

# Aviation impact on cirrus cloudiness

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## Abstract

Aviation induced cloud cover (AIC) changes are derived from the diurnal cycle of cirrus cover observed over the North Atlantic flight corridor (45° W – 10° W, 45° N – 55° N). The cirrus cover is derived with high spatial resolution and 15 *min* time resolution from 11 months of Meteosat-8 infrared data for the year 2004, using the MeCiDA cirrus detection scheme [6]. Air traffic density data were provided by EUROCONTROL with high spatial and 15 *min* temporal resolution, integrated over 6.1-13.7 *km* altitude, for the same region and time period. Air traffic in the North Atlantic region peaks at about 4 UTC due to eastbound traffic and at about 13 UTC due to westbound traffic. The observed diurnal cycle of cirrus cloud fraction shows a pattern that looks similar the diurnal cycle of air traffic, shifted by about 2 - 3 *h*. We developed simple linear response models which reproduce the observed cirrus variation as a function of the air traffic density. The observed and the simulated cirrus cover cycles have similar patterns. A unique fingerprint is also the difference in the diurnal cycle of the cirrus cover in the western half and the eastern half of the North Atlantic region. Therefore, the results indicate a significant contribution of aviation induced cirrus clouds (mainly contrail cirrus) to the total cirrus cover in that region. The time shift of about 2 - 3 *h* suggests a corresponding lifetime of contrail cirrus. The cover of detected aviation induced cirrus clouds amounts to about 0.8 - 1.2%. This value is uncertain by about a factor of 2 because of unknown contributions from natural processes and limited sensitivities of the satellite sensor and cirrus detection algorithms for AIC.

**Keywords:** contrails, contrail cirrus, aviation, infrared remote sensing

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## 1 Introduction

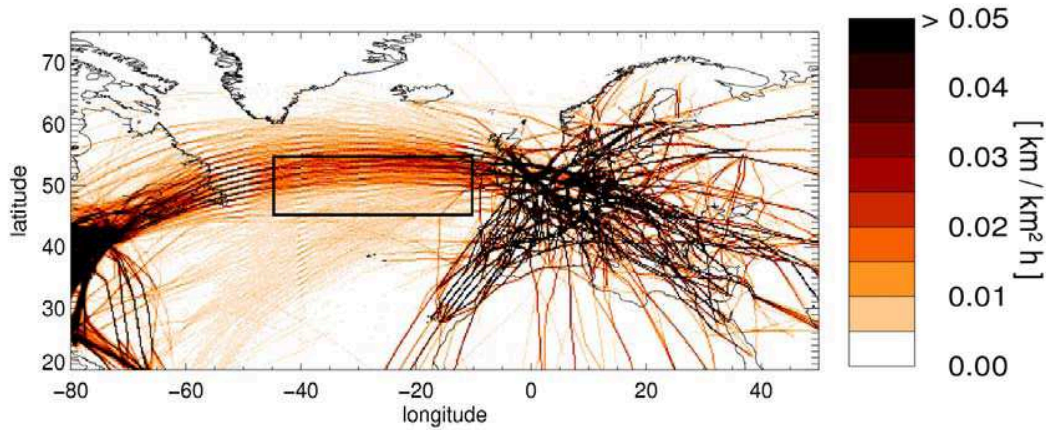
Aviation causes contrails and induces particles behind aircraft which may trigger the formation of contrail cirrus and may affect cloud formation at cruise altitudes [14,3]. An increase in cloudiness cools the Earth-atmosphere system by an increase of Earth albedo and warms the system by reducing terrestrial radiation to space [16,7]. Hence aviation induced clouds (AIC) impact climate [4,5]. Contrail formation and line-shaped contrails detectable from satellite data have been investigated in several studies, e.g. [15,9]. However, the amount of contrail cirrus, which is no longer line-shaped and therefore not easily distinguished from natural cirrus, is not well known [5]. Past studies estimated the amount of AIC from observed trends in cirrus cloud cover in correlation with the growing air traffic density (ATD) [1,10,11,17,18,2]. Such trends cannot be attributed to aviation with full certainty. As a consequence the amount and radiative forcing by AIC is not well known [12]. This deficit represents the largest part of uncertainty in assessing the climate impact of aviation [4]. Until now not even an accepted (IPCC-level) best estimate of radiative forcing due to aircraft-induced cirrus changes exists and the level of scientific understanding is assessed to be poor [5]. This paper intends to identify, for the first time, AIC contributions in a region where aviation seems to cause a unique fingerprint in cirrus cover. This fingerprint may be used to investigate possible cause and effect relationships between aviation and cloud changes. The present paper provides only results on cloud cover but leaves the optical thickness and radiative effects of the observed cloud changes open. These effects should be quantified in follow-on studies.

