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Potential climatic effects of cirrus contrails for the subarctic setting of Fairbanks, Alaska

G. Wendler, M. Shulski, and **B. Hartmann**

With 10 Figures

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Summary

Continuous all-sky camera images supported by direct visual observations of jet contrails have been carried out in Fairbanks since March 2000. These data together with FAA information of all commercial flights and the twice-daily radiosonde data, give the meteorological conditions at flight level under which contrails are formed. If we correct for daylight and clear sky conditions, which make contrail observations possible, winter has the maximum and summer the minimum in the occurrence of contrails. This is a result to be expected, as the layer in which contrails can form has in winter nearly twice the thickness when compared to summer.

In November 2002, a radiation station was added to the observations. For a contrail in the path between the sun and the observation point, we found a strong decrease in the direct beam radiation; this loss was in part compensated by increased diffuse radiation. The combined effect leads to a reduction in global radiation. However, the back radiation of the atmosphere in the infrared region of the spectrum increased somewhat. Altogether, this affects the net radiation negatively in the summer, but positively in the winter.

Comparing the observed temperature conditions of clear days with those of high-level cloud cover, we found for 8 months of the year a higher temperature for days with clouds. For the other four months, May through August, clear days were warmer. On the average of the year, days with high-level cloudiness were warmer than clear days as well as days with low-level overcast.

High-level cloudiness has increased in Alaska over the last decades. This increase in cloudiness was more pronounced under the much-traveled flight corridor from Anchorage to Europe than for more remote areas of Alaska. Further, we found a temperature increase for the same time period, which was most pronounced in winter, followed by spring, a result consistent of the expectations of increased high-level cloudiness.

1. Introduction

About half a century ago, regular jet air traffic commenced. Presently, these planes typically fly at the 10,000 m level. In the tropics and midlatitudes the tropopause is above this level, and the planes fly in the upper troposphere, where enhanced vertical mixing and precipitation processes take place. For the subarctic setting of Fairbanks, the tropopause is lower, and for part of the year the planes fly in the lower stratosphere, where the conditions are much more stable, vertical mixing is reduced, and the residence time of water vapor is prolonged. This fact will lead to an enhancement of the climatic effect of contrails (Graßl, 1990; IPCC, 1999).

Fairbanks lies below the much traveled flight corridor from Anchorage to Europe (Fig. 1). Heavily loaded cargo planes, mostly Boeing 747, fly daily from Asia to Europe, refueling in Anchorage. Since 1970, the number of landings at the Ted Stevens International Airport at Anchorage has increased 4-fold, while the total freight increased even more, 8-fold. The total

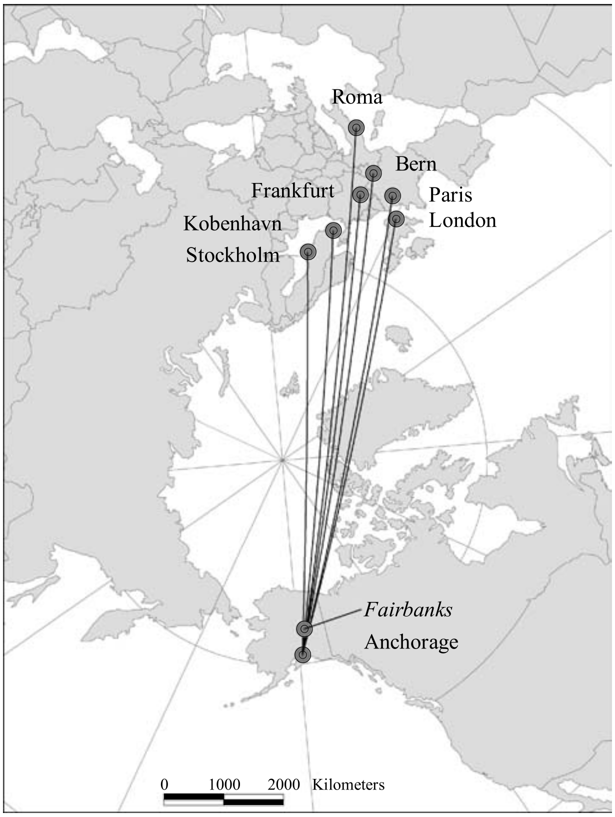

Fig. 1. Flight pass (great circle route) between Anchorage, Alaska, and major European airports. Note, that Fairbanks lies below the much traveled flight route

daily number of take-offs is presently 250, and the mean amount of daily cargo is 800,000 kg.

2. Background

Contrails are a frequently observed phenomenon in Europe and North America, where jet aircraft traffic is common. They can be very striking against a blue sky (Fig. 2), and even a casual observer can see large differences in appearance: some disappear after a few seconds, other ones might last longer time periods and might drift with the wind aloft, and other ones might spread over part or the whole sky, eventually covering it with a thin cirrus cloud cover.

