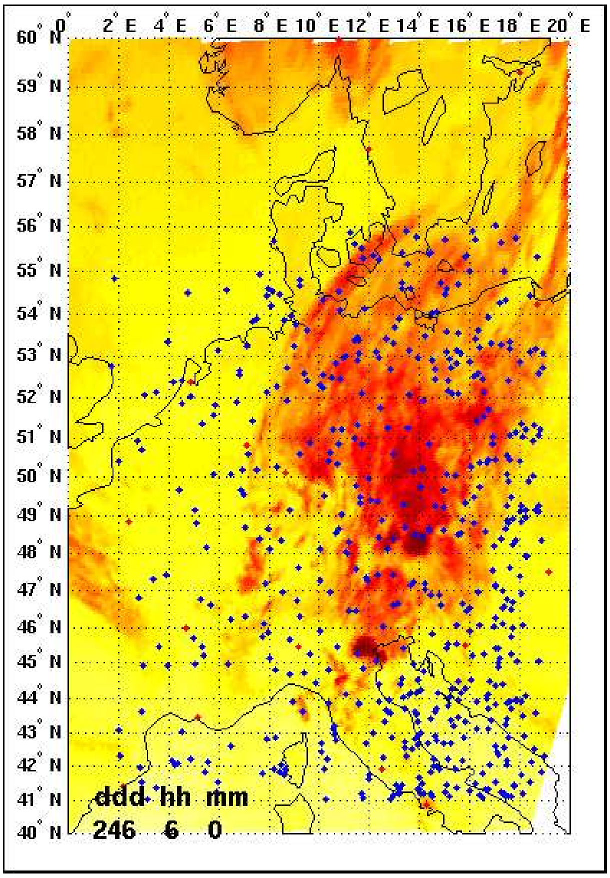
Danish Meteorological Institute
Ministry for Climate and Energy

Danish Climate Centre Report 09-02

Correlation of airplane emissions with Meteosat 7 IR/WV images

Johannes K. Nielsen



Colophone

Serial title:
Danish Climate Centre Report 09-02

Title:
Correlation of airplane emissions with Meteosat 7 IR/WV images

Subtitle:
Derivation cirrus nucleation properties, a feasibility study.

Authors:
Johannes K. Nielsen

Other Contributers:

Responsible Institution:
Danish Meteorological Institute

Language:
English

Keywords:
Contrails, cirrus, trajectories, ECMWF, Meteosat

Url:
www.dmi.dk/dmi/dkc09-02

ISSN:
1399-1957

ISBN:
978-87-7478-575-0

Version:

Website:
www.dmi.dk

Contents

Dansk Resume

Som en del af det Europæiske QUANTIFY projekt har det været meningen at DMI skulle analysere emissionsdata fra kommercielle passagerfly. Disse emissioners videre skæbne skulle følges ved hjælp af trajektorier beregnet fra ECMWF vindfelter. Det skulle derefter undersøges om man kunne detektere en ændring af cirrusdannelsen langs disse trajektorier ved hjælp af Meteosat 7 infrarøde billeder. I givet fald skulle det undersøges om denne information kunne anvendes til at fastlægge parametre for nukleation af cirrus partikler i luftmasser som har været forurenet af fly. Under dette arbejde blev det imidlertid klart at alle trajektorier, uanset om de er forurenede eller ej har en tilbøjelighed til at glide mod områder med klar himmel. Dette er en konsekvens af at konvektionsceller er associerede med divergens i den øvre troposfære, og det er et resultat i sig selv, og det bør undersøges om denne effekt skal inkluderes i globale modeller som inddrager flykondensstriber.

Abstract

Real time flight data for September 2005 provided by German Flight Control Service are used as initial coordinates for ECMWF trajectory calculations. These trajectories are then correlated with Meteosat 7 infrared images. A reference run of randomly initiated trajectories shows that there is a tendency of air parcels close to the tropopause to drift toward clear sky areas on diurnal timescale. The tendency has been confirmed by applying the same analysis, i.e. randomly initiated trajectories, to September 2004. Due to large variability of radiance, - and due to extremely dense airplane emissions over Europe it is not possible to infer any effect from airplanes on the radiances from this dataset.

