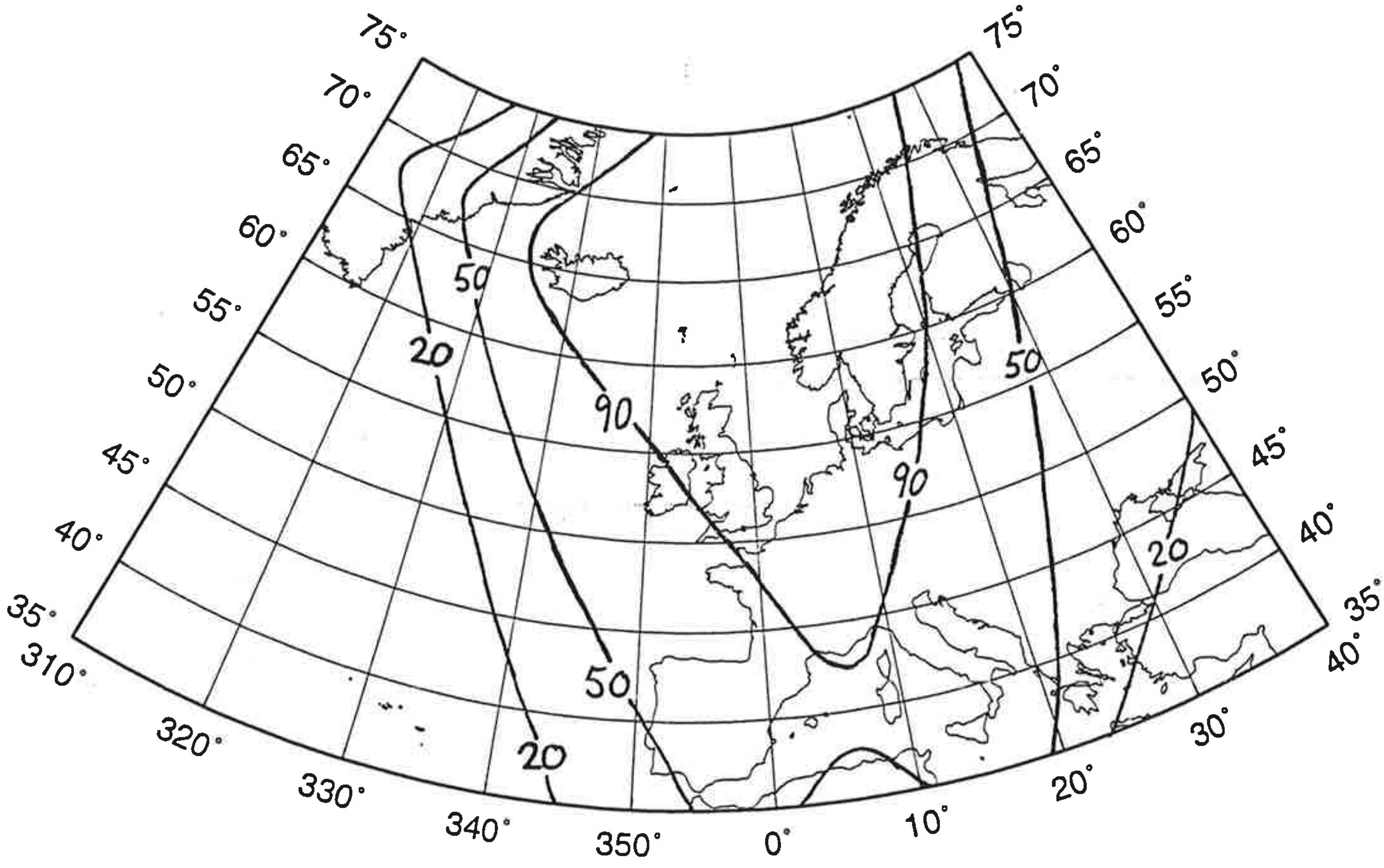


Figure 1: Visibility frequency of a certain geographic area during the six years analysed.