Theoretical consideration of cirrus contrail formation goes back to Schmidt (1941) and Appleman (1953) and since then a great amount of literature has been accumulated. The water vapor saturation pressure is a logarithmic function of the temperature; hence, in a cold air mass the formation of a contrail is more likely. If the air is very cold, contrails of very short duration

Fig. 2. Contrail observed over Fairbanks, Alaska on 16 December 1999 looking towards the South (Photo taken by Sam Harrel, used with permission of Fairbanks Daily News-Miner)

can even form with a relative humidity value below saturation, as under these circumstances the mixing ratio deficit is small. However, they will only persist for extended times if the air is supersaturated with respect to ice. Besides atmospheric parameters, aircraft characteristics such as air speed, engine type, fuel consumption and sulfur content of the fuel are of importance (Busen and Schumann, 1995).

Minnis et al. (2003) carried out a detailed study on contrail frequency in the contiguous US from surface observations, while Carleton and Lamb (1986) employed the high-resolution Defense Meteorological Satellite Program (DMSP), from which they were able to distinguish contrails from naturally occurring cirrus. Modeling efforts were carried out by Travis et al. (1997). Possible influences of increasing air traffic on the structure of the atmosphere and the climate are discussed in the comprehensive investigation by the IPCC (1999).

When contrails are present, an increase in diffuse radiation is observed. The magnitude of this increase depends on the percentage of the sky that is covered by the contrails. The direct beam radiation is not affected unless the contrail lies within the intervening path between the solar disk and the measuring point. Under those circumstances a substantial decrease in the direct beam can occur, while the global radiation is only slightly reduced, as the decreased direct beam radiation is in part compensated by the increased diffuse sky radiation. Most of the direct beam radiation hitting the contrail is forward scattered, while reflection and absorption are of less importance. Further, the long wave incoming radiation is increased. Hence, the combined radiative effect of contrails on the surface radiation budget is always positive at night or at times when the global radiation is weak. However, in summer at noon the combined effect can be negative even in the subarctic. This is especially true as contrails normally form fairly close to the tropopause, the coldest part of the atmosphere. Hence, the additional infrared radiation from these cirrus contrails is less than for other clouds, which are occurring at lower (and warmer) altitudes. As the cloud amount has great importance on the back radiation of the atmosphere, cloudy days are in winter, on average, warmer than clear ones. Hence, in winter increased cloudiness due to cirrus contrails should lead to warming, while in summer it should result in cooling. Integrated over the year, enhanced cloudiness will lead to increased temperature in the subarctic (Seinfeld, 1998).

3. Observations

3.1 Jet contrails

In March 2000 we established an observational program of contrails at the University of Alaska in Fairbanks (Wendler and Stuefer, 2002). Like in lower latitudes, contrails are frequently observed for this subarctic setting. Continuous digital images of the sky using a fish-eye lens (Fig. 3) are being obtained, supported by FAA flight data (FlyteComm) and radiosonde ascents at the Fairbanks International Airport. Images were taken originally in 2.5-minutes intervals and since October 2002 in 1-minute intervals and are frequently supplemented by visual observations. FlyteComm supplies the position, altitude, plane type and direction in real time, in addition to other data, for all flights within 50 miles of Fairbanks. Data for all commercial flights are obtained, however, we do not have access to military flight data. Our data set allows, in the absence of opaque cloud cover and darkness, to judge the occurrence/non-occurrence of contrails. We distinguish 3 contrail classes, namely short lasting (<1 minute), medium duration (1–10 minutes) and long lasting contrails (>10 minutes). From March 2000 to December 2003 we observed a total of 560 contrails, 42% were of short, 26% of medium and 32% of long duration. Looking over the annual distribution, spring (March, April, May) is the season of the year during which most contrails were observed. However, it is also the season during which the minimum in cloudiness is observed, making observations more frequently possible. Correcting for this, winter displays the maximum and summer the minimum in occurrence of contrails. This is understandable, as the layer in which contrails are expected to form (Stuefer and Wendler, 2004) is in winter nearly twice as thick as in summer. In the context of their radiative influence, the long lasting ones are here of greatest interest.

Fig. 3. All sky camera photo of a spreading contrail, Fairbanks, 17 October 2003

Schmidt (1941) and Appleman (1953) carried out original work on the formation of contrails. Using an algorithm based on work from Schumann (1996) and using the profile data from the Fairbanks radiosonde, we were able to predict the occurrence/non-occurrence of contrails 91% correctly. Using atmospheric profiles derived from MM5, similar values were found for real time, however, for the 30 hour forecast, the success rate decreased by 6%. Considering only long lasting contrails (Fig. 4), 68% are found in the upper troposphere, while 32% are located in the lower stratosphere. The tropopause changes altitude over the year, from just below 11,000 m in summer, to somewhat above 9,000 m in winter. In winter the mean thickness of the contrail forming layer as determined by our contrail forming algorithm (Stuefer and Wendler, 2004)

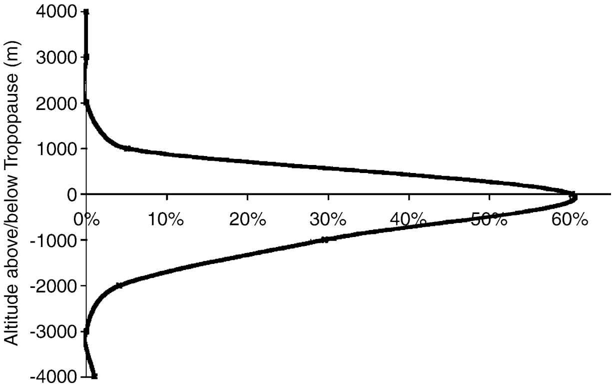

Fig. 4. Altitude distribution of longer lasting contrails (>10 minutes) in reference to the tropopause. Positive values refer to contrails in the stratosphere

is 3,300 m, but is reduced in summer to 1870 m. Long lasting contrails are found at cold temperatures, with the highest frequency of occurrence being observed around −56 °C.

