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World War II contrails: a case study of aviation-induced cloudiness

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ABSTRACT: Dense and persistent condensation trails or contrails were produced by daytime US Army Air Force (USAAF) bombing raids, flown from England to Europe during World War II (WW2). These raids occurred in years when civilian air travel was rare, giving a predominantly contrail-free background sky, in a period when there were more meteorological observations taken across England than at any time before or since. The aircraft involved in the raids entered formation at contrail-forming altitudes (generally over 16 000 ft, approximately 5 km) over a relatively small part of southeast England before flying on to their target. This formation strategy provides us a unique opportunity to carry out multiple observation-based comparisons of adjacent, same day, well-defined overflown and non-over-flown regions.

We compile evidence from archived meteorological data, such as Met Office daily weather reports and individual station meteorological registers, together with historical aviation information from USAAF and Royal Air Force (RAF) tactical mission reports. We highlight a number of potential dates for study and demonstrate, for one of these days, a marked difference in the amount of high cloud cover, and a statistically significant (0.8 °C) difference in the 07 : 00–13 : 00 UTC temperature range when comparing data from highly overflown stations to those upwind of the flight path on the same day. Although one event cannot provide firm conclusions regarding the effect of contrails on climate, this study demonstrates that the wealth of observational data associated with WW2 bombing missions allows detailed investigation of meteorological perturbations because of aviation-induced cloudiness. Copyright © 2011 Royal Meteorological Society

KEY WORDS contrails; condensation trails; World War II; aviation-induced cloudiness; cirrus; diurnal temperature range; cloud cover

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1. Effect of aviation on climate

With passenger air travel growing at a rate of 3–5% per year and cargo transportation increasing by 7% per year (Lee *et al.*, 2009), the climate effects of aviation have received a considerable amount of attention over the last decade (Intergovernmental Panel on Climate Change 1999; Sausen *et al.*, 2005; Forster *et al.*, 2007; Lee *et al.*, 2009). However, quantification of the radiative and climate impact of aviation is poor, particularly with respect to condensation trails (contrails) and aviation-induced cloudiness (AIC).

Aircraft can affect cloudiness through the production of contrails. These form when the hot, humid, aerosol-laden air that is emitted from aircraft jet engines mixes with the cold air of the upper troposphere (Appleman, 1953). Some contrails evaporate almost immediately after being formed and so have minimal potential climate-forcing effect, whereas others persist for several hours (Minnis *et al.*, 2002, 2004) and can go on to form widespread cirrus cloud. This process is different to wing-tip vortices that may appear in humid air at very low altitudes, often on take-off and landing, but which do not produce AIC (Schumann, 2005).

A number of studies have examined the impact of line-shaped contrails and AIC on climate. Some have indicated that there may be a significant link between AIC over a region and changes in the climatic properties of the same region (Meerkotter *et al.*, 1999; Travis *et al.*, 2002; Marquart *et al.*, 2003; Carleton *et al.*, 2008; Haywood *et al.*, 2009), whereas other studies have suggested that AIC has a limited climate impact (Kalkstein and Balling, 2004; Shine, 2005; Dietmuller *et al.*, 2008).

Both persistent line-shaped contrails and widespread AICs reflect incident sunlight back to space, thereby exerting a negative radiative forcing (a cooling effect) in the short-wave solar spectrum. However, they also trap long-wave, terrestrial, radiation within the Earth's atmosphere, resulting in a positive radiative forcing (a warming effect). The overall outcome of these two competing effects is uncertain. Recent estimates of the global radiative forcing of line-shaped contrails vary from 30 (Stordal *et al.*, 2005) to 2.0 mW m^{-2} (Stuber and Forster, 2007). The IPCC assigned a 90% confidence interval of 6–30 mW m^{-2} in their 2007 report (Forster *et al.*, 2007), but it is unlikely that this interval fully encompasses the

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uncertainty even in contrail forcing without considering subsequent AIC. Haywood *et al.* (2009) examined a single persistent contrail formed by an airborne warning and control system aircraft and found that this single contrail produced a radiative forcing some 5000 times higher than recent estimates of the average persistent contrail radiative forcing from the entire civil aviation fleet. Their results suggested that, on balance, persistent contrails exerted an over-riding cooling effect on climate.

In another study, Travis *et al.* (2002) analysed the climate impact of AIC on the daily temperature range (DTR) during and immediately after the banning of all commercial aircraft activity over the United States for 72 h in September 2001. Their data indicated a statistically significant 1.8 °C increase in the average DTR when compared with the adjoining 3-d period of normal aircraft activity and an approximate 1 °C increase when compared with the long-term, yearly averages (Travis *et al.*, 2002). However, the results from this study have been questioned because of its reliance on a single episode (Schumann, 2005; Forster *et al.*, 2007; Dietmuller *et al.*, 2008). Furthermore, an alternative hypothesis, based on the unusually clear weather at the time, has been suggested to explain the observed increase in DTR (Kalkstein and Balling, 2004). Both Dietmuller *et al.* (2008) and Haywood *et al.* (2009) suggest that uncertainty regarding estimates of AIC radiative forcing could be reduced by additional observational studies.