1. Background and Introduction

As a part of the European QUANTIFY project, DMI's task was to analyse available commercial flight data from September 2005 in three steps: First calculate, by use of ECMWF reanalysis, trajectories initiated from positions where aircrafts had been located according to the flight data. Second run through the Meteosat 7 images, recorded every 30 minutes, and count the radiances in the pixels where trajectories passed over. Third, label these radiance values with their trajectory age, and produce plots of mean change in irradiance along trajectories as function of time. Last, evaluate the feasibility of optimizing the heterogeneous nucleation scheme in the MPC model by use of the obtained information. This report present the results of this analysis.

2. Method

2.1 Trajectories

ECMWF reanalysis fields latitudes 40-60°N, longitudes 0-20°E were downloaded for September 2005, levels 14-46 (60 level model), corresponding to approximately 10-750 hPa. The wind fields were interpolated on a lattice with equidistant altitude levels and $29\times30\times17$ points. The trajectory calculations were done with second order Runge Kutta and linear interpolation between grid points. In each step the altitude was adjusted to ensure that the parcel propagates along an isentrope. For each day 21×10^4 trajectories were traced up to 48 hours after their release. As baseline a run with 10 randomly initialized trajectories per 0.25 hours were performed for September 2005 and September 2004.

2.2 Infrared Images

Two broad bands series of the Meteosat 7 (first generation) product were used in the analysis, the WV band (5.5 - 7.2 μm) and the IR band (10-13 μm). Operational data, available each 1/2 hour, on a $2500\times$ 2500 pixel grid were downloaded from the EUMETSAT archives. The pixel counts, representative for the broad band radiance, of trajectories were evaluated by transforming the trajectory coordinates to pixel indexes. The software for unpacking and coordinate transformaion of the Open MTP format used by Eumetsat, were lifted from http://www-icare.univ-lille1.fr/tools/ (Antoinette Alias (ICARE)), generalized and converted to Matlab. The calibration constant of the WV channel were set to $\alpha_{WV} = 0.01$ Wm^{-2} sr^{-1} count^{-1}, with the space count C_{sIR} set to 6, and the calibration constant for IR channel were set to $\alpha_{IR} = 0.1$ Wm^{-2} sr^{-1} count^{-1}, with the space count C_{sIR} set to 5. The calibration relation $R = \alpha(C_p - C_s)$ gives the radiance[Eumetsat, 2000]. The radiance images have been pruned: A few obvious outliers has been removed, but also consequently all frames between 00:00 UT and 02:30 has been removed because both the mean WV and IR radiances are suspiciously low in many of these frames.

2.3 Flight records

Flight records were provided by The German Air Traffic Control for the whole of September 2005. For each day a few hunderd thousands emission points are registered. Among these only each 10'th point were taken and used for the analysis in order to reduce the computation time.

3. Results

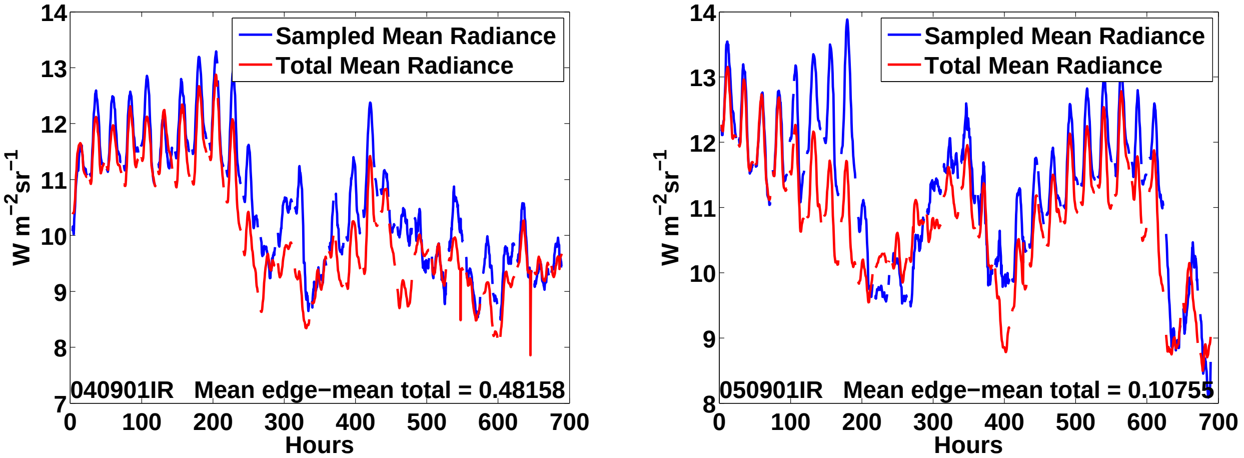


Figure 3.1: Mean radiance of IR channel over Central Europe September 2004 (left) and 2005 (right). The blue "sampled" curve is the mean over the set of randomly selected trajectories at a given time. Red curve is the total mean of the whole area. No area corrections has been used, so the northern areas are somewhat overrepresented in the random initialization. Generally the radiance decreases with latitude so this cannot explain the enhanced radiance.