3.2 Radiative measurements

We established a climate and radiation station on the roof of the Geophysical Institute beside the dome housing the all-sky camera. This station has operated satisfactorily since November 2002. In the context of this study, only the following four instruments are of interest:

1) The direct solar radiation was measured with an Eppley normal incident pyrheliometer, which is mounted on a solar tracker. This instrument measures the direct radiation on a surface perpendicular to the solar rays in the wavelength from 280–2800 nm
2) The global radiation, consisting of direct solar and diffuse sky radiation, was measured with an Eppley precision spectral pyranometer on a horizontal surface.
3) The diffuse sky radiation was measured also with an Eppley precision spectral pyranometer equipped with a shadow band blocking out the direct solar radiation.
4) The long wave incoming radiation was measured with an Eppley precision infrared radiometer on a horizontal surface.

All data are collected continuously at 1 minute intervals and stored on a Campbell Scientific data logger. They are also accessible by computer in real time, as the system is networked.

The global radiation displays a strong annual course in Fairbanks (Dissing and Wendler, 1998), as daylight of less than 4 hours in midwinter increases to nearly 22 hours in midsummer. In midwinter there is hardly a systematic diurnal variation in temperature, as the solar radiation is weak due to the low solar elevation, which has a maximum of 3° at solar noon.

4. Results

4.1 Long lasting contrails

For climatic effects, short and medium lasting contrails are of minor interest, and we will concentrate on long lasting contrails, which were defined previously as >10 minutes. They are observed most frequently at a temperature of −56 °C, but the temperature range is large, spanning from −45 °C to −70 °C (Fig. 5a). This represents a lower temperature range than contrails of shorter duration. The relative humidity over ice varied widely (Fig. 5b), but generally showed an increase with increasing persistence

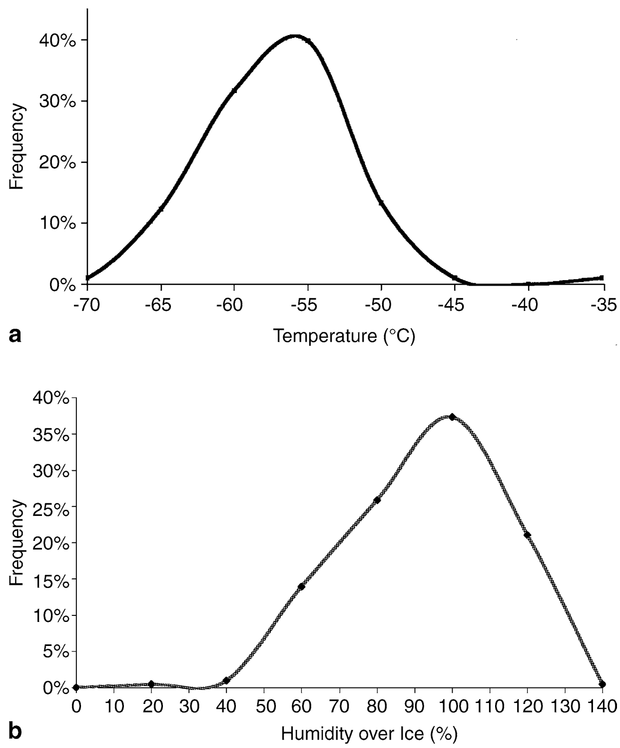

Fig. 5. Temperature (**a**) and relative humidity (**b**) at flight level for long lasting (>10 minutes) contrails at Fairbanks, Alaska

of contrails. It should be pointed out that humidity measurements of radiosondes are not good at very low temperatures (Elliott and Gaffen, 1991). Miloshevich et al. (2001) showed a strong bias towards low humidity values at low temperatures for the Vaisala RS80-A radiosonde. He reported underestimation factors in relative humidity of 1.3 at −35 °C, and 2.4 at −70 °C. The measurements of our database were obtained with the Vaisala RS-80-57H for the upper air measurements, for which no correction factors are available; however, the data in Fig. 5b suggest strongly, that the humidity values are still too low.

Contrails of 10-minute duration are still very short for having any climatic effect; hence we concentrate on contrails lasting 1 hour or longer. The duration of the contrails was obtained by analyzing the all sky digital imagery, which was originally taken in 2.5-minute intervals, and since 2002 in 1-minute intervals. In Fig. 6 temperature, relative humidity over ice, mixing ratio deficit and wind speed at flight level are presented as a function of the contrail duration. The duration of a contrail was a function of decreasing temperature, increasing relative humidity, decreasing mixing ratio deficit and increasing wind speed, even though for all parameters a great amount of scatter is observed. The mixing ratio deficit, which is the amount of water vapor necessary to add to an air mass to reach saturation, combines nicely temperature and relative humidity. The lower the value, the easier it becomes to reach saturation. We found values between 0.01 and 0.18 (g water/kg air). The mean mixing ratio deficit (mrd) for contrails lasting between 1–2 hours is 0.07 g/kg, and for those lasting more than 2 hours 0.03 g/kg, while short duration contrails form, on average, at higher values of mixing ratio deficit. The higher wind speeds for very long lasting contrails are not unexpected, as they facilitate the spreading.