## 2 Methods and data

### 2.1 Region

In order to perform the idea of this study, the selected region must fit the following requirements: (1) Air traffic density must comprise considerable variability throughout the day – if possible with a distinguished pattern; (2) the diurnal cycle of natural cirrus cover should be small, as it may hide the AIC contribution to the total diurnal cycle of cirrus cover; (3) cirrus and air traffic data must both be available for the region; and (4), the region has to be large enough to make sure that most of the air traffic induced cirrus remains within that region during the life time; moreover, a larger region may be split into parts for detailed analysis. Under these circumstances we selected the North Atlantic region  $45^{\circ}$  W –  $10^{\circ}$  W,  $45^{\circ}$  N –  $55^{\circ}$  N, see Fig. 1. This region will be addressed as North Atlantic region (NAR) in the following text. The region includes a large fraction of the North Atlantic flight corridor and is fully covered by Meteosat-8. As this region is over ocean, convection is weak compared to land and therefore the natural diurnal cycle in cirrus cover should be small. In

addition, variations of surface temperature and emissivity are far smaller over ocean than over continents.



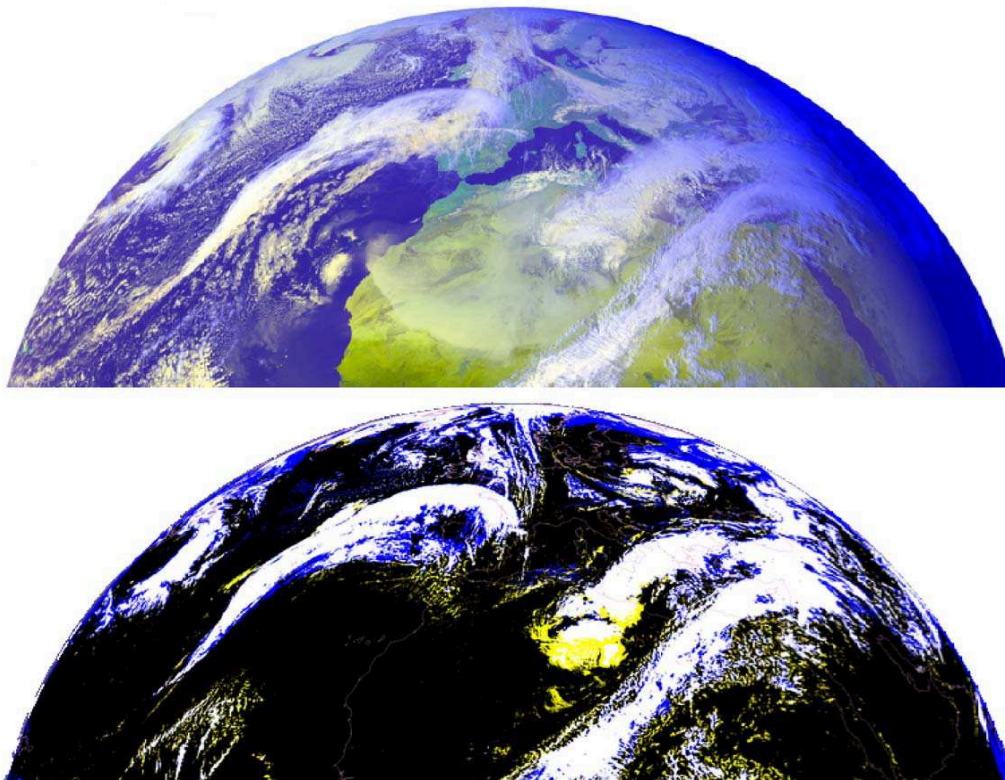
**Figure 1: Map of air traffic density (average for May 2004) and location of region NAR considered in this study.**