We propose to invert the Travis *et al.* (2002) study by considering strong contrail events against a no-contrail background to provide a spatial and temporal analysis of the impact of AIC on radiative forcing in an unperturbed atmosphere. World War II (WW2) military aircraft operations, in particular those of the US Army Air Force (USAAF), provide an ideal example of such conditions. We describe a method that may be used to examine the impact of AIC over take-off locations for daylight WW2 bombing raids from England to Europe, carried out by Allied forces from the period 1943 to 1945. Using historic documents, such as tactical mission reports and archived meteorological data, raid suitability is assessed using a score matrix. Hourly meteorological information (cloud cover, humidity, dew point temperature, surface air temperature, present and past weather, wind speed and direction and, where possible, total sunshine) is then extracted from archives for each suitable raid. An example case is provided where cloud and temperature records in heavily overflown areas are compared to those upwind of the flight path to establish the impact of AIC. This approach highlights the value in using historical aviation events to investigate meteorological perturbations to climate because of AIC, although additional examination of further events is required before any conclusions can be drawn.

2. WW2 operations

2.1. USAAF structure

In the summer of 1942 the USAAF joined the strategic bombing campaign, concentrating their efforts on precision daylight bombing. Long-range fighter escorts were used for their bombers, significantly adding to the number of aircraft involved, and therefore the number of contrails formed, in any one mission. The majority of the USAAF fighter and bomber groups stationed in England during the war came under the command of the Eighth Bomber Command (renamed the Eighth Air Force in February 1944). Each numbered Air Force had a number of subordinate commands, which were further divided into numbered Divisions. A Division, consisting of five or six Wings, was a very large administrative and operational organization, usually in control of several combat groups and service organizations such as Bomb Groups, Fighter Groups and Photographic Reconnaissance. A Group was the smallest self-contained tactical bombardment unit and consisted of a number of squadrons. The number of aircraft in each squadron varied depending on the responsibility the Squadron held. Normally, a minimum of one full Group would be sent on a mission although a combination of Groups could be sent depending on the target. It was considered more efficient to keep whole combat groups together and so both fighter and bomber units were stationed in the same locale. This resulted in large concentrations of USAAF stations, personnel and aircraft in East Anglia, the Midlands and the West Country. In general, each fighter group consisted of three squadrons, whereas each bomber group had four. Both groups had 14–18 aircraft per squadron.

2.2. General aspects of USAAF bombing raids

All aircraft involved in a raid would take-off at approximately the same time from their respective bases. They would climb to a pre-determined altitude over the general area of the base; find the appropriate squadron and then gather into the specified formation. Once the squadron was assembled, the formation would group together with other complete airborne squadrons into the overall wing configuration that would fly the mission. This process of formation could take 30 min to 1 h with aircraft circling the general area of their base during this time. The aircraft of the USAAF generally entered formation above the location of their bases at altitudes above 16 000 ft (approximately 5 km), with subsequent cruise altitudes up to 30 000 ft (approximately 9 km). Both of these altitudes are well inside the cirrus-forming altitude range (4–20 km according to the World Meteorological Organization). Therefore under favourable conditions significant numbers of contrails (caused by the injection and mixing of warm, moist air into the atmosphere rather than wingtip vortices) could form over land in the vicinity of the bases and along the flight paths (Figure 1). During WW2 civilian aircraft operations were rare, so there are strong spatial contrasts between the intensively overflown areas and other sparsely overflown areas. We can

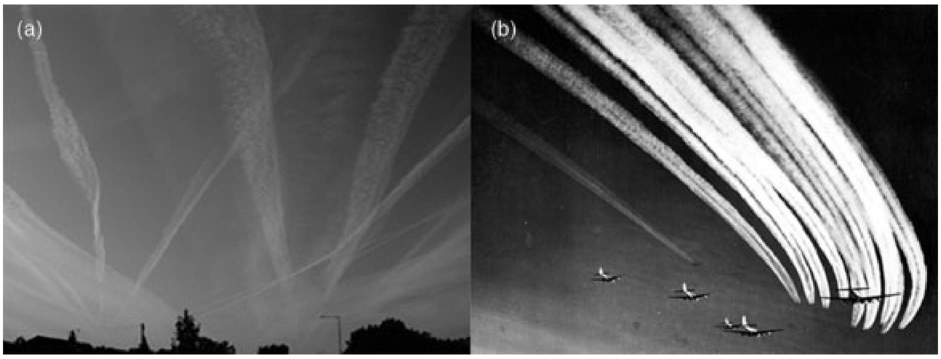

Figure 1. Photographic evidence of present-day widespread, persistent and dispersed contrails over Willingdon, East Sussex, at 06 : 35 UTC, 1 August 2007 (courtesy of John Flude, National Contrail Observers' Network) (a) and a formation of B-17 bomber aircraft producing a more spatially defined ribbon of dense contrails during an operation in WW2 (b). Note that the aircraft at lower altitude in (b) are not producing contrails.