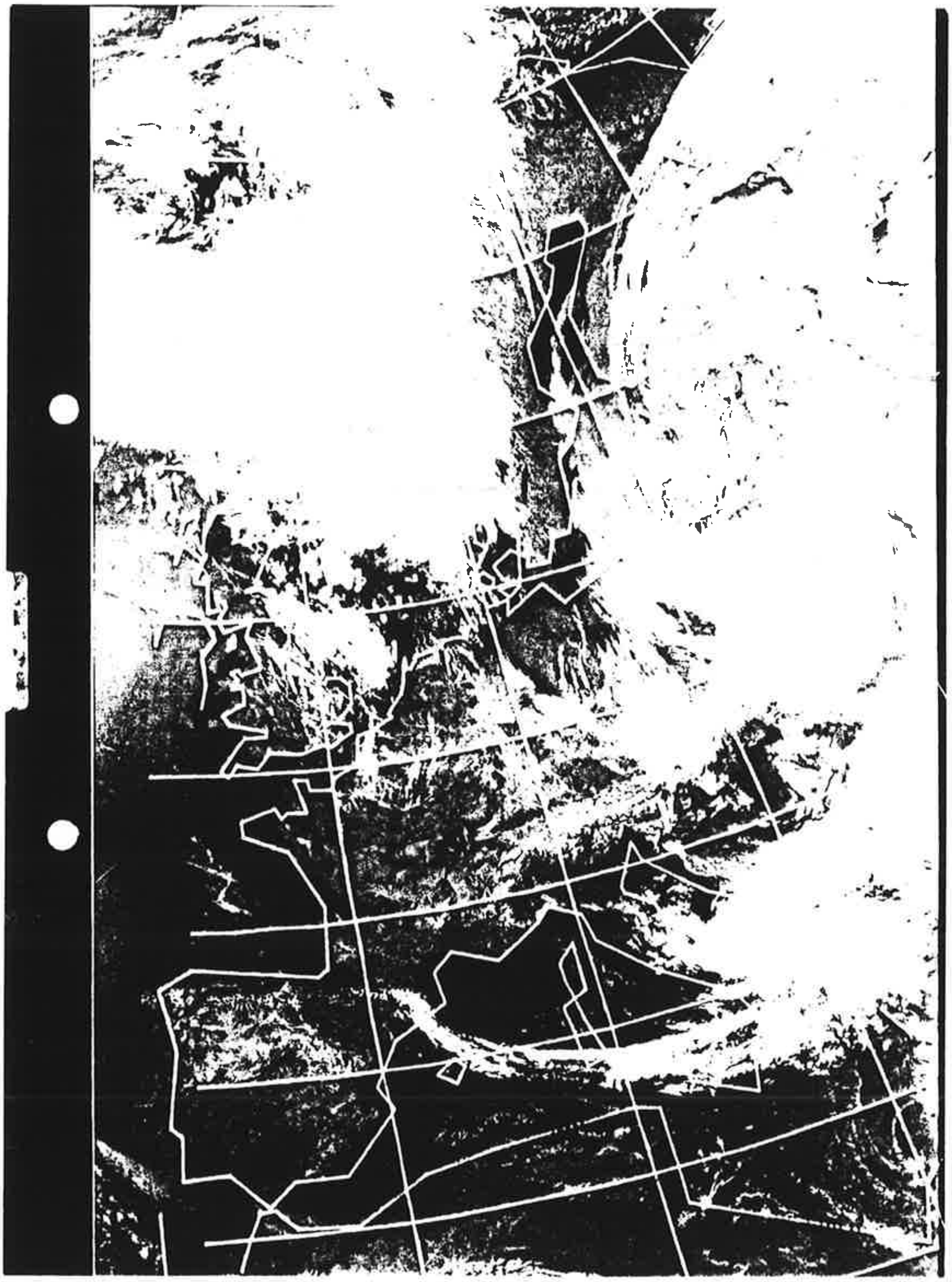


Figure 2: Example of a photographic quicklook as used in the study. (NOAA-8/AVHRR channel 4 image of 13 October 1985, 7:40 UT as recorded at the University of Dundee). The region enclosed between $55^o N - 45^o N$ and $10^o W - 10^o E$ shows many linear cloud formations recognized as contrail areas.