This allows for high and spatially homogeneous cirrus detection efficiency from satellite data. To avoid too large observation angles which could also affect the cirrus detection from Meteosat-8, the region was only extended up to 55° N. Finally, both, air traffic as well as cirrus data are available and the region is large enough so that only a small fraction of the AIC can move in and out of the region in the course of a day.

## 2.2 Cirrus data and determination of the diurnal cycle

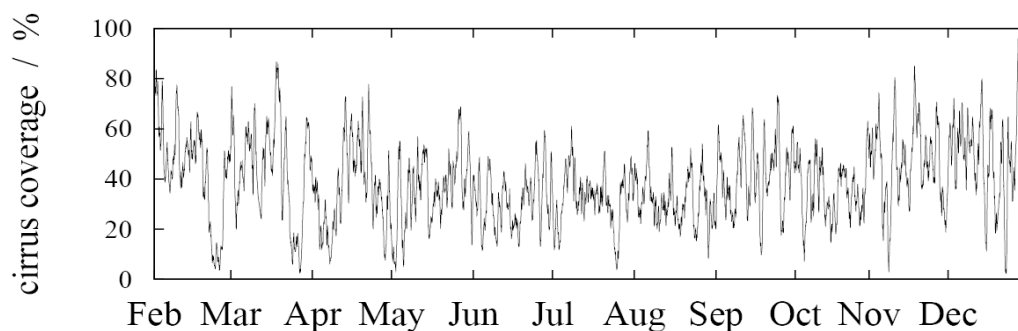
In order to determine diurnal cycle of cirrus cover, a high temporal resolution is necessary. SEVIRI (Spinning Enhanced Visible and Infrared Imager) on board Meteosat-8 [13] positioned in geostationary orbit at 0° provides a temporal resolution of 15 *min*. Since operational service of Meteosat-8 started end of January 2004, cirrus cover data are available for eleven months in 2004. For cirrus detection the day- and night-time Meteosat cirrus detection algorithm MeCiDA [6] was applied. MeCiDA combines morphological and multi-spectral threshold tests and detects optically thick and thin ice clouds making use of seven thermal channels, in particular the water vapor channels WV 062 and WV 073 centered at 6.2 respective 7.3  $\mu\text{m}$ , the three window channels IR 087, IR 108, and IR 120 centered at 8.7, 10.8, and 12.0  $\mu\text{m}$ , the IR 097 channel including the ozone absorption band at 9.7  $\mu\text{m}$ , and IR 134 channel located CO<sub>2</sub> absorption band at 13.4  $\mu\text{m}$ . Since MeCiDA uses only the thermal IR-channels of Meteosat-8-SEVIRI, the sensitivity of the cirrus classification is the same

day and night; possible artefacts due to usage of solar channels are prevented.



**Figure 2: top: RGB false color composite of MSG- Seviri, 2004-03-03, 14:30 UTC. bottom: MeCiDa cirrus detection result for the same timestep. [6]**

MeCiDA provides a discrete cirrus decision (0 or 1) for each Meteosat-8 pixel (see Fig. 2). The dataset covers 335 days, from which mean diurnal cycles of cirrus cover are determined for NAR.



