Evaluating the Significance of the Contrail Effect on Diurnal Temperature Range Using the Eyjafjallajökull Eruption-Related Flight Disruption

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Abstract Meteorological data collected during the post-9/11 flight grounding in the United States suggested that the removal of contrails increased diurnal temperature range (DTR), but subsequent research has contested this result. The 2010 Eyjafjallajökull eruption resulted in a 97% flight cancelation rate across the UK, offering another rare opportunity to compare DTR under contrail-free skies against those with contrails. Temperature data from 199 UK meteorological stations indicate that a +3.4 °C DTR anomaly occurred during the grounding interval across the region previously affected by the highest flight densities, substantially larger than the +1.1 °C anomaly previously observed but smaller than other DTR anomalies (up to ~ +6 °C) that were independent of the grounding. Although the observed DTR anomalies are largely attributable to weather system migration, a contribution of up to +1 °C from contrail absence appears reconcilable with both the observed time evolution in DTR during the Eyjafjallajökull grounding period and previous results.

Plain Language Summary Due to permanent and near-constant aviation activity, directly comparing atmospheric conditions underneath skies with and without contrails under equivalent ambient conditions is difficult. Previous research used the post-9/11 flight groundings in 2001 to detect a contrail effect on diurnal temperature range across the United States. The removal of contrails was found to have increased daytime high temperatures and decreased nighttime low temperatures. However, subsequent research challenged this result and the overall effect of contrails on weather remains unclear. Here we use a very high density network of meteorological stations across the United Kingdom to assess the importance of contrails on diurnal temperature range during a more recent flight grounding following the Eyjafjallajökull volcanic eruption of 2010. We find that subtle, but substantial, temperature shifts related to contrails may have been overprinted by larger shifts in weather systems passing over the United Kingdom.

1. Introduction

Aviation represents a small (e.g., ~3.5% of total anthropogenic forcing in 2005; Lee et al., 2009), yet potentially significant climate forcing whose non-CO₂ effects remain imperfectly quantified (Lee et al., 2009, 2010; Penner et al., 1999). Air traffic is predicted to grow up to 5% per year globally over the next 40 years (Minnis et al., 2003, 2004; Ponater et al., 2005; Rap et al., 2010), but how exactly aviation may affect local-to-regional-scale surface temperatures into the future remains unclear (Minnis et al., 2004; Sassen, 1997; Travis et al., 1997). Aircraft-related condensation trails, or contrails, are formed in the upper troposphere and can develop into cirrus-like clouds, potentially reflecting both incoming solar radiation and outgoing terrestrial infrared radiation (Myhre & Stordal, 2001) and leading to cooler days and warmer nights (Travis et al., 2002, 2004). Climate model simulations have shown that these contrail cirrus clouds may well be the most important contribution to the radiative forcing associated with aviation (Bock & Burkhart, 2016; Burkhart & Karcher, 2011; Karcher, 2018; Schumann et al., 2015). Typically, studies measure the percentage of contrail cirrus sky coverage by using satellite imagery; however, challenges presented in algorithm tuning complicate contrail detection by this method (Duda et al., 2013; Minnis et al., 2013). Comparing time intervals with contrails to intervals without contrails over any discrete geographical area circumvents some of these issues, although because contrail formation requires specific meteorological conditions (e.g., sufficiently cold and moist air; Jensen et al., 1998; Kästner et al., 1999), replication of this type of result is difficult (Dai et al., 1999).

Only a few studies have been based on a direct comparison of meteorological observations of contrail-free versus contrail-rich skies (e.g., Hong et al., 2008; Travis et al., 2002). Travis et al. (2002) argued that an anomalous increase in mean diurnal temperature range (DTR) occurred across the United States following
The role of contrails on regional- to local-scale temperature is therefore controversial and not well quantified. It is clear that more data are required to resolve the question of whether or not contrails decrease DTR over restricted areas. Because air traffic in many regions never ceases completely, it is very difficult to determine the extent to which contrails may decrease DTR using direct observations. Here we use a more recent flight grounding following the 2010 AD eruption of the Icelandic volcano Eyjafjallajökull, to investigate the effects on DTR across the United Kingdom and consequently to provide information for model simulations (e.g., Huszár et al., 2013; Marquart et al., 2003; Wild, 2009) focusing on predicting future climate change that will incorporate aviation-associated radiative forcing.