Table I. Aviation and meteorological data requirements necessary to investigate any meteorological impact because of contrails formed by specific World War II bombing raids.

Historical aviation information	Historical meteorological information
All significant aircraft movements to define raid and non-raid days on each day of the period in question	The synoptic situation, including wind speed and direction and Lamb classification on raid and non-raid days
Time of take-off and return of aircraft involved in raid from bases and over English coast	Location of meteorological stations directly under or adjacent to the flight path
Take-off and landing location, and flight path of both outward and return journeys	Location of meteorological stations unaffected by the flight path
Altitude at which aircraft entered formation and flew to, and returned from, target	Hourly observations from relevant meteorological stations from station registers and daily weather reports
First-hand observations of the production, density and persistence of any contrails produced	Maximum and minimum temperature at each station
Number of aircraft involved	Cloud cover, type and altitude (high, medium or low)
–	Total sunshine (where recorded)

exploit these contrasts for climate effect studies. WW2 aviation events are also reasonably well localized in time and space, which aids signal detection.

3. Methodology

3.1. Data collection

To undertake such a study a wide range of historical aviation and meteorological information is required (Table I). The majority of information from the WW2 period is archived on paper. An extensive information-gathering search was carried out, but it was not always clear whether the required data existed because of a lack of metadata or whether the available data was qualitative or quantitative. To make the search as efficient as possible, a two-tier approach was employed. The first tier was a broad search of all easily accessible computer records and reference materials. This showed that, for southeast England, 1943–1945 was the most relevant period during the war years for this study. Information on the strategy employed by both RAF bomber command and the USAAF was collected to assess the contrail forming potential of the raids, as well as any initial meteorological information provided in diaries or flight logs (diaries and flight summaries available in the USAAF tactical mission reports and from squadron web pages, such as www.381st.org/histories/transcriptions.html). Previous observational studies of contrails have shown an annual cycle, peaking in spring and winter, in the middle latitudes (Minnis *et al.*, 2004; Screen and MacKenzie, 2004); therefore this study concentrates on raids carried out during these periods.

Synoptic charts based on the National Center for Atmospheric Research (NCAR) daily Northern Hemisphere sea-level pressure grids of the period in question were also examined. This gave an initial analysis of the weather conditions (i.e. the passage of fronts and therefore changing air masses) at the time of the raid and adjacent days to ascertain whether or not a contrail effect could be determined over and above the normal climatic variations.

3.2. Sources of information on raids and meteorology

Historical aviation records (RAF Museum, Hendon) were searched for information relating to raid strategy such as number and type of aircraft involved, take-off time and location for each Group, flight path, rendezvous point, altitude and time of return. Notes were made of remarks

Table II. Details of the different types of weather stations used during World War II.

Station type	Details
Type 1	Main Meteorological Offices (MMO) which provided fully independent observation and forecasting services on a 24 h basis. Located at RAF Command and Group headquarters (HQ)
Type 2	Manned by one or more experienced forecaster(s) and observer(s). Forecasters were allowed to predict without supervision for specific operations. Twenty-four hour coverage available when required (i.e. for specific operations)
Type 3	Manned by forecasters and observers supervised by their Group MMO. Some stations provided 24 h forecasts but mostly covered the local hours of flying
Type 4	No forecasters present. Manned by assistant grade staff who not only acted mainly as observers but also supplied up-to-date weather reports and Group forecast products as and when needed (Ogden, 2001)

made by the crew regarding contrail formation and weather encountered. This identified first-hand accounts of contrail formation during specific raids, including the heights and locations at which the contrails formed and the time particular locations were overflown (e.g. south coast of England, individual Bomb Group bases).

The UK Meteorological Office (Met Office) archive was then used to find daily registers for meteorological stations that were operational during the war and were under or adjacent to the flight path of each of the raids. This could number over 100 meteorological stations, each with hand-written hourly observations made 24 h-a-day (Appendix for an example register). Hourly observations of cloud cover, maximum and minimum temperature, present and past weather and 10-m wind speed and direction for the day of the raid and the adjoining days were collected. Total sunshine amount was also noted, although this was not recorded at all stations.