**Figure 3: MeCiDa-derived time series of cirrus coverage in NAR, 2004**

### 2.3 Air traffic data

Air traffic density (ATD) data for the North Atlantic were provided by the European Organization for the Safety of Air Navigation (EUROCONTROL). The data set contains vertically integrated flown distances on a cylindrical equidistant  $0.25^\circ \cdot 0.25^\circ$  grid with a temporal resolution of 15 *min* for the region NAR and for each day in 2004. Only flights in the altitude range of 200 – 450 hectofeet (6.1 - 13.7 *km*) are taken into account, since lower flights trigger contrail formation only rarely. ATD is given in units of  $\text{km km}^{-2}\text{h}^{-1}$ . From these data, the average diurnal cycle of air traffic was calculated with 15 *min* time resolution. The diurnal cycle of ATD in NAR shows two traffic peaks (see Fig. 6). We see that the major traffic flow between Europe and North America takes place in two distinct clusters during each 24 *h* period. This special feature is a consequence of the traffic management in the North Atlantic flight corridor. The majority of the eastbound traffic leaves North American airports in the evening arriving in Europe in the morning (local time). The majority of the westbound traffic leaves European airports in the late morning to early afternoon and arrives at Eastern North American coastal airports during the afternoon.

In order to attribute observed cirrus variations to aviation, we performed the analysis separately for the Eastern and Western half parts of the NAR, NAR-E and NAR-W, respectively. Due to the eastbound/westbound pattern of the air traffic, the time when the maxima occur and in particular the distance between the maxima depend on longitude. The traffic peak is moving with typical airplane speed of  $900 \text{ km h}^{-1}$ . In the Eastern part of the region the maxima are closer to each other than in the Western part. This longitude dependence of the pattern should be reflected in the diurnal cycle of cirrus cover.

### 2.4 Response models

The diurnal variation of cirrus cloud cover  $C(t)$  is approximated by a simple conceptual model:

$$C(t) = C_{mean} + C_0(t) + c_{AIC}(t), 0 \leq t < 24h$$

where  $C_{mean}$  is the mean cirrus cover without air traffic,  $C_0(t)$  is defined as the diurnal variation of cirrus cover without air traffic, and  $c_{AIC}(t)$  is the cirrus cover due to aviation. The diurnal cycle of cirrus cloud cover  $C_0(t)$  without air traffic is assumed to be zero. Once knowing  $c_{AIC}(t)$ , we can compute the mean aviation induced cloud  $C_{AIC}$  for the region NAR. The diurnal cycle of the aviation induced cloudiness  $c_{AIC}(t)$  should approximately follow the diurnal cycle  $a(t)$  of ATD, though with some temporal delay.

We consider the following four simple response functions:

1. The most simple relationship assumes that the cirrus occurs at a time  $\tau$  after an aircraft passed. This is expressed by the delayed  $\delta$ -function:

$$r_1(t) = s \cdot \delta(t - \tau), \delta(t) = 0 \text{ for } t \neq 0, \int_{-\infty}^{\infty} \delta(t) dt = 1$$

with amplitude  $s$  and delay time  $\tau$  as the free parameters. Based on our discrete time intervals of 15 min, the delta function corresponds to a triangular.

2. [8] suggested a simple response function with linear (shear controlled) initial increase and later exponential decay (with life time  $\lambda^{-1}$ ):

$$r_2(t) = \begin{cases} s \cdot t \cdot e^{-\lambda \cdot t} & \text{for } t \geq 0 \\ 0 & \text{for } t < 0 \end{cases}$$