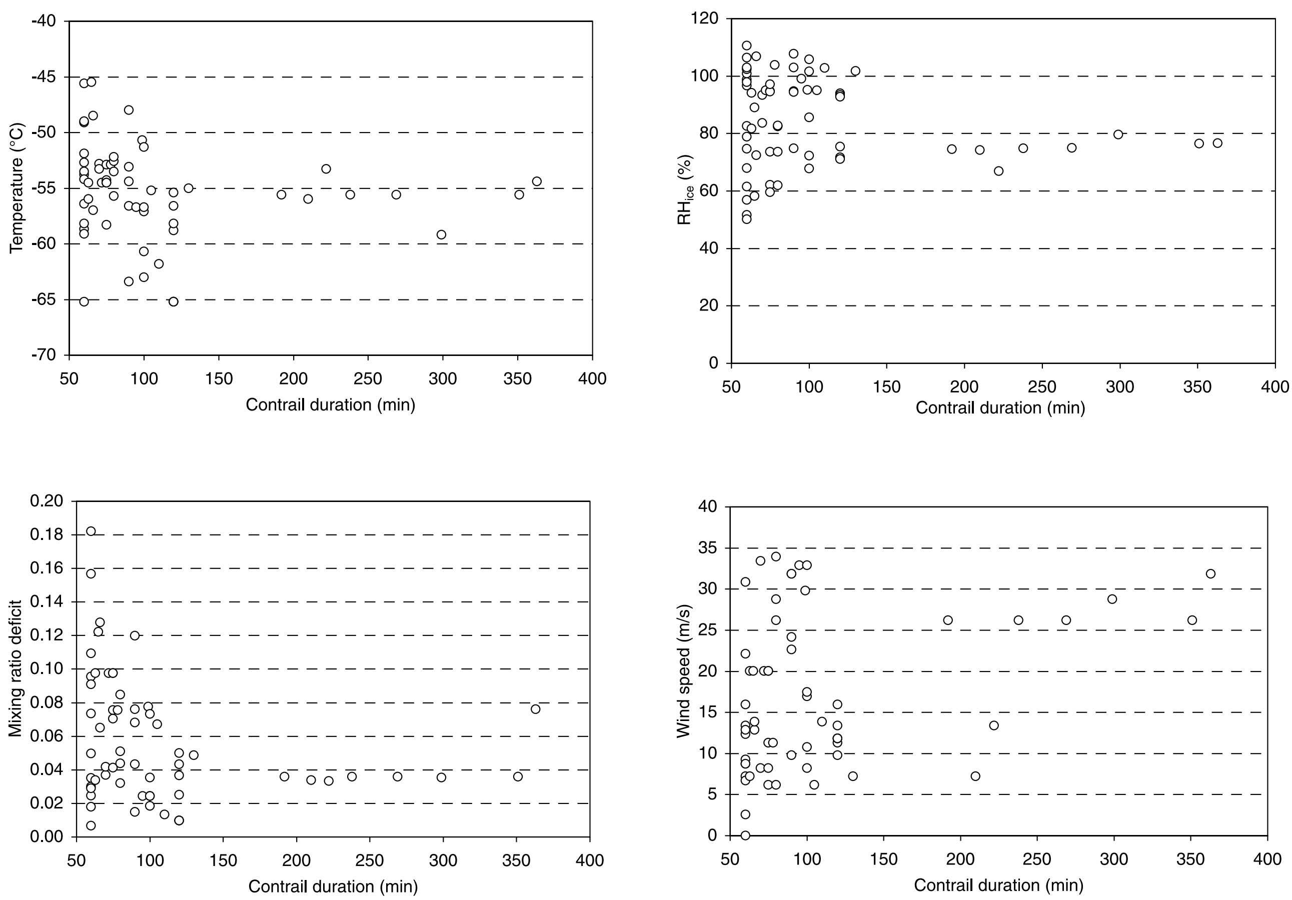

Fig. 6. Temperature, relative humidity, wind speed and saturation mixing ratio deficit as function of contrail duration for contrails lasting longer than 60 minutes, Fairbanks, Alaska

Table 1. Climatological conditions at flight level for the formation of contrails lasting more than 1 hour, Fairbanks, Alaska. T = temperature, RH = relative humidity, Mrd = mixing ratio deficit, u = wind speed, Dt = distance to tropopause, negative values below tropopause, $d\theta/dz$ = potential temperature gradient at flight level, du/dz = wind speed shear, Ri = Richardson number, σ = standard deviation

	60–120	>120	all
T (°C)	−54.7	−57.8	−55.5
σ	4.3	4.0	4.4
RH (%)	86.0	79.9	84.6
σ	16.8	10.3	15.7
Mrd (g/kg)	0.064	0.035	0.056
σ	0.040	0.017	0.038
u (m/s)	16.6	17.4	16.8
σ	9.6	8.4	9.3
Dt (m)	−697	−313	−603
σ	1025	667	959
$d\theta/dz$ (°C/100 m)	1.44	1.55	1.47
σ	1.05	1.23	1.10
du/dz (ms^{-1}/100 m)	2.7	2.3	2.6
σ	2.7	1.6	2.4
Ri	0.06	0.10	0.07
σ	0.13	0.25	0.18