3.1 Baseline

Approximately 3×10^4 trajectories were started from random positions between 9 and 11 kilometers altitude, 41-59° N 1-19°E throughout September 2004 and September 2005. Each trajectory was followed until it either left the simulation box or the time window (September 1'st through 29'th). Each half hour the radiances at the positions of all existing trajectories are recorded along with the radiances on the starting points for each trajectory. In addition the mean radiance of the simulation area is recorded every half hour. In Figures 3.1 and 3.4 the mean radiances during two whole months, calculated by two different methods, are plotted as function of time. The first method is simply a direct average over the whole simulation area. In the second method averaging is performed over the existing trajectories on a given time. It is seen that the first method (straight average) generally gives a lower mean radiance than the trajectory average does. The question is what causes this enhanced radiance effect. First it should be noted that the simulation box extends from 4 to 14 km altitude, and no trajectories escapes the box through the top or the bottom. Secondly there is a time dependence which is illustrated in figure 3.2 and 3.5.

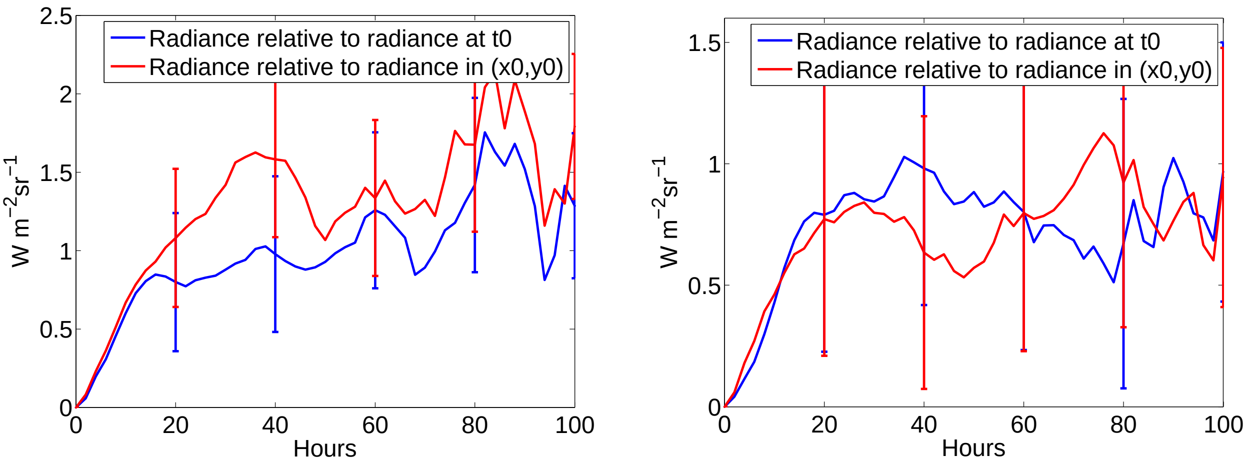


Figure 3.2: Mean IR Radiance along trajectories relative to initial radiance, as function of trajectory age (blue). The red curve shows almost the same, except here the reference radiance is the radiance at the initial spatial point evaluated at the actual progressed time. Left: September 2004 and right: September 2005.