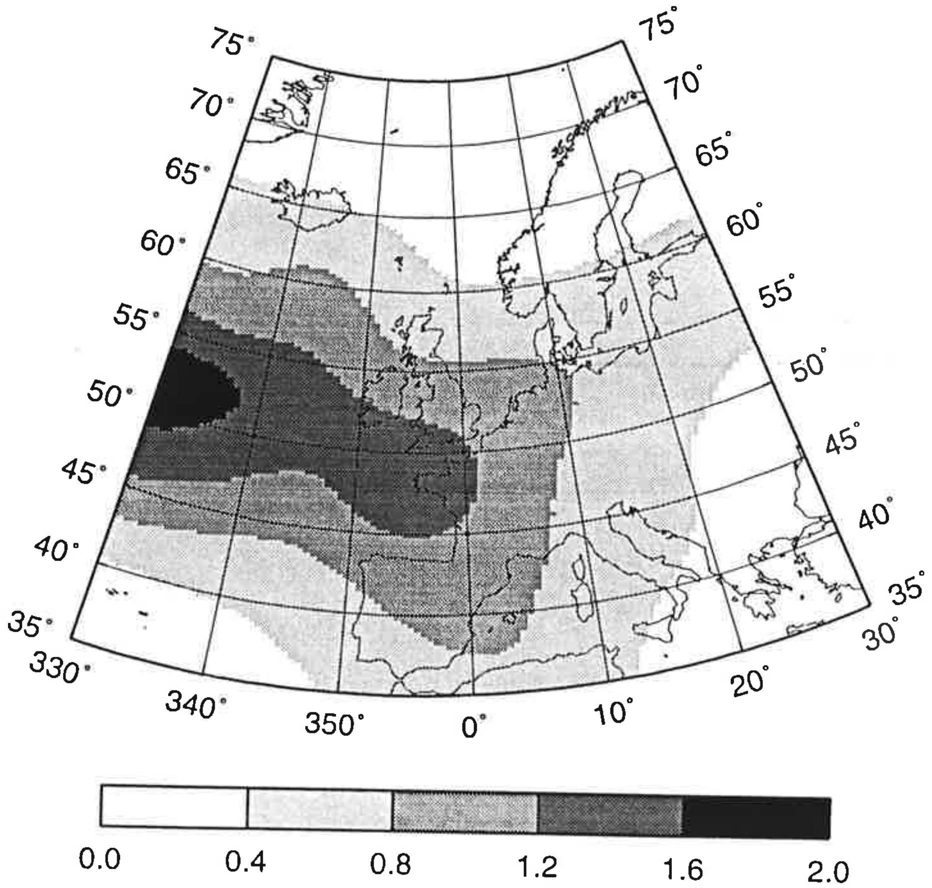


Figure 3: Yearly averaged contrail cloudiness -in per cent- over Europe and the eastern part of the Atlantic Ocean for the total analysis period Sept. 1979-Dec. 1982; Sept. 1989-Aug. 1992.