For a study such as this, it is important to have confidence in the quality of all the data sets used including the weather observations. Maintaining a good, coherent meteorological observations network was considered critical during WW2. During WW2 the Met Office was fully integrated into RAF operations, and the majority of meteorological stations were associated with RAF fighter and bomber airfields. This association means that observations are likely to have been consistent across different locations. In addition to the Central Forecast Office at Dunstable Down, there were four types of operational Met Office outstation (Table II) and meteorological observations were made at all station types, often on an hourly basis. During periods of heavy bombing (e.g. throughout the Battle of Britain) meteorological offices were moved away from the airfields to areas deemed to be less vulnerable to attack. As a result, from autumn 1940 to autumn 1944, meteorological observations reported to be from sector HQ airfields in southeast England were actually made from sites up to 2–3 miles (3–5 km) from the airfields (Ogden, 2001).

3.3. Score matrix for the potential impact of WW2 aviation on cloudiness

Due to the large number of raids that occurred between 1943 and May 1945, a scoring system was devised to allow for comparatively fast selection of raids suitable for the study. Given no prior observations of the minimum number of WW2 aircraft needed to produce a detectable AIC signal, it was decided that aircraft number was the most important criterion. Raids with over 1000 aircraft participating were thus identified to maximize the potential for detection of any AIC signal. A score of 1 was assigned to raids involving 250–499 aircraft, 2 to raids with 500–999 aircraft and 3 to raids with more than 1000 aircraft. This was followed by a requirement for raid-free days with good weather on either side of a raid event to give the option of undertaking additional temporal comparisons. The number of adjacent raid-free days is set to 0 if neither day on either side of the specified date is raid free, 1 if only 1 d either before or after the raid is raid free and 2 if both days before and after the raid are raid free. From December 1944 to May 1945, no raids occurred which had adjacent raid-free days; therefore, this period was eliminated from the search. Although no observational evidence of contrail formation or cloud cover had been sought at this point (deliberately to avoid biasing the score matrix results), the contrail-forming potential of the synoptic situation was taken into account. These were ranked based on the work by Screen and MacKenzie (2004) in which synoptic situations, based on their Lamb classification, were assessed for the probability that contrails would form. A score of 3 indicates contrails were very likely, whereas 1 indicates contrail formation is unlikely. The total score then allowed the raids to be ranked in order of potential suitability.

3.4. Statistical tests

Once a suitable raid was identified and meteorological data gathered, simple statistical tests were used to determine if there were significant differences between overflown and upwind areas. Given the data available, the adoption of a simple null hypothesis was warranted. This null hypothesis was that there would be no significant difference between observations in overflown and upwind regions. This test of the effect of the aircraft on cloudiness and temperature assumes that the aircraft effect is not dwarfed by inter-station differences. A Student's t-test (SPSS statistical package, PASW Statistics v17.0) was used to determine if there were statistically

Table III. Top 20 most suitable raids for contrail study based on selection criteria. Lamb classifications are anticyclonic (A), cyclonic (C), northerly (N), southerly (S), easterly (E), westerly (W).

Rank	Raid date	Aircraft number	Synoptic situation (lamb class)	Contrail potential	No. of adjacent raid-free days	Total score
1	14 January 1944[a]	3	6 (AW)	3	2	**8**
2	9 October 1944[a]	3	0 (A)	3	2	**8**
3	30 October 1944[a]	3	0 (A)	3	2	**8**
4	30 December 1943[a]	3	7 (ANW)	3	1	**7**
5	21 November 1944[a]	3	6 (AW)	3	1	**7**
6	29 May 1943[b]	1	0 (A)	3	2	**6**
7	22 June 1943[b]	1	5 (ASW)	3	2	**6**
8	14 October 1943[a]	1	0 (A)	3	2	**6**
9	**16 December 1943**	**1**	**0 (A)**	**3**	**2**	**6**
10	**24 December 1943**	**2**	**6 (AW)**	**3**	**1**	**6**
11	1 November 1944[a]	2	8 (AN)	3	1	**6**
12	**11 May 1944**	**3**	**6 (AW)**	**3**	**0**	**6**
13	8 February 1944[a]	3	17 (NW)	1	2	**6**
14	25 June 1943[b]	1	7 (ANW)	3	1	**5**
15	3 November 1943[a]	2	20 (C)	1	2	**5**
16	15 April 1944[a]	2	12 (E)	1	2	**5**
17	31 December 1943[a]	3	17 (NW)	1	1	**5**
18	21 January 1944[a]	3	16 (W)	1	1	**5**
19	**5 September 1944**	**3**	**20 (C)**	**1**	**1**	**5**
20	12 October 1944[b]	3	26 (CW)	1	1	**5**

[a] Cloudy weather.
[b] Aviation records not available at the time of search. Raids in bold are considered suitable for additional study.

significant differences in high cloud cover between overflown and upwind areas. One-way analysis of variance was used to ascertain if there were statistically significant differences in the temperature range of overflown and upwind stations. Differences were considered significant if $P < 0.05$.