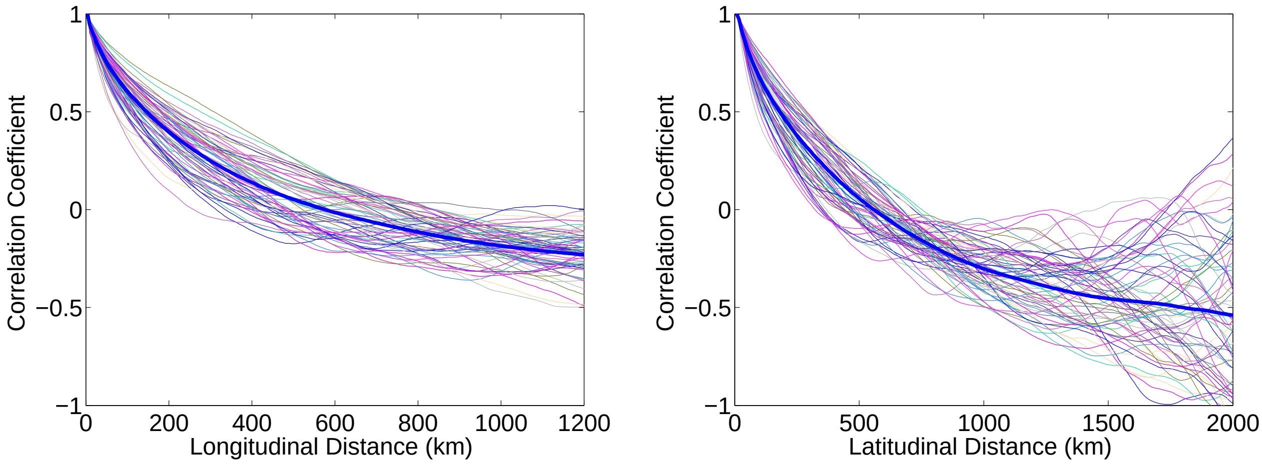


Figure 3.3: Longitudinal auto-correlation (left) and latitudinal auto-correlation (right). The uncertainty of the radiance increase in figure 3.2 is reflected in the difference between the two years. It is not trivial to put error-bars on these functions since the trajectories are by no means statistically independent. The errorbars are estimated in the following way: A spatial (longitudinal) auto-correlation function was calculated from the series of Meteorosat images. The auto-correlation reaches zero at an approximate correlation length scale of 450 km, but actually the images are slightly anti-correlated at larger distances, and this anti-correlation does persist at least to 1200 km which is approximately the scale of the simulation box. The latitudinal auto correlation is harder to calculate because there is a climatic north-south gradient, which is the reason for the strong auto-correlation. Strictly speaking it is not possible to draw more than one independent sample from each satellite image because the correlation length exceeds the image size. Since the response time is close to the duration of one diurnal cycle it is assumed that it is possible to produce only one effectively independent trajectories per day. The radiance increase function is composed of a broad ensemble of functions each representing one trajectory with variance σ^2_{Ra}. Thus the error-bars of figures 3.2 and 3.5 are calculated as $\sqrt{(\sigma^2_{\mathrm{Rad}}/N)}$, where $N = 27$ is the number of days used in the analysis.

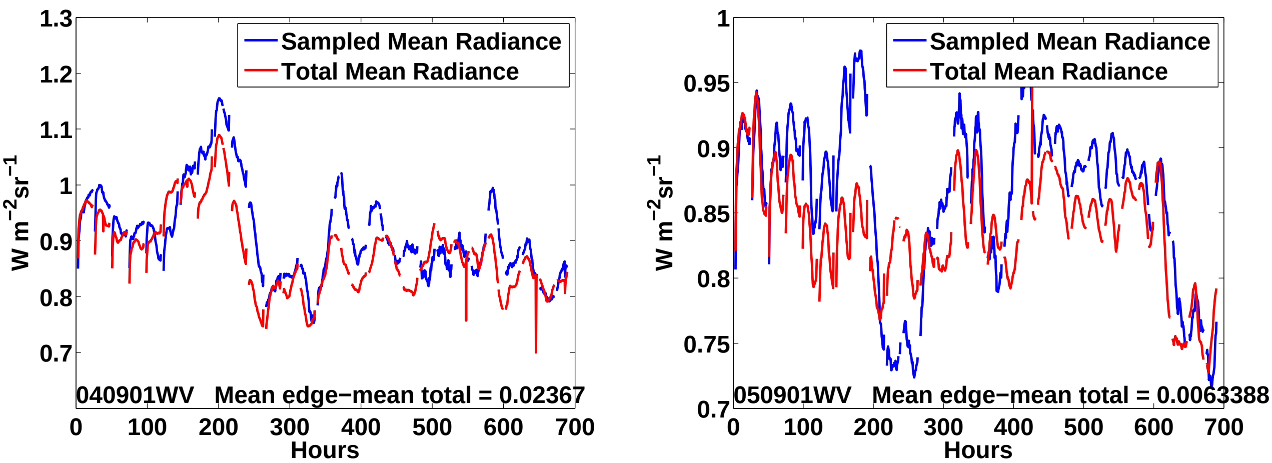


Figure 3.4: Mean radiance of WV channel over Central Europe September 2004 (left) and 2005 (right). The blue “sampled” curve is the mean over the set of randomly selected trajectories at a given time. Red curve is the total mean of the whole area.