2. Methods

We utilized the Met Office Integrated Data Archive System (United Kingdom Met Office, 2012) archives to retrieve daily maximum and minimum temperatures ($T_{\text{max}}$ and $T_{\text{min}}$) at meteorological stations across the United Kingdom. At the time of acquisition for this study, the data comprised approximately 5 million data records with broad coverage across the entire United Kingdom. For the purposes of this study, only sites that recorded temperatures from 1991 to 2010 were used. In total, 199 sites remained, still offering excellent spatial coverage of the United Kingdom overall, although the coverage is somewhat lower in Cornwall, sections of northern England, and sections of northern Scotland (Figure 1). Although the geographic area of our study is far smaller than that of Travis et al. (2002), the site density is 65% higher; consequently, our results provide a higher-resolution snapshot into any climate repercussions of contrails. To isolate any contrail effect during the 5-day grounding (16–20 April 2010), the study covers calendar dates during the grounding and those bracketing the flight grounding interval (11–15 April) and (21–25 April). This
parameterizes any local climatic effects before the grounding and covers any long-standing effects that may have persisted after the grounding.

Each of the 199 meteorological stations that had unbroken records from 1991 to 2010 was assigned to one of three flight density zones (1 = High, 2 = Medium, 3 = Low) based on air transport density estimated by using the locations of high-altitude flight routes over the United Kingdom derived from data from the United Kingdom’s Aeronautics Information Data Unit (AIDU, 2012; Figure 1). Anomalies for any given calendar date were calculated as the difference between that date in 2010 and the mean for the same date across 1991–2009; these station- and date-specific anomalies were then averaged across zones or intervals of time as required. Concerns that the ash cloud associated with the 2010 Eyjafjallajökull eruption might affect aircraft prompted flight cancelations across northern Europe, and in the United Kingdom the interval 16–20 April was characterized by a 97% flight cancelation rate. We focus on this interval to attempt to corroborate the results of Travis et al. (2002).

3. Results and Discussion

The distance between Eyjafjallajökull and UK air space is approximately 1,000 km. The volcanic ash cloud had no documented effect on UK temperature, as expected for a low sulfur eruption plume (Walker et al., 2012) that only rarely breached the tropopause (Flemming & Inness, 2013; Petersen, 2010). During the flight disruption interval from 16 to 20 April 2010, the mean DTR anomalies were as follows: Zone 1 = +3.4 °C, Zone 2 = +3.9 °C, and Zone 3 = +1.5 °C (Figure 2). The pronounced DTR increase in the two zones most affected by regular air traffic is consistent with the removal of a contrail effect, although of a much larger magnitude than expected. However, in Zone 1 the large DTR anomaly was driven by particularly large DTR values of +5 °C and +6.5 °C on 17 and 18 April, followed by a substantial decrease to +1.7 and +2.6 °C on 19 and 20 April. The elevated values occurring on 17 and 18 April are greater than 2 standard deviations above the 1991–2009 mean, but values during the rest of the grounding interval are less anomalous (Figure 2). Averaged over the entire grounding interval, DTR shifts in both Zones 1 and 2 are well within natural variability observed over the 1991–2009 baseline and are lower than the mean values for the 5 days immediately following the grounding interval (Figure 2). Over the period from 1 April to 31 May, DTR excursions more than 2 standard deviations above the mean also occurred after the grounding interval on 24 April and again on 23–24 May. United Kingdom Met Office records demonstrate that a high-pressure system moved over the United Kingdom between 16–19 April 2010, coincident with both the steadily increasing DTR and the flight grounding. This high-DTR interval ended in Zone 1 following the arrival of a low-pressure system on 20 April. These records are consistent with Moderate Resolution Imaging Spectroradiometer imagery that confirms that regions experiencing the highest DTR anomalies had the least cloud cover (Figure 3). This is particularly notable on 17 and 18 April, when Zone 1 (southern England) was largely cloud-free (Figure 3), and the DTR anomalies on those days were +5.0 and +6.5 °C, respectively. These observations strongly suggest that cloud effects associated with synoptic-scale weather systems are at least partially controlling DTR. Although the DTR does increase during the grounding interval, the fact that larger deviations exist not associated with any flight grounding suggests that other phenomena overprinted any contrail effects present. The simplest explanation for the elevated DTR during the grounding interval is, therefore, that it was predominantly caused by the movement of weather systems, consistent with previous results (e.g., van Wijngaarden, 2012).