4. Results

4.1. Raid selection

The top 20 raids based on the criteria in the score matrix are given in Table III. The requirements for aircraft numbers and clear skies on the raid day were considered more important than the requirement for adjacent raid-free days. This was to ensure fulfilment of the primary study objective – to compare overflown and non-overflown geographic areas on the same day. The first five raid events in the table were all found to have poor or cloudy weather associated with them, so although their contrail forming potential was high, they had over 1000 aircraft participating and they had adjacent raid-free days, these dates were not used. Raids ranked 6–11 had either poor or cloudy weather, missing military records or too few aircraft participating according to our criterion. Therefore, the first most suitable raid event for this study occurred on 11 May 1944. Although this had no adjacent raid-free days, this was the highest ranked event which had good weather, military records indicating that over 1000 aircraft participated and observations of contrail formation in the flight logs. Detailed meteorological data was then collected from 113 operational meteorological stations under and adjacent to the flight paths, totalling approximately 7750 hourly, hand-written meteorological records for the 3-d period from 10 May to 12 May 1944. Data for the 3-d period was collected so that the stability of the synoptic situation could be ascertained.

4.2. Case study on 11 May 1944

On 11 May 1944, two raids from England to Europe were undertaken. The first involved 364 B-24s and 536 fighter aircraft of the Eighth Air Force, second and third Bomb Divisions, which took off from their bases at approximately 10 : 15–11 : 00 Co-ordinated Universal Time (UTC). The second raid, involving 609 B-17s and 471 fighter aircraft of the first and third Bomb Divisions, took off at 14 : 45–15 : 30 UTC. There were some aircraft movements before these times; Attlebridge meteorological station noted in their station meteorological register that a crash had occurred at 09 : 15 UTC, and Coltishall meteorological station noted the formation of contrails to the north of the station at 10 : 00 UTC. No mention of aircraft activity before the raids is made in the tactical mission reports and the contrails are formed slightly earlier than the given time for take-off. These contrails may have been produced by RAF aircraft returning after a night flight, although it is more likely that some of the USAAF aircrafts were airborne 15 min early.

The tactical mission reports state that there were no or few low and middle level clouds. This is consistent with the meteorological station observations for 00 : 00–23 : 00 UTC that show that the majority of the

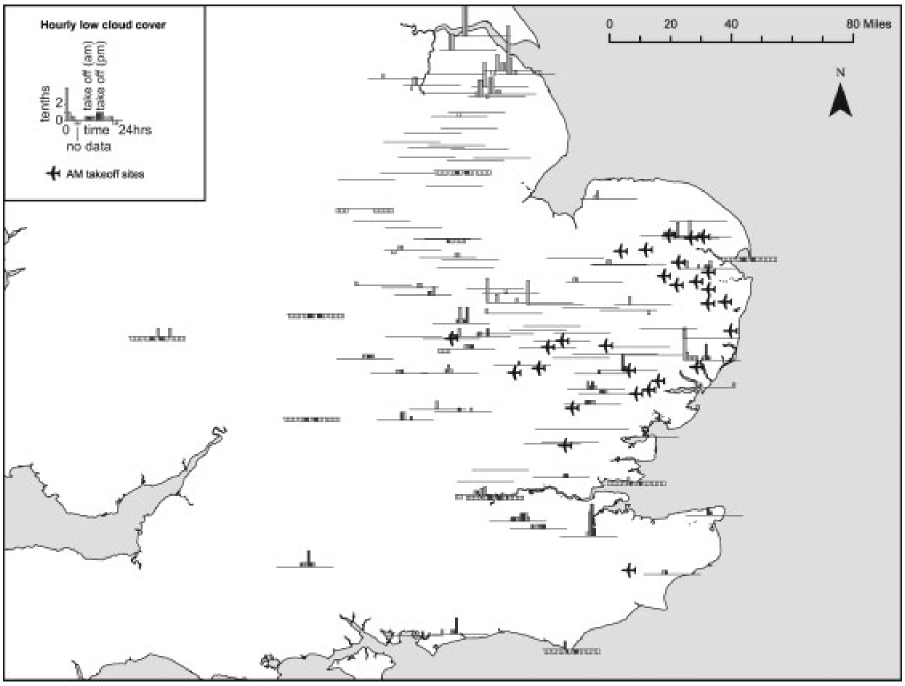

Figure 2. Low cloud cover for the 11 May 1944 between 00 : 00–23 : 00 UTC. Cloud amounts are in tenths. Points below the line indicate missing or indecipherable data. Aircraft symbols indicate the take-off location of the aircraft participating in the morning raid. Mid grey bars indicate the cloud amounts during the morning raid take-off time (10 : 00–11 : 00 UTC), the dark grey bars indicate the low cloud amounts during the time of take-off for the afternoon raid (14 : 00–15 : 00 UTC) and light grey bars indicate low cloud amounts at all other times during the day.

stations reported less than 2/10th small cumulus cloud (Figure 2).