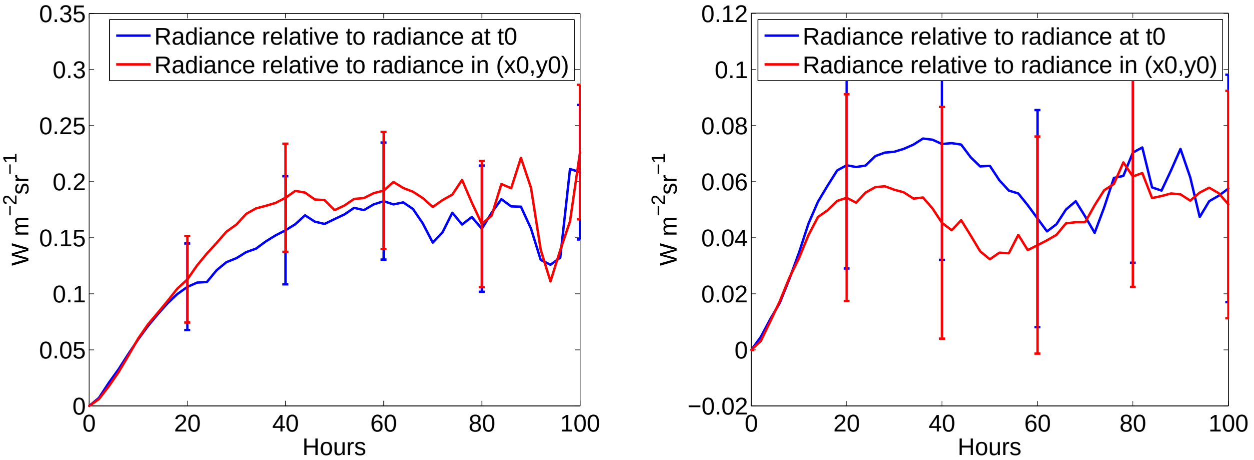


Figure 3.5: Mean WV Radiance along trajectories relative to initial radiance, as function of trajectory age (blue). The red curve shows almost the same, except here the reference radiance is the radiance at the initial spatial point evaluated at the actual progressed time. Left: September 2004 and right: September 2005. The errorbars are calculated as in 3.2.

Note that the random trajectories are started at all times with equal probability, so the diurnal cycle should not influence the trajectory radiances. There is, however, a tendency for the mean radiances to increase along trajectories during the first 20-30 hours for then to saturate on a higher level. In the caption of figure 3.3 a discussion of the uncertainty establishes that the effect is probably not due to noise. There are basically two ways for this radiance enhancement to happen. Either the trajectories drift towards areas with higher radiance (clearer sky), which would then be a physical effect which could have influence on the climate impact of contrails and contrail cirrus, - or alternatively the high radiance and low radiance parcels do not leave the box with the same probability. The latter possibility would then be an artifact. In both cases the effect is an obstacle for the intended analysis of nucleation properties along trajectories. Now the question is whether one of these causes can be excluded? This question has to be dealt with before continuing with the actual flight data analysis. Maybe it is better formulated like this: Either the value of each ensemble member increases on average, or the ensemble members values stays constant on average, while they are removed from the ensemble with unequal probability - or as an inconvenient third possibility both effects could be present simultaneously. For each half hour the mean radiance on the trajectories leaving the ensemble within that specific time frame were calculated for September 2004/2005, in order to distinguish between the two possible reasons for the radiance increase. It appeared that the sub-ensemble departing from the simulation box in each time step had a *higher* mean radiance. In figures 3.1 and 3.4 the numbers reported in the bottom are the average differences between radiance of departing trajectories and radiance of the whole ensemble in $W/m^2/sr$. The “Mean Edge” denotation is maybe a little misleading because only members actually leaving the ensemble is counted. Therefore one can conclude that for these particular periods the radiance increases are due to some geo-physical effect, which of course could be specific for this period.