In Table 1, the mean meteorological conditions at flight level for contrails lasting 1 hour or longer are presented. Sometimes it is difficult to distinguish between aged contrails and natural occurring cirrus in a single image, however, the time series of sky observations made such a distinction possible. We subdivided the data into two classes: 1–2 hours and >2 hours. It can be seen that for contrails lasting above 2 hours the temperature is lower, the relative humidity is higher, the mixing ratio deficit is lower, and the distance to the tropopause is less when compared to the 1–2 hour class. However, no systematic differences were observed in wind speed, shear in wind speed, temperature gradient with height and Richardson number. The Richardson number is a stability criterion, being a function of the ratio of the potential temperature gradient to the square of the vertical wind shear. We had hoped that the duration of the contrails could be related to it, however, our number of observations might be not large enough to find meaningful results. From all very long lasting contrails, 73% were found in the upper troposphere, 9% at the tropopause (within 100 m), and 18% in the lower stratosphere, while for the summer months (May through September), all contrails were found at or below the tropopause. About twice the frequency of stratospheric contrails were found if we consider all observed contrails. This is understandable as the temperature in the lower stratosphere has already increased from the tropopause, which caused drying of the air mass, hence contrails do not last so long at that region. Further, the table shows that the distance to the tropopause is less for the longest lasting contrails, again understandable, as the lowest temperatures are observed at the tropopause.

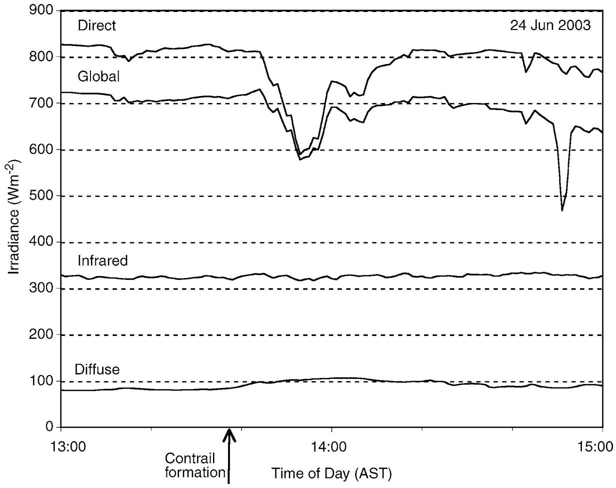

Fig. 7. The effect of a contrail on the radiation fluxes for a summer day (24 June 2003) at Fairbanks, Alaska

4.2 Radiative effects

As mentioned previously, the radiation fluxes at the surface are affected by the presence of jet contrails. In Fig. 7 we present an example of the effect of a contrail on the radiation fluxes for close to midsummer (24 June 2003). The contrail was formed at 13:39 AST (close to local solar noon) by a Boeing 747-200 flying from Anchorage to Hamburg at an altitude of 9144 m. The ambient temperature at flight level was −48.2 °C, the relative humidity over ice was 59% and the wind speed was light with 6.5 m/s. The contrail moved in the line of sight between the sun and the radiation instrumentation some 12 minutes later. The direct beam radiation measured perpendicular to the solar rays decreased from 814 Wm^{-2} to 617 Wm^{-2}, a loss of 24%. However, for the same time period the diffuse radiation increased by 20%, a sign that part of the radiation is not reflected back to space or absorbed, but forward scattered. The global radiation, which represents the sum of the direct solar radiation on the horizontal surface and the diffuse sky radiation, decreased by 16%. The infrared radiation showed little change; it decreased by less than 1%. This is a small change, as in summer the atmosphere is relatively warm and moist, and most of the back radiation of the atmosphere is derived from the lowest layers of the troposphere under clear sky conditions. Hence, the contrail, which has formed close to the tropopause at an ambient temperature of −48.2 °C increases the back radiation in the IR only slightly. The situation is different in winter, when the atmosphere is cold and dry. Under these circumstances the contributions in the infrared region of the spectrum become more important. In addition, the position of the contrail in reference to the solar disk is, of course, for the infrared fluxes of no importance.

In Table 2 the effects of contrails, which moved in the direct path of the sun, are evaluated for the different radiative fluxes for six observed occasions. In all cases the direct beam, which is measured perpendicular to the sun's rays, and the global radiation, decreased. In absolute terms the decrease in the direct beam radiation was always larger. The global radiation decreased by values between 4 and 16%, showing the importance of contrails on the incoming solar radiation. Large variations are expected, as the optical characteristics of contrails vary widely, as can be seen by visual observations. In addition, the solar elevation, and with it the path length through a contrail layer, varies with time and season. The diffuse radiation increased in all cases between 7 and 29%; this was to be expected as ice crystals are a good forward scatterer. The effects of a contrail on the global radiation would be more pronounced if part of the losses in the direct beam radiation were not balanced by increased diffuse radiation.