3. Assuming that the AIC decay is composed of a nonlinear increase and a quadratic decay term leads to

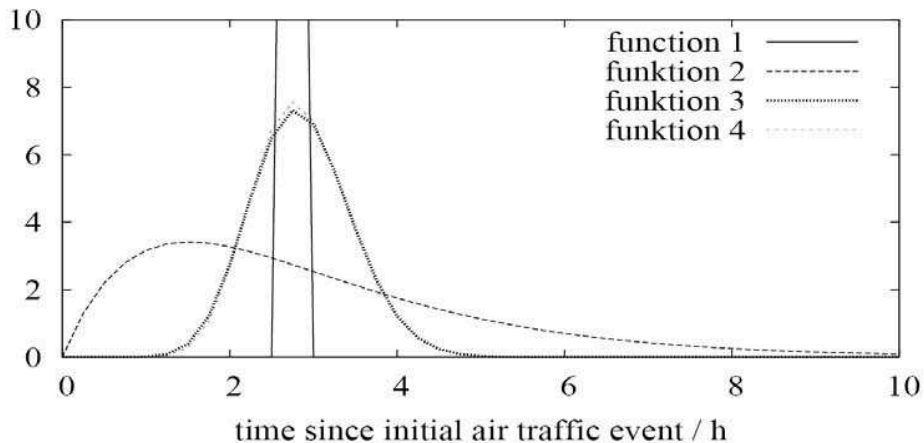
$$r_3(t) = b \cdot t^c \cdot e^{-d \cdot t} \cdot e^{-f \cdot t^2}$$

with four free parameters  $b$ ,  $c$ ,  $d$ , and  $f$ .

4. Finally, we tested a model which allows independent variation of the delay time and the width of the response function

$$r_4(t) = b \cdot t^c \cdot e^{-d \cdot (t-f)^g}$$

with five free parameters  $b$ ,  $c$ ,  $d$ ,  $f$ , and  $g$ . The response functions are plotted (for best fit results) in Fig. 4.

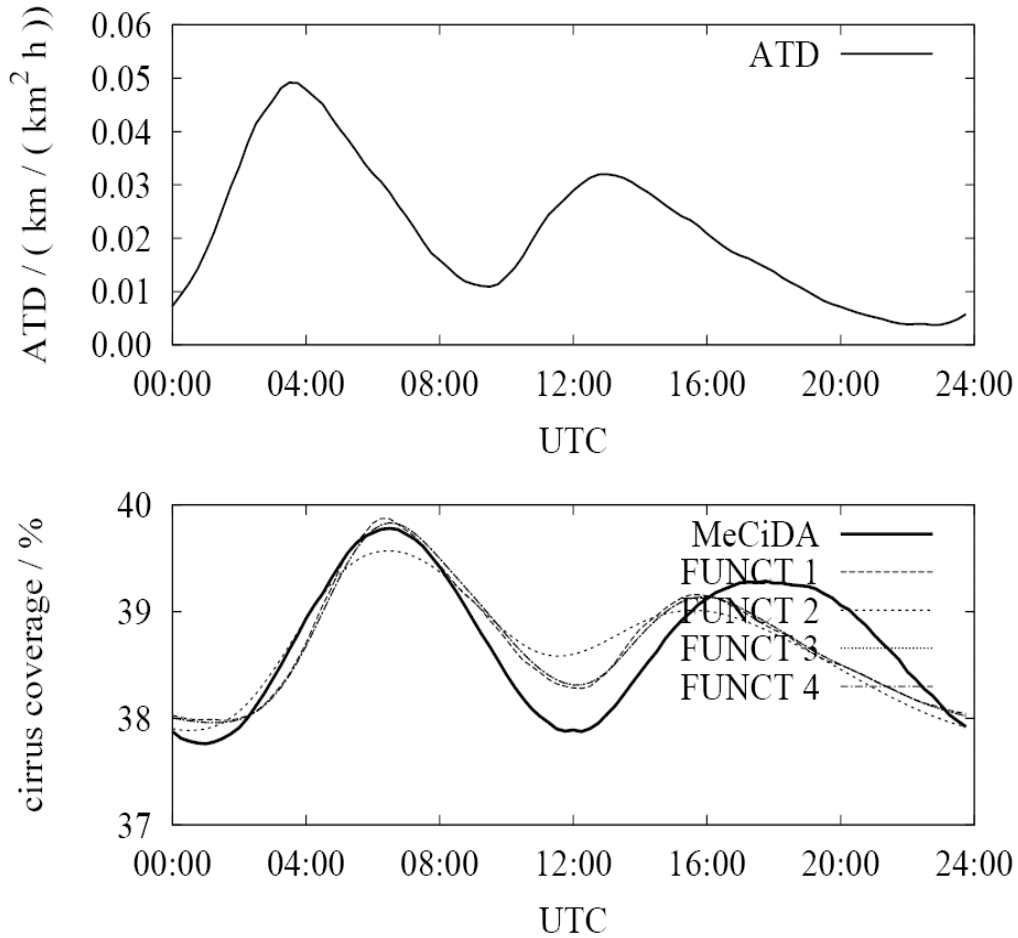


**Figure 4: AIC response functions 1 - 4 for best fit result**

### 3 Results

#### 3.1 Air traffic and cirrus cover in NAR

The diurnal cycle of air traffic density and cirrus cover in the NAR is shown in Fig. 6.