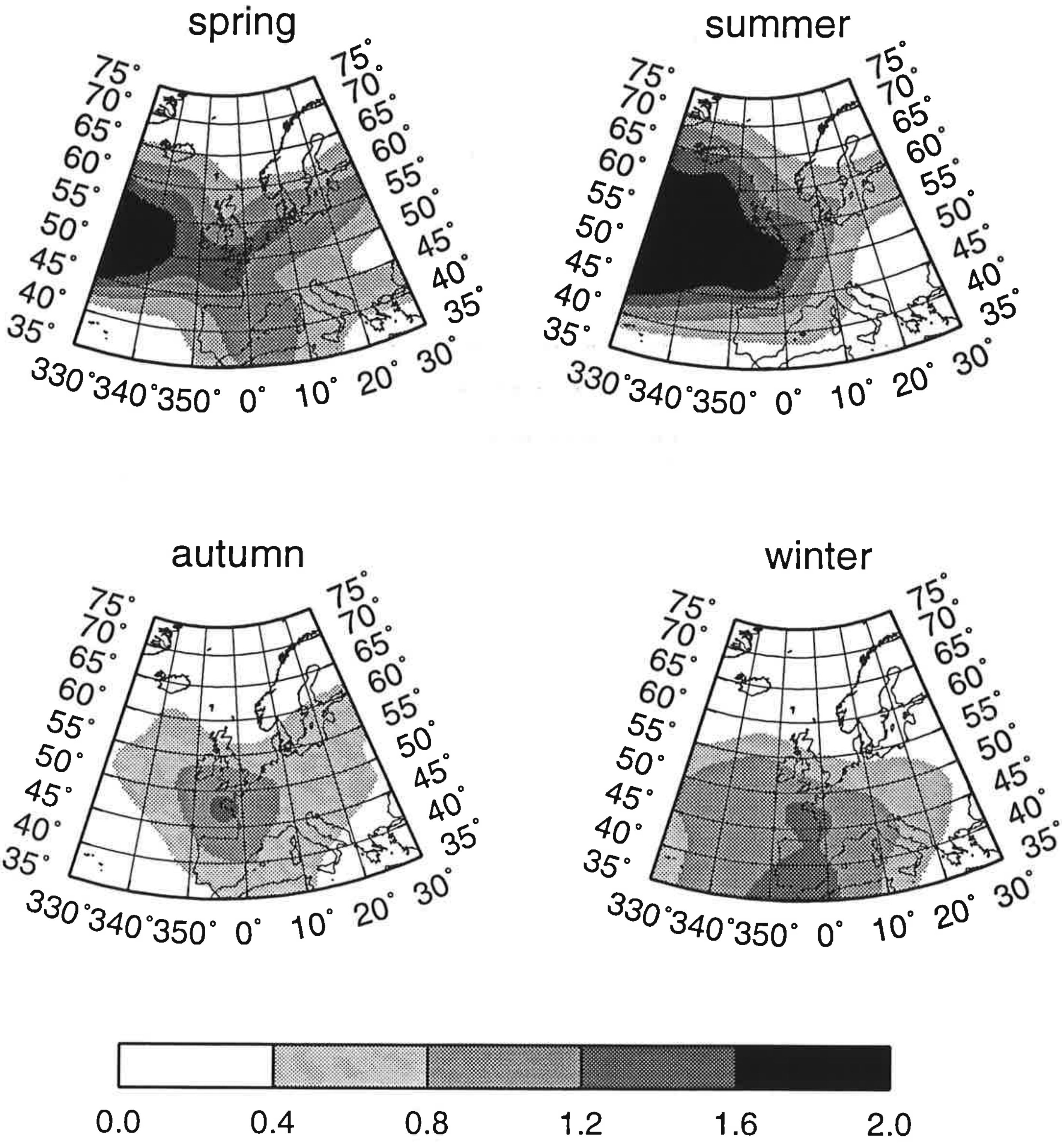


Figure 4: Monthly averaged contrail cloudiness -in per cent-in spring (a.), summer (b.), fall (c.) and winter (d.) for the same time period as in Fig. 3.