The effects on the long wave incoming radiation are small and mixed. For the infrared radiation it makes little difference where a contrail is located in relation to the sun. More important is the percentage of the sky which is covered by it. Hence, spreading contrails should give increased values, while dissipating ones will reduce the value.

In Fig. 8 the global and the infrared incoming radiation as well as the temperature are presented for a winter and spring day. The diurnal course is given for 1-minute intervals for high-level overcast days. For the winter case (Fig. 8a), there is a very weak response in the diurnal temperature variation being observed. The temperature follows closely the long wave incoming radiation. The global radiation, which reaches its maximum around 14:00 AST (close to solar noon) with 50 Wm^{-2}, has little observable influence on the temperature. This might be partly due to the fact that most of the shortwave radiation is reflected due to the high albedo of the snow cover.

The spring case (Fig. 8b) is quite different. Both temperature, and to a lesser extent, the infrared radiation, display a diurnal variation.

Table 2. The effects of contrails in the direct path of the sun's rays on the different radiative fluxes (Wm^{-2}), Fairbanks, Alaska

	Global	Diffuse	Direct	Infrared
4 June 2003				
clear	704	100	813	314
contrail	663	111	736	318
change	−41	+11	−79	+4
change %	−5.8	+11.1	−9.7	+1.2
24 June 2003				
clear	714	86	814	322
contrail	598	103	617	320
change	−116	17	−197	2
change %	−16.2	+19.7	−24.2	−0.6
19 Aug. 2003				
clear	572	47	851	298
contrail	517	56	782	298
change	−55	+9	−69	0
change %	−9.6	+21.3	−8.1	0
15 Oct. 2003				
clear	233	63	646	245
contrail	223	68	576	245
change	−10	+5	−71	0
change %	−4.3	+7.9	−10.9	0
16 Oct. 2003				
clear	232	31	780	227
contrail	206	40	667	225
change	−26	+9	−113	−2
change %	−11.3	+29.0	−14.5	−0.9
22 Oct. 2003				
clear	285	46	610	207
contrail	256	51	577	209
change	−29	+5	−33	2
change %	−10.2	+11.1	−9.4	+1.0

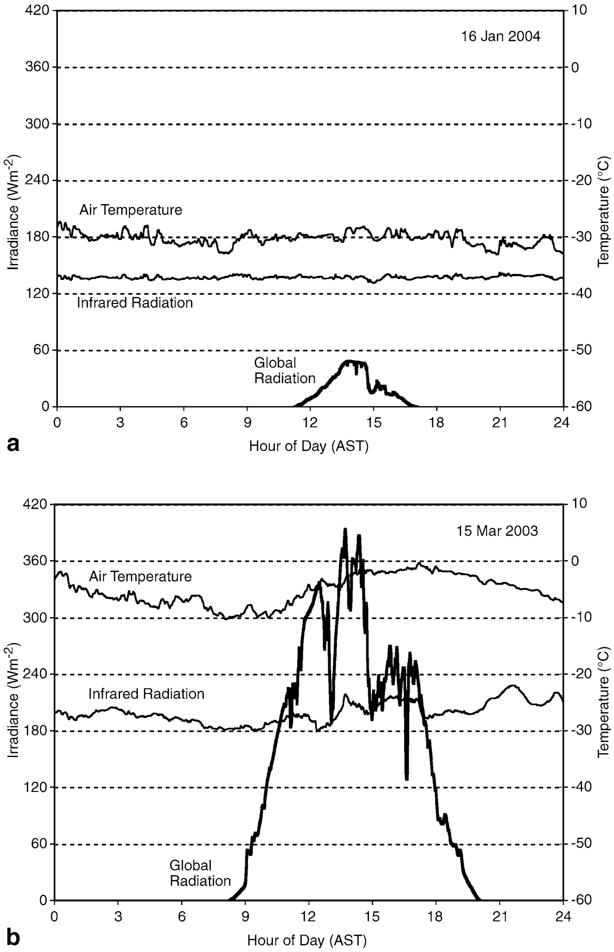

Fig. 8. Diurnal variation of the long wave incoming radiation and temperature on a winter (**a**) and spring (**b**) day with high-level cloud cover. Data in minute intervals are plotted

The temperature starts increasing shortly after sunrise when the global radiation increases strongly. A maximum of 375 Wm^{-2} is reached around solar noon; the temperature lags the radiation by about 4 hours.

4.3 Effects on surface climate

Our climate monitoring site, which is located next to the radiation equipment, showed slight cooling when a contrail moved into the path of the direct solar radiation. However, the effect was relatively small and varied and it was not possible to isolate the radiation effect from other effects such as changes in other energy fluxes. For example, local heating on the roof induces small-scale turbulence, which is again a function of the solar radiation flux. As we have in addition a relatively small number of measured cases, the direct determination of contrails on the surface temperature was not possible. This is even more the case, as there is a strong diurnal as well as annual cycle of the influence of the surface temperature, hence a great number of observations are essential. An indirect measure is the comparison of the temperature behavior on clear days and days with high-level cloudiness, independent of the fact if these were naturally occurring cirrus or cirrostratus clouds, a mixture of cirrus type clouds and contrails or contrails which had spread. They all consist of ice crystals in the upper troposphere or lower stratosphere.