**Figure 5: top: mean diurnal cycle of air traffic density in NAR, 2004. bottom: mean diurnal cycle of cirrus coverage in NAR and best fit results for functions 1 - 4**

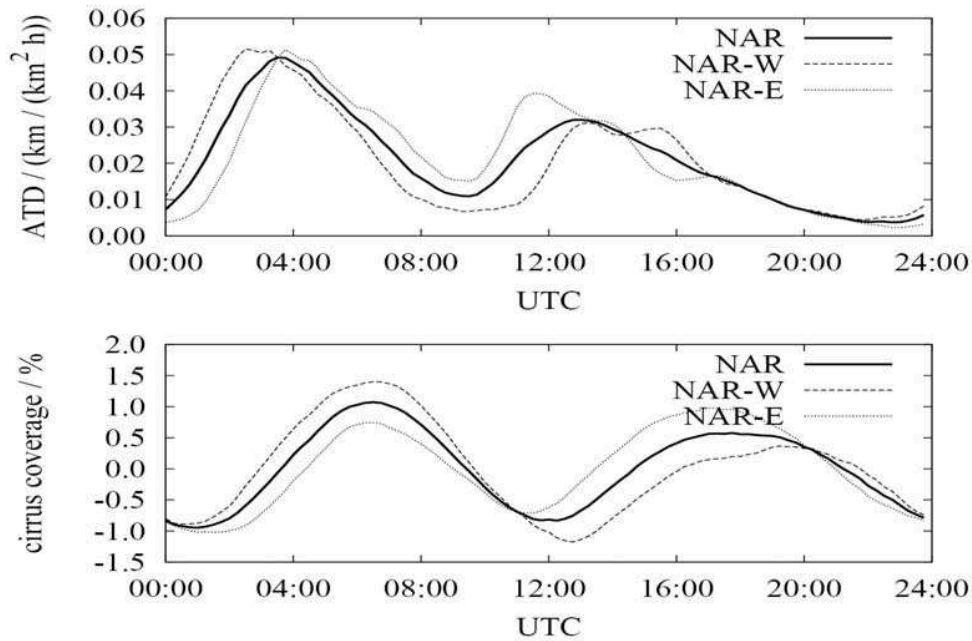
For NAR, the diurnal cycle of cirrus cover has two maxima, the first occurring at 06:30 UTC (cirrus cover 39.8%) and a second maxima occurring at 17:45 UTC (39.3%) whereas the mean cirrus cover has a minimum at 12:00 UTC (37.9%) and at 1:00 UTC (37.8%).

The mean cirrus cover of nearly 40% is consistent with other observations [19]. The diurnal cycles for cirrus in NAR show similarities with the diurnal cycle of ATD in the NAR: The two cirrus peaks are obviously related to the rush hours of air traffic

with destinations Europe and America, respectively. The cirrus cover follows the ATD signal with about 2-3  $h$  delay, which appears to be a reasonable time for forming and decaying contrail cirrus. The first cirrus peak is larger than the second one, as is the case for ATD. Hence, as discussed below, the NAR cirrus cover show a characteristic fingerprint of aviation induced cirrus changes.