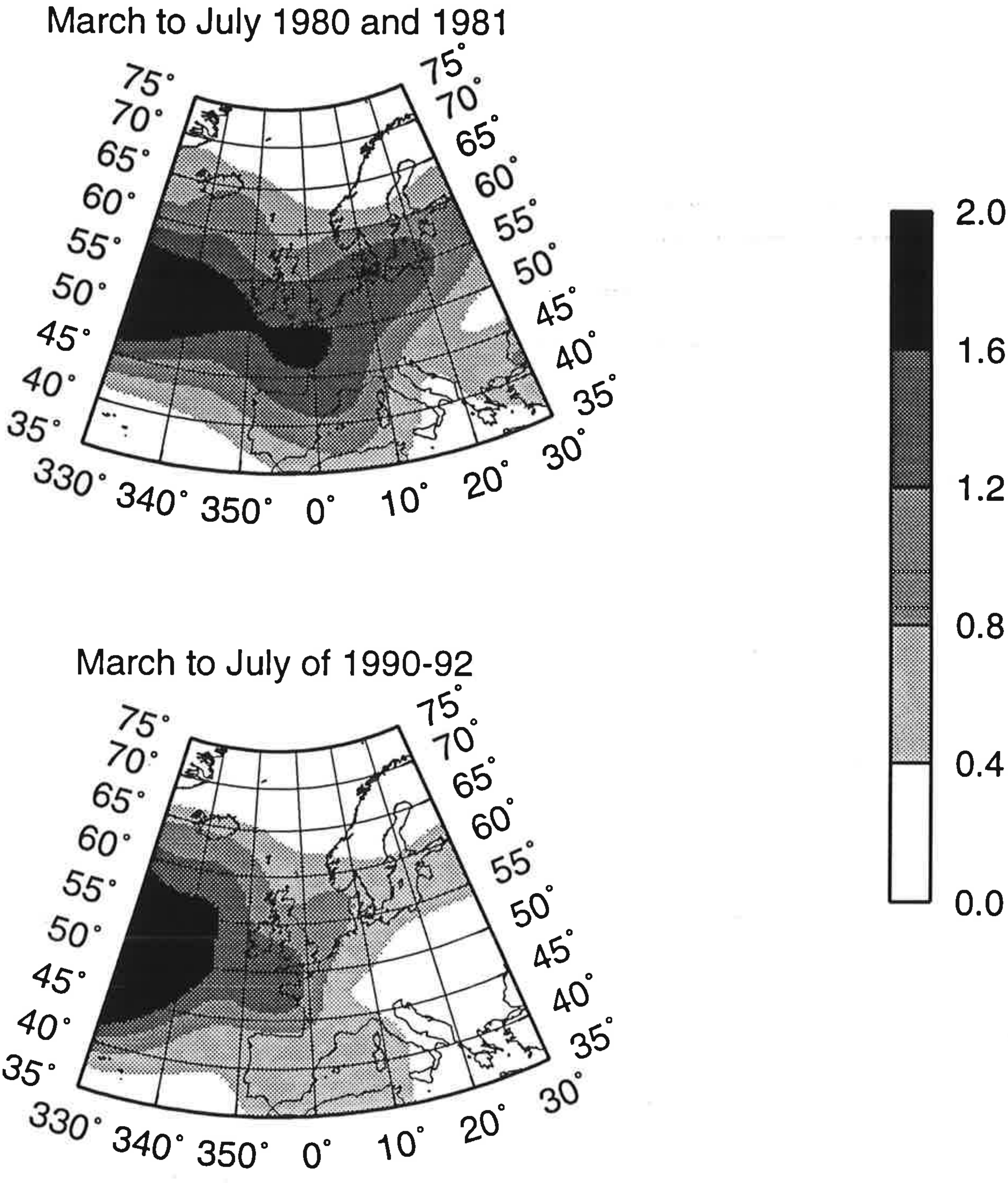


Figure 5: Contrail cloudiness averaged for the months March to July exhibits significant differences between the two analysis periods (a.:1980-1981;b:1990-1992).

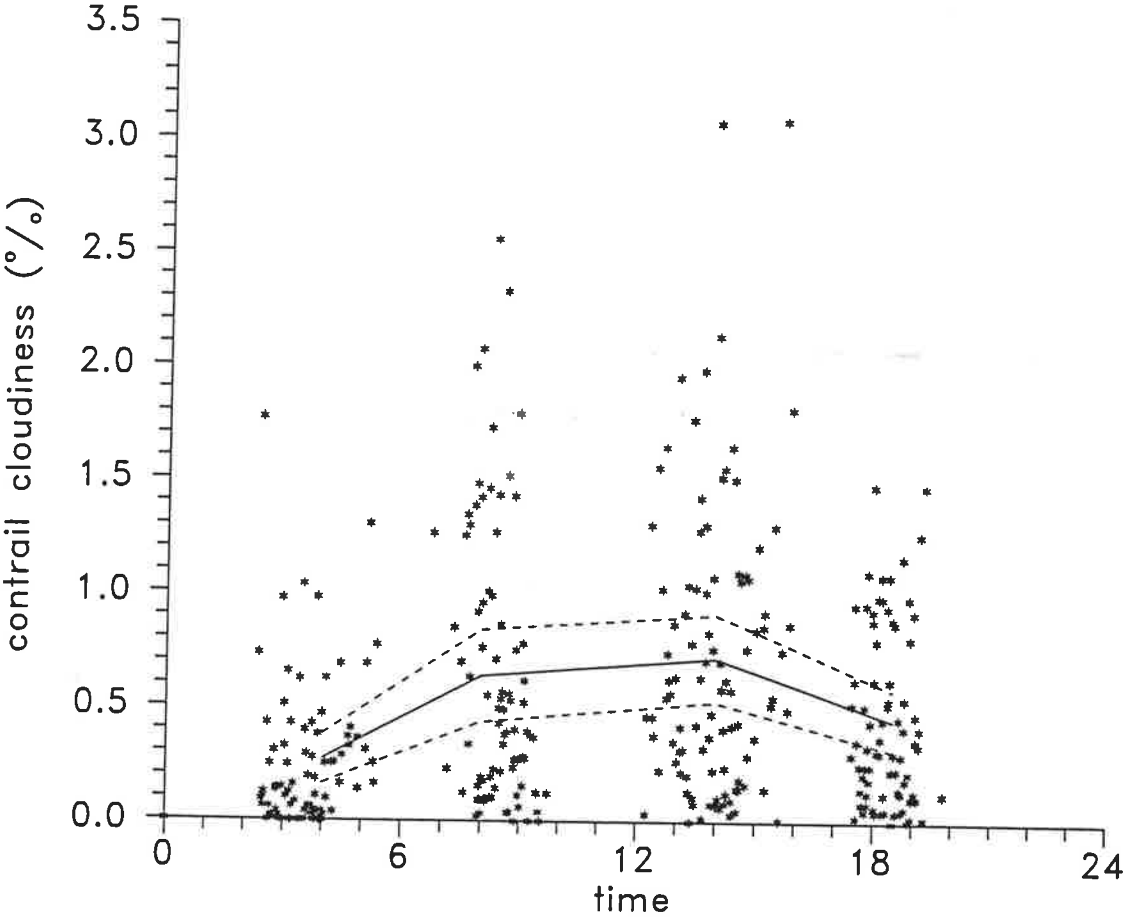


Figure 6: Daily cycle of contrail cloudiness over Europe and the eastern part of the Atlantic Ocean for Aug. 84 and Sept. 85. Solid line: mean value, dashed line: 95%-confidence region for the mean value.