The second Bomb Division reported the formation of moderate, non-persistent contrails in patches from 12 000 to 16 000 ft (3.6–4.9 km) during wing assembly. The third Bomb Division de-brief does not mention contrails; however, their altitude during the first raid was only 12 000 ft (3.6 km). Both Divisions involved in the second of the two raids remark that no contrails were formed or observed, therefore our analysis concentrated on the effects of the morning raid only. The choice of 07 : 00–13 : 00 UTC for the analysis of total high cloud amount and temperature reflects this and avoids any overlap with the second raid. The upper-level winds, pertinent to the geographic extent of the contrails, for both raids from the aircraft bases to 50°N are given in Table IV. Observations during Raid 2 indicate no major change in wind speed or wind direction over the course of the day, which improves confidence that the forecast was accurate and that the synoptic situation did not change significantly.

Table IV. Upper level wind speed and direction for the 11 May 1944.

Upper level winds 11 May 1944 – aircraft bases to 50°N				
Altitude	Raid 1 (10 : 15–11 : 00 UTC)		Raid 2 (14 : 45–15 : 30 UTC)	
	Wind speed (kts)	Wind direction (°)	Wind speed (kts)	Wind direction (°)
5000 ft (1.2 km)	10.8	280–320	5.4	270
10 000 ft (3.0 km)	13.5	280–320	8.1	270
15 000 ft (4.6 km)	16.2	280–320	13.5	270
20 000 ft (6.1 km)	18.9	280–320	16.2	270
25 000 ft (7.6 km)	21.6	290–330	18.9	270
30 000 ft (9.1 km)	21.6	290–330	18.9	270

Data is from the weather forecast given to the aircrew and included in the mission reports. The accuracy of the forecast was commented upon favourably when compared with the actual weather encountered in the crews de-brief.

The high cloud cover at stations upwind of the flight path, as reported in the meteorological registers, remained low throughout the day. In contrast, those stations that were underneath the flight path reported significantly increased high cloud cover coinciding with the outbound ($F = 142.2$, $P < 0.001$) and return ($F = 303.2$, $P < 0.001$) sections of the first raid, when compared to the upwind stations (Figure 3).

Analysis of the 07 : 00–13 : 00 UTC temperature difference (TD) also showed a significant 0.8 °C ($P = 0.023$) suppression (equivalent to a reduction in TD of 8%) when comparing overflown (TD = 9.8 °C) to upwind (TD = 10.5 °C) stations (data not shown). Although the stations downwind of the flight path also show increased high cloud cover after the take-off time for the morning raid and concomitant suppressed temperature ranges (by an average of 3.7 °C), the majority of these stations are coastal. Therefore, any differences in high cloud cover or temperature range are likely to be attributable to natural