**Table 1: Best fit results**

fit nr	$c_{mean}$	s	$\tau$ in h			$\rho$	$\Delta c$	$C_{AIC}$	
1	0.378	0.416	2.75	-	-	0.871	0.0030	0.0083	
	$c_{mean}$	s	$\lambda$	-	-				
2	0.375	0.061	0.66	-	-	0.790	0.0038	0.0119	
	$c_{mean}$	b	c	d	f				
3	0.378	0.0044	7.05	0.345	0.71	0.867	0.0031	0.0095	
	$c_{mean}$	b	c	d	f	g			
4	0.378	0.5605	17.39	1.50	2.25	1.60	0.870	0.0031	0.0092



**Figure 6: top: mean diurnal cycle of ATD in NAR, NAR-W, and NAR-E in 2004. bottom: mean diurnal cycle of cirrus coverage in NAR, NAR-W, NAR-E**

### 3.2 Western and Eastern parts of the North Atlantic Region

The eastbound traffic arrives first in the western part of the NAR and the westbound traffic arrives first in the eastern part of the NAR. Hence, we expect corresponding differences in the cirrus cover cycles for NAR-W and NAR-E. The diurnal cycles of the ATD and the cirrus cover are shown in Fig. 6 with respect to UTC. As expected, the eastbound air traffic peaks first in NAR-W (at 02:30 UTC) and then in NAR-E (03:45 UTC), whereas the westbound air traffic peaks in NAR-W later (13:15 UTC) than in NAR-E (11:30 UTC). Hence, the time differences between the traffic peaks are about 10.75 *h* and 7.75 *h* in NAR-W and NAR-E. With a delay of about 2-4 *h*, a similar peak pattern occurs in the cirrus cycle of NAR. Cirrus coverage peaks in NAR-W at 06:30 UTC and 19:45 UTC, and peaks in NAR-E at 6:15 UTC and 17:45 UTC. This is a strong indication for a significant AIC contribution to the diurnal cycle.

## 4 Discussion

For several reasons the double cycle of cirrus cover in the NAR may be caused by aviation:

1. Both the observed cirrus cover and the air traffic show a temporal pattern with basically the same cycle, which can be identified as fingerprint of aviation contribution to cirrus cloud changes. The pattern is characterized by two narrow peaks with the first more narrow and larger than the second, and with a characteristic shorter than 12 h time difference between the times of peaks. The minima also show characteristic patterns: the evening minimum is lower and wider than the morning one (see Figs. 5, 6).
2. The diurnal patterns are statistically significant. The random fluctuations of the diurnal cirrus cover values are of order 0.03%, which is far smaller than the mean AIC amplitude of about 1%. The correlation coefficients are larger than 72% for all response functions.
3. MeCiDA consists of six individual tests, each of which has a sensitivity to different types of high ice clouds. The results of these six tests are added, to give the final product. In particular, simple threshold tests, temperature difference tests, and morphological tests are combined to detect as many of the high ice clouds as possible.

However, there are still possible contributions due to any natural effect triggering a diurnal cycle in cirrus coverage. Further work is in progress in order to eliminate natural contributions in the AIC signal.

## 5 Conclusions

Cirrus cloud cover was derived from Meteosat-8 observations using the MeCiDa algorithm [6] with high temporal resolution. Air traffic data were available with similar resolution from EUROCONTROL. Both exhibit a special, non-harmonic fingerprint in terms of a diurnal cycle with maxima in the early morning and early afternoon in NAR. The observed cirrus cycle is suggestive for an aviation induced cirrus contribution. Different from trend analysis, the present data and analysis methods allow to investigate an aviation contribution to cloud changes at short time scales although part of the induced cloud cover may be caused by non-aviation effects. Simple linear response models provide cirrus cycle estimates as a function of the air traffic cycle very similar to the observed cirrus cycle. The delay time of about 2 h suggest a corresponding lifetime of aviation induced cloudiness. Therefore, the results indicate a significant contribution of air traffic induced cirrus clouds to the total cirrus cover in that region. The cover of detected aviation induced cirrus clouds, if correct, amounts to about 1% in that region. Assuming a 60% detectability (value depending on the sensitivity of the satellite sensor and the used detection algorithms), the actual AIC cover could be 1.7%. Further analysis is ongoing on this issue.

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