In Fig. 9a, the mean annual temperature course for Fairbanks is presented for clear days (cloudiness $<3/10$) and days with high-level ($>$20 000ft or 6100 m) overcast (cloudiness $>7/10$). This is based on daily values, which were derived by averaging the eight 3-hourly observations. For

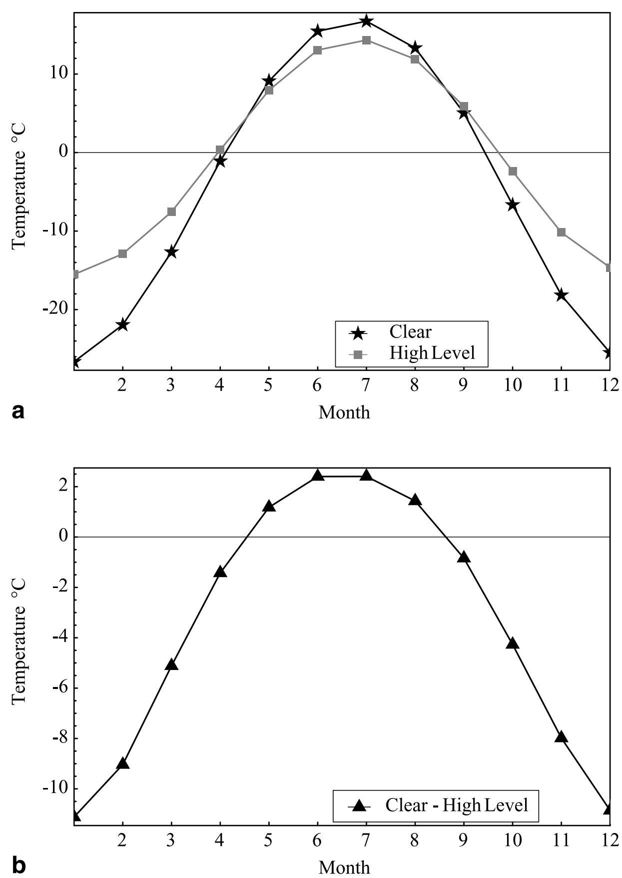

Fig. 9. Mean annual temperature course of Fairbanks for a clear day and a day with high-level cloudiness (**a**) and the temperature difference between the two (**b**) for Fairbanks, Alaska. Note, that with the exception of May through August, days with high-level cloudiness are warmer than clear days

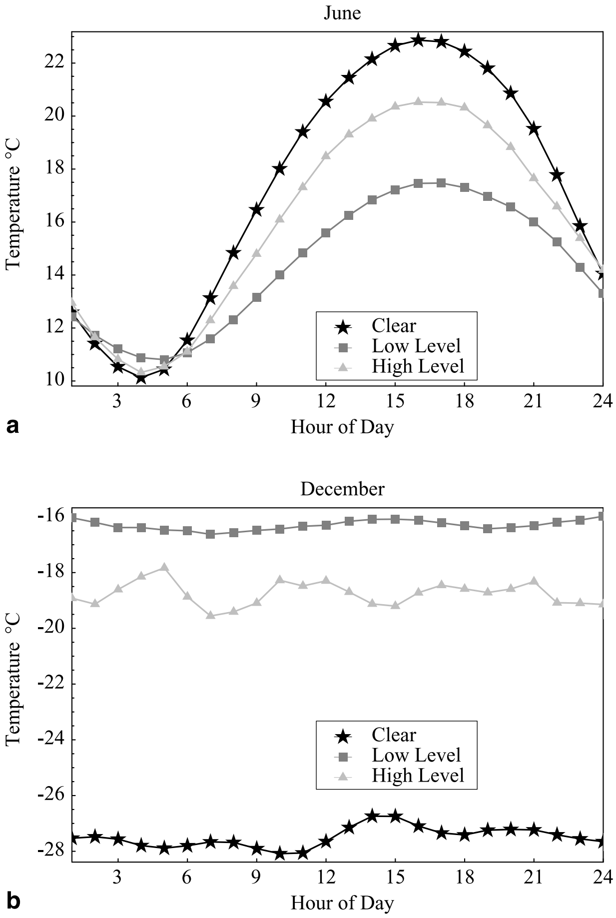

Fig. 10. Diurnal temperature variation for June (**a**) and December (**b**) for a clear day as well as days with high-level and low-level overcast, Fairbanks, Alaska

clear conditions with a daily average of 25% or less sky cover, some contrails will have occurred. The database was over the period 1948–96; in 1997 an automatic observation system (ASOS) was installed by the National Weather Service, and cloud observations above 6000 m are unreliable. A large database was essential, as days with high-level cloudiness, or clear days in late summer, are relatively infrequent. The graph shows that, with the exception of summer (May through August), days with high-level cloudiness are on average warmer than clear ones, the difference being 5.5 °C on average over the year. In winter, the difference increases to more than 10 °C (see Fig. 9b). This result shows, that with the exception of the summer months, the somewhat reduced global radiation under high-level cloudiness is overcompensated by increased long wave back radiation from these clouds. Only in summer, when the days are long and the solar elevation is relatively high at noon, the increase in short wave radiation is more important than the increased losses in the long wave radiation balance. This is, of course, typical for polar and subpolar regions, where the net radiation becomes negative for an extended time of the year.