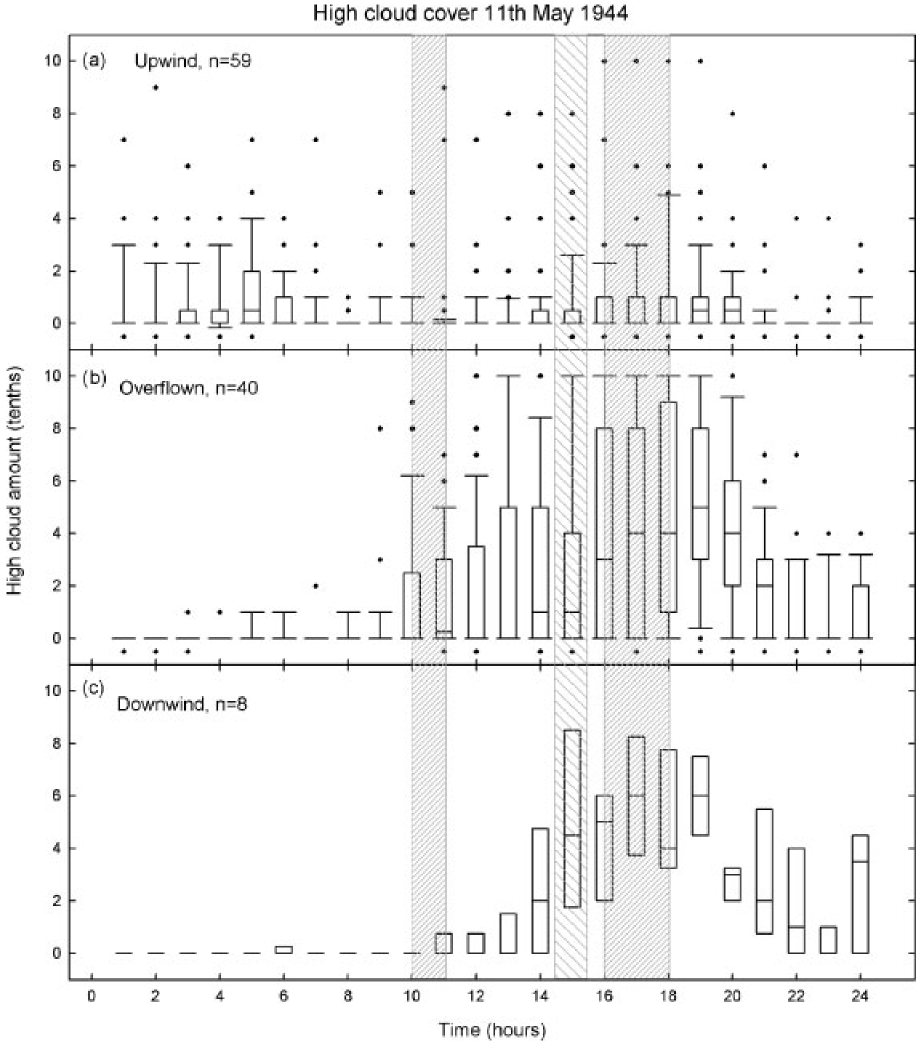

Figure 3. High cloud amounts reported by meteorological stations upwind, underneath and downwind of the reported morning raid flight path for the period 00:00–24:00 UTC on 11 May 1944. The number of stations from which data was collected is indicated by n. Dots indicate outliers from the mean cloud amount. The fine hashed boxes indicate the time of take-off for the morning raid and the time of return for both the morning and afternoon raid. The coarse hashed box indicates the time of take-off for the second raid. The boundary of the box closest to zero indicates the 25th percentile, a line within the box marks the median and the boundary of the box farthest from zero indicates the 75th percentile. Whiskers (error bars) above and below the box indicate the 90th and 10th percentiles.

changes in wind direction, humidity and air temperature, in addition to aircraft activity. Because these effects cannot be separated in this analysis, these stations were not included in the comparison.

5. Conclusions

The results from the single case study presented here are clearly not sufficient to draw conclusions regarding the impact of aviation on climate; however, this study demonstrates a method of selecting and examining the suitability of using daylight WW2 bombing raids from England to Europe, carried out by Allied forces from the period 1943 to 1945 to study AIC events. Using historic documents, such as tactical mission reports and archived meteorological data, the suitability of raids was assessed against multiple criteria (Tables I and III). Our requirement for over 1000 aircraft and at least one raid-free days adjacent to the main raid day proved to be extremely limiting. Using our criteria only one of a potential 56 raids (taken from May 1943to May 1945) was considered suitable for further study (Table III).

Because of time restraints, only the case that came closest to fulfilling our original, stringent criteria was studied in detail. Our aim was to show that historical data, such as WW2 bombing raids, may be an extremely important tool in closing the gap between the overwhelmingly large number of theoretical-based modelling studies that have been published in recent years (Marquart *et al.*, 2003; Minnis *et al.*, 2004; Dietmueller *et al.*, 2008; Lee *et al.*, 2009) and the limited number of observation-based studies (Travis *et al.*, 2002, 2004). During our case study raid, on 11 May 1944, contrails were formed during wing assembly over specific locations in southeast England. The resultant AIC event from even these moderate, non-persistent contrails significantly increased the total amount of high cloud during the time of wing assembly and return period (Figure 3), and significantly suppressed the 07 : 00–13 : 00 temperature range (coincident with the time of aircraft activity), in regions which were heavily overflown.

We have suggested criteria by which WW2 raids can be selected for the investigation of AIC events. Given the importance of the synoptic situation at the time of the raid, this should be the first limiting criterion. Rather than restricting the number of suitable raids by selecting only those with the highest numbers of aircraft participating, we suggest that raids with more than 250 aircraft are suitable for further study. In addition, although having raid-free days adjacent to raid days are important for temporal comparisons of AIC effects, it is equally important to be able to compare overflown with adjacent non-overflown regions. Therefore, less emphasis should be placed on the need for raid-free days and more placed on the contrail forming potential of the synoptic situation. We find that with less stringent restrictions, for example on aircraft number as suggested above, nearly 130 raids can be found that are potentially suitable for spatial or temporal comparison, or a combination of both. Indeed, a preliminary re-classification of the raids based on the altered criteria found that, of the nearly 130 possible suitable raids, 42% occurred during periods when the synoptic situation was likely to be favourable to contrail formation (Lamb class A) (Ledson, 2003). Moreover, 12% of these were adjacent to raid-free days.