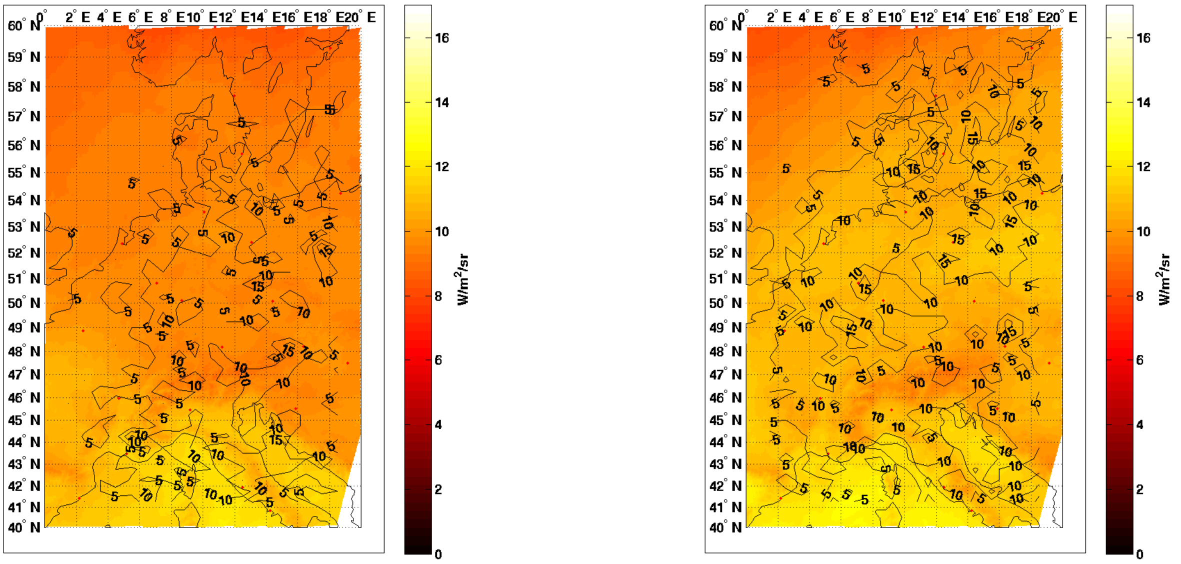


Figure 3.6: Mean IR radiance during September 2004 (left) and 2005 (right) (color scale). The black contours shows the “mean density of 25 hours old trajectories”. I.e. for each trajectory the position 25 hours after its release is marked. From the distribution of these positions a probability density is calculated and plotted as contours. The normalization is arbitrary (number of trajectories per 0.5 deg^2).

Figure 3.6 gives one hint of what could be going on. The mean radiance shows a tendency to decrease in certain areas, - most prominently over the North Sea and the Alps (2005). The aged trajectories have a tendency to avoid these areas, especially over the North Sea. This may to some extend be caused by the lows coming from west and the partly dissolve as they cross the continent. The Alps are characterized by periods of intense convection. The picture is not so clear in 2004 though where the enhanced radiation along trajectories is most pronounced. The North sea is still depleted from trajectories, but the tendency of growing radiance across the continent is absent, so in this case the reason must be found elsewhere. I suggest that it is a more local effect; i.e. the trajectories respond to local convection. It is possible that air parcels in the upper troposphere are pushed away from such an intense convective area by the up welling air masses, and this could increase the radiance along the trajectories. If the convection is not located the same place every day, the effect will be smeared in the average pictures in figure 3.6. If this idea is correct one could expect a systematic decrease of altitude along trajectories because they moves into less convective (descending) areas. This is, however, not the case. Figure 3.7 shows that the trajectory mean altitudes are actually decreasing in 2005 and increasing in 2004. So even though September 2004 and September 2005 were qualitatively different in terms of mean vertical wind velocity the trajectory enhanced radiance effect persisted.

Finally the mean radiances along the real trajectories, initialized with actual flight data, is plotted in figure 3.8. The spread is quite large, but so it were in the random ensemble. The problem, however, is that the airtraffic is not equally distributed throughout the diurnal cycle. In fact they most traffic occurs in daytime where the radiance is highest. What can be done is to plot the radiance relative to the mean radiance of the whole area at the particular time (green curves in figure 3.8). Actually this should converge towards the red curve, provided that the initial points are randomly distributed, which it also does. The radiance enhancements in figure 3.8 resembles more or less the radiance enhancements of the background run well within the error bars. Obviously there are some obstacles preventing a study of possible changes of microphysical properties downwind from aircraft