However, this explanation does not exclude the possibility that the removal of contrails contributed a smaller amount to the observed large DTR shifts. Considering geographical heterogeneities in DTR across the United Kingdom during the 2010 grounding interval provides additional insights (Figure 4). For example, on 16 April the highest DTR values were found in Zone 3, and (because of the typically low contrail density over northern Scotland) were almost certainly due to the high-pressure system beginning to affect the area rather than to the removal of contrails. As the system moved to the south, DTR values became progressively higher in the southerly Zone 1 (and progressively lower in the northerly Zone 3), culminating in particularly high values on 18 April. The DTR anomaly over Zone 1 subsequently dropped to +1.7 °C on 19 April (from +6.5 °C on 18 April) coincident with an increase in cloud cover over Zone 1 (Figure 3). Interestingly, the DTR anomaly in Zone 1 on the first day of the flight grounding (16 April before the region was affected by the main high-pressure system) was +1.1 °C, the same value as that derived by Travis et al. (2002). Therefore, although the maximum DTR
anomaly of +6.5 °C on 18 April and the mean DTR anomaly of +3.4 °C across the entire grounding interval (16–20 April) observed in Zone 1 were almost certainly due predominantly to variable weather, this large DTR anomaly could include a component linked to the removal of contrails. Our results differ from those of Travis et al. (2002) in that, whereas these authors found that the intervals before and after were characterized by negative anomalies, the DTR values for Zone 1 were slightly above the 1991–2009 mean (+0.6 °C) during the 5-day interval prior to the flight grounding and were 4.6 °C higher in the 5-day interval following the grounding. It is clear that the frequent (almost daily) movement of weather systems across large portions of the United Kingdom complicates isolating any shifts caused by the sudden absence of contrails during the grounding interval, but available data are not inconsistent with the removal of a

Figure 2. Mean diurnal temperature range (DTR) anomalies from 1 April to 31 May 2010 for the three zones of flight density discussed here (a–c). Values are normalized by subtracting value for that station and day from mean values across 1991–2009 for that same station and day, and then averaging all stations within each zone. The gray-shaded region represents two standard deviations from the mean 1991–2009 value for each station and day (averaged across each zone). The light green insets illustrate the mean DTR values across 5-day windows preceding (11–15 April), during (16–20 April), and after (21–25 April) the flight grounding interval (red bars) in 2010 compared with the mean DTR values from 1991 to 2009 (black circles). Two standard deviations from this value are also shown (black vertical lines).
contrail effect during the grounding interval of approximately the same magnitude as that reported in Travis et al. (2002).

Examining $T_{\text{max}}$ and $T_{\text{min}}$ trends clarifies the structure of the observed DTR variability throughout the study period (Figure 5). During the grounding period, in Zones 1 and 2 clear but not unique $T_{\text{min}}$ reductions ($\sim 1.5$ °C) and $T_{\text{max}}$ increases ($+3.5$ °C) are apparent and combine to produce a $+5.0$ °C net DTR shift. This observation is consistent with the removal of contrails, which should produce smaller $T_{\text{min}}$ decreases compared to much larger $T_{\text{max}}$ increases due to (i) contrails only contributing a small amount to longwave surface warming during the night compared to larger amounts of shortwave surface cooling during the day.