This study has demonstrated a method for detecting quantifiable climate-forcing effects because of AIC produced by historical aviation events. However, we do not take into account any weighting of those effects because of aircraft efficiency, fuel type or altitude. It has been suggested in a number of studies (Meerkotter *et al.*, 1999; Marquart *et al.*, 2003; Mannstein and Schumann, 2005) that the particles emitted by the aircraft may have a significant effect on the radiative impact of contrails by altering their optical properties. Quantification of any cloud albedo effect and determination of the reflectiveness of contrails compared to naturally produced cirrus is outside the scope of the present study. It should also be borne in mind that, although the aircraft studied here generally flew at 18 000–30 000 ft (5.5–9 km), and therefore produced contrails at these altitudes, modern aircraft fly significantly higher at 35 000–40 000 ft (11–12 km). Lower, and therefore warmer, contrails will have a smaller effect in the infrared but a similar effect in the visible, so that we can expect WW2 contrails to have more of a cooling effect than contemporary contrails.

It is also known that contrails are able to advect hundreds of kilometres as they develop (Minnis *et al.*, 2004). While, in this study, we found impacts on the total high cloud amount and temperature range of regions directly under the flight path, it may be that additional impacts of AIC also occur some distance from the point of origin. As such, further investigation into the contrail impact on each of these parameters should be carried out in any additional study.

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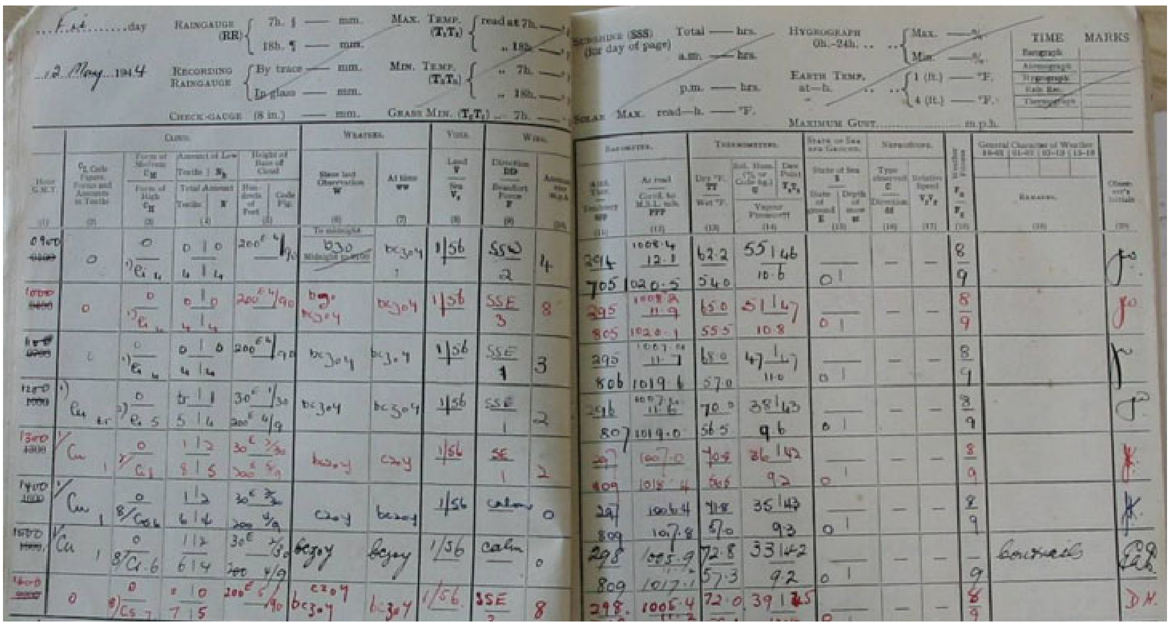
6. Appendix: Synoptic Meteorological Observations

The photograph below shows a typical station meteorological register (Cranfield) for 12 May 1944. Contrails are noted at 15 : 00 UTC. Low, medium and high cloud types, amounts and heights are all reported separately. Some stations reported low cloud amount separately, but



grouped medium and high cloud amounts together. These could often be separated as many observers added extra notes in the cloud form column relating the amount of cloud per type. Units used are cloud heights (ft), cloud amounts (tenths), visibility (yards and miles), and temperature (°F). Beaufort notations and cloud forms are same as present day met observations.

Synoptic observations were made at the same time all over the world with major observations taken at 01 : 00, 07 : 00, 13 : 00 and 18 : 00 UTC, and minor observations taken at 04 : 00, 10 : 00, 16 : 00 and 22 : 00. Most stations recorded observations every hour.

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