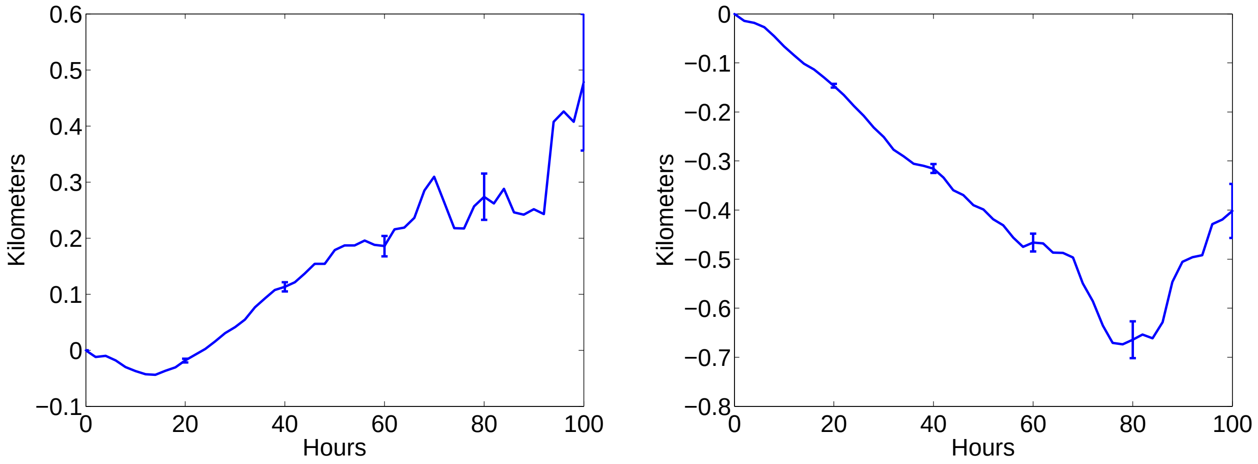


Figure 3.7: Average altitude along trajectories as function of time. Left: September 2004 and right: September 2005.

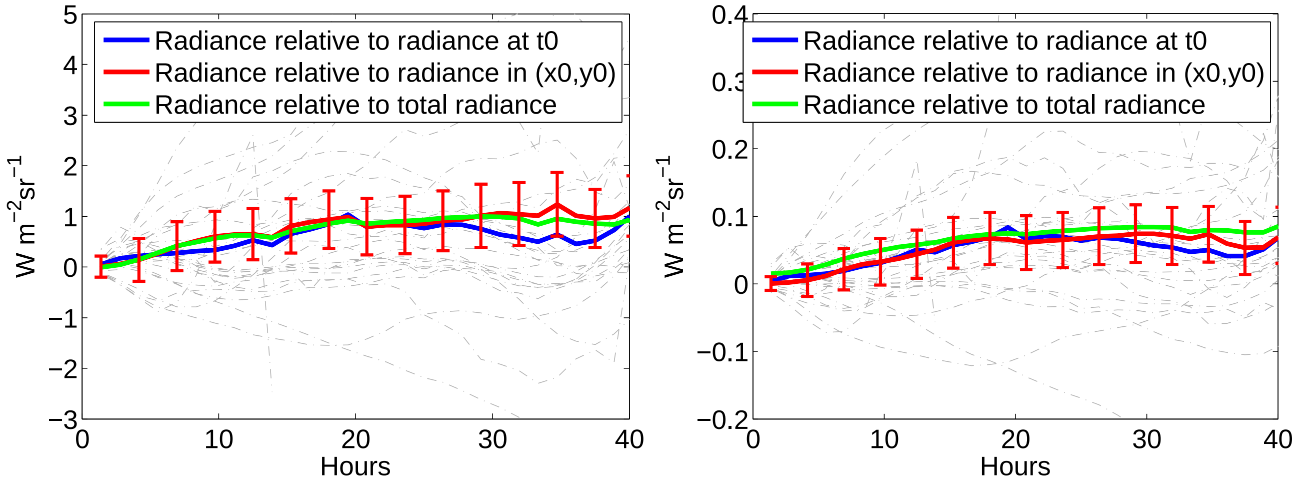


Figure 3.8: Average change in mean IR (left) and mean WV (right) radiance along trajectories, started from real airplane data, as function of time. September 2005. The blue curve is calculated by subtracting the radiance at $t = 0$ for each trajectory and the grey curves are the averages of this property for individual days. The red curve is produced by subtracting the radiance in the initial spatial point at the actual given time, as in the baseline runs. The green curve is the radiance with the mean radiance subtracted. The errorbars are calculated as in 3.2.

emissions. Any time dependent change must be evaluated relatively to the background change of radiance along trajectories, which is not trivial. In order to achieve this, seasonal variations and precise information of the background radiation enhancement must be established by running the analysis over longer time and larger geographical areas. The large variability is a challenge. In order to reduce the error bars on the radiance enhancement functions with a factor of 10 one would virtually need a 100 year data set (100 versions of September), or e.g. a 10 year data set on 10 independent equivalent sites. That could be achieved for the background run, but for the actual flight data it is not possible. Furthermore there is the problem that each day contains more than 200000 registered emission points over the area, which means that it is hard to interpret the baseline run, simply because it can never be "clean". A less frequently visited area than Central Europe would be a better choice for this study.

3.2 Discussion

In order to detect changes in Meteosat IR/WV images related to air traffic it is necessary to characterize the background radiances and their inherent correlations with ECMWF winds. This task has turned out to be less trivial than expected because there is a surprising correlation between trajectory age and radiance in the raw data. The correlation seems to have a physical origin, but it is unclear what causes the effect. The effect is robust, in the sense that it is present both in the 2004 and the 2005 analysis, and the difference between the radiance increase functions between the two years are consistent with the estimated uncertainty derived from the radiance variations on diurnal timescale. A plausible explanation is that diverging windfields above convective areas are transporting airparcels towards non-convective areas with higher radiance. A characteristic wind velocity may be derived from the spatial and temporal correlation functions: v= 450 km/24 hours (5.2 m/s). This is the wind needed to depart from a convective area within 24 hours. A very naive consideration, implying that the convective area is circular with a radius of 450 km, leads to an estimated divergence of 23×10^{-6} s^{-1}. In [Schmetz et al., 2005] a measure of the divergence is calculated directly from Meteosat 8 images in a tropical mesoscale convective system. These authors finds divergence values up to 450×10^{-6} s^{-1}, which of course is an extreme case. This is mentioned only to point out that the divergence winds are comparable to the synoptic winds in magnitude, and therefore the convection induced divergence could be, at least a part of, the explanation of the enhanced radiance along trajectories. It is noted in [Schmetz et al., 2005] that ECMWF divergences do not compare too well to the divergences derived from satellite. So if this divergence driven departure from convective areas is the right theory one should anticipate a more pronounced enhancement effect if a study, similar to the one presented here, were performed on pure model data, using the outgoing long wave radiation from the ECMWF instead of the Meteosat data. It would also be interesting to do the analysis with a larger dataset, including more seasons. Alternatively a study where the wind divergence is derived from the satellite images themselves could shed more light on the topic. The question is whether this mechanism should be taken into account when evaluating the impact of air traffic. The radiative forcing of cirrus is more severe if the cirrus are positioned over an otherwise clear troposphere, so an implication of this process could be enhanced radiative impact of air plane induced changes in cloud formation. On the other hand air parcels are generally expected to sink in areas apart from convective systems, and therefore any cirrus-like clouds would be expected to sublimate faster than they would have done, had the effect not been there. These are two competing processes, and the balance between their mutual impacts, could be investigated with microphysical modelling of air parcels undergoing transport from convective to non-convective areas.

4. Conclusion

The trajectory age/radiance correlation seems to be robust. It may be partly caused by lows over the Atlantic dissolving over the continent, and partly by convective outflow from continental convective systems. It is worthwhile to consider this behaviour when assessing the impact of air-traffic on climate. The original intension with this study, to derive microphysical nucleation parameters by combining the provided flight data, the ECMWF fields and the Meteosat images is not feasible for several reasons, including large variance of radiance and absence of a clean background reference. Such an analysis *could* be possible in a less visited area, depending on the strength of the anticipated indirect aerosol effect. The present analysis does not give a clue about the strength of any indirect aerosol effect.

5. References

[Eumetsat, 2000] Eumetsat (2000). http://www.eumetsat.int/. Technical report, Eumetsat.

[Schmetz et al., 2005] Schmetz, J., Borde, R., Holmlund, K., and König, M. (2005). Upper tropospheric divergence in tropical convective systems from Meteosat-8. *Geophysical Research Letters*, 32:24804.

Previous reports

Previous reports from the Danish Meteorological Institute can be found on:
http://www.dmi.dk/dmi/dmi-publikationer.htm