![Figure 3. Daily Aqua Moderate Resolution Imaging Spectroradiometer corrected reflectance imagery for the United Kingdom from 15 to 20 April 2010, including the flight disruption interval (b-f) and the preceding day (a). Images courtesy of the National Aeronautics and Space Administration Earth Observing System Data and Information System Land Processes Distributed Active Archive Center, United States Geological Survey/Earth Resources Observation and Science center.](image-url)
(Schumann & Mayer, 2017) and (ii) the nature of the daily aviation cycle (Stuber et al., 2006). This same pattern of somewhat lower $T_{\text{min}}$ and substantially higher $T_{\text{max}}$ is not apparent in Zone 3 where the normal flight density was already low (Figure 5). However, other intervals with a similar pattern also exist that were not

**Figure 4.** Diurnal temperature range daily values for each of the 199 meteorological stations from across the United Kingdom (shaded contours) and the Eyjafjallajökull ash cloud coverage (light gray overlay) (panels a-e). White regions are areas unaffected by the ash cloud. Ash cloud limits are based on the United Kingdom Met Office’s London Volcanic Ash Advisory Centre for flight level 200 (20,000 feet).
associated with a flight grounding. For example, the intervals from 30 May to 1 June and from 28–30 June are both characterized by negative correlations between \( T_{\text{max}} \) and \( T_{\text{min}} \) in Zones 1 and 2, but a positive correlation in Zone 3. The relative frequency of similar statistical trends suggests that if temperature during the flight grounding interval was affected by the absence of contrails, this effect was small compared with other effects or that no effect was present, and the slight statistical anomaly was simply the result of weather patterns. It is clear that synoptic-scale weather systems exerted considerably more control on the DTR than contrails. The relatively large geographic extent of these systems over the United Kingdom during the grounding period may explain why the contrail effect was more subtle than the effect observed in the United States in the 2001 flight groundings (Travis et al., 2002, 2004). The United States’s area (excluding Alaska and Hawaii) is approximately 30 times the United Kingdom’s area,

![Figure 5](image-url)
and consequently, a large weather system over the United Kingdom will dominate the weather of the entire country compared with the United States, which is large enough to typically average out individual weather systems.

4. Conclusions

This study reveals that DTR increased substantially during and after the 2010 AD Eyjafjallajökull eruption-related flight disruption across the United Kingdom (16–20 April). The DTR increases were far larger (a mean DTR anomaly of +3.4 °C across Zone 1 during the entire grounding interval) than those observed by Travis et al. (2002) during the 2001 US flight groundings (+1.1 °C). We conclude that in the United Kingdom during the 2010 flight disruption the movement of synoptic-scale weather systems caused the majority of the DTR shifts. However, some component of these DTR shifts may also have been due to the removal of a contrail effect. Notably, the first day of the grounding interval (16 April) was characterized by a 1.1 °C DTR increase across the region with the highest air traffic, a value identical to that found by Travis et al. (2002) averaged across the United States during the 2001 flight grounding interval. Additionally, the DTR shifts during the 2010 flight grounding were characterized by T_{\text{min}} decreases and T_{\text{max}} increases, consistent with the removal of daytime incoming ultraviolet and nighttime longwave scattering by contrail cirrus clouds, though not necessarily conclusive because similar oscillations were also observed during other intervals not associated with any flight grounding. Our results are therefore broadly consistent with a contrail effect on DTR of up to −1 °C in zones of high air traffic. The United Kingdom’s smaller land area meant that a single large weather system could affect nearly the entire country, whereas in the United States even synoptic-scale weather systems are typically averaged out. Our conclusions also confirm the results of Hong et al. (2008), who predicted that weather patterns might overprint the contrail effect but that a small effect might still exist. We also note that a smaller DTR reducing effect of contrails, of about −0.02 °C as Rap et al. (2010) suggest for spring/summer conditions, would not be inconsistent with our results, given the large DTR day-to-day variations (Figure 2). Our conclusions are qualitative, and clear-cut statistical significance is difficult to obtain based on short 3-day or 5-day aviation-free periods (Dietmüller et al., 2008).

This study utilizes a remarkably high density of meteorological stations (65% higher density than Travis et al., 2002) to attempt to isolate a contrail effect on DTR during the 2010 Eyjafjallajökull eruption-related flight disruption. As only the second large-scale flight grounding of modern times (to our knowledge), this interval provides an excellent, and rare, opportunity to test the results of Travis et al. (2002) using observational data. We conclude that although UK temperature trends during the Eyjafjallajökull eruption-related flight disruption were consistent with the expected DTR shifts, these were nonunique and that the simplest interpretation is that DTR was mostly controlled