Table 3. Mean surface temperatures (°C) at Fairbanks (1948–1996) for clear, high-level clouds and opaque cloudiness conditions

	Spring	Summer	Fall	Winter	Year
Clear	−1.8	+16.8	−7.8	−26.7	−4.9
High-level	+3.2	+16.2	+0.2	−17.4	+0.6
Opaque	+0.9	+14.3	−2.1	−15.6	−0.6

In Table 3 the mean values for clear (<3/10) and high-level cloudiness (>7/10) are presented for the seasons and the year. We also give values of the temperatures for opaque cloudiness (>7/10). The table shows, that for the summer months, the temperature is highest under clear conditions, closely followed by high-level cloudiness; it is, on average, about 2 °C cooler for opaque overcast. In winter the trend is just the opposite with low-level cloudy days being the warmest, and clear days being the coldest. In the intermediate seasons, spring and autumn, clear days are again the coldest as in winter; however, days with high-level cloudiness are the warmest.

Averaging over the year, days with high-level cloud cover are the warmest, followed by low-level overcast. Hence, an increase in high-level cloudiness due to contrails should lead to a temperature increase for all seasons but summer, as well as for the mean annual value for a subarctic setting.

In Fig. 10 the diurnal temperature course is presented for close to mid-summer (June) and mid-winter (December) for clear days and days with high level and low level overcast. The time period on which this is based is again 1948–1996. For June (Fig. 10a), a large diurnal temperature variation is observed, with clear sky conditions the largest diurnal range of 12.8 °C. The maximum is reached in the early afternoon, and for 19 hours of the day clear sky conditions display higher temperatures than days with high level and low-level cloudiness, respectively. Days with low-level cloudiness have about half the diurnal range when compared to clear days, mostly an effect of a reduced maximum, however also the minimum is somewhat increased.

In December (Fig. 10b) hardly and diurnal temperature variation can be observed. Clear days are on average more than 10 °C colder than days with low-level cloudiness. More interesting is the fact that the temperature of days with high-level overcast resembles more the days with low level overcast than clear days, the difference in temperature being less than 3 °C.

One of the reviewers of this manuscript raised the important question of how natural occurring cirrus and cirrus contrails compare radiatively, believing that contrails are optically much thinner. While it is correct that newly formed contrails consist of smaller size particles, these particles grow with time and only in long lasting contrails are radiatively important. Naturally occurring cirrus can be very faint, hardly visible with the naked eye (e.g. Kärchner, 2002), while contrails can be very distinct, but becoming less so with time. On the other hand, natural occurring cirrus can be fairly thick and contrails can be faint. The spectra in optical thicknesses will overlap each other, however, our radiative data base is insufficient to carry out a systematic quantitative assessment.

Nakanishi et al. (2001) have previously shown that the high-level cloudiness has increased in Alaska, the increase being larger close to the much traveled flight corridor to Europe than in more remote areas of Alaska. Further, during the last decades the temperature has increased in Alaska (Stafford et al., 2000). The temperature increase has its maximum in winter. In winter, the layer in which contrails form is about twice as thick as in summer. In addition, in winter the atmosphere is very cold and dry, hence the infrared radiative effect of jet contrails is more pronounced.

The observed temperature increase can also be explained by circulation changes or increased greenhouse gases and it is difficult to judge the contribution by the increased occurrence of cirrus contrails. Maybe the best indication that the jet traffic might have an effect on the atmosphere is the high-level cloudiness increase, which was more pronounced close to the flight corridor. While changes in the amount of high cloudiness might be connected with circulation changes, such local changes would be hard to explain.

5. Conclusion

Air traffic has increased substantially in the last five decades in Alaska and jet contrails are frequently visible in Fairbanks. Nakanishi et al. (2001) showed that high-level cloudiness has increased in Alaska, more below the flight corridor to Europe than in other areas of Alaska.

Radiative measurements showed a reduction in the short wave radiation, but also a slight decrease in the infrared losses in the presence of contrails. Integrated over a year, increased high-level cloudiness leads to a temperature increase. As shown from the 48-year dataset, days with high-level cloudiness are warmer than clear days for all seasons but summer. Previous research has shown that Alaska has warmed during the last 5 decades. This warming was especially pronounced in winter followed by spring, while summer temperature changed little. The observed increased temperatures are consistent with the increased high-level cloudiness.

Minnis et al. (2004) recently carried out a comprehensive investigation on contrails, cirrus trends and their effect on climate. Based on the time period from 1975–1994 for the contiguous United States, he found good agreement between the observed temperature increases with those expected from radiative forcing models due to increased cirrus cloud cover from contrails. Further, the seasonal variations of the estimated temperature trends with the greatest warming in winter and spring are also in good agreement with the corresponding observations. We find similar results for the subarctic.

Increased jet traffic has an effect on local climate. However, its effect globally is difficult to judge. We agree with Schumann (2001) who states: *The impact of global air traffic on global climate is larger than its share in global emissions but still small in natural climate variations.*

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Authors' address: Prof. Gerd Wendler (e-mail: gerd@gi.alaska.edu), Martha Shulski, Brian Hartmann, Geophysical Institute of the University of Alaska, Fairbanks, 903 Koyukuk Dr., P.O. Box 757320, Fairbanks, AK 99775-7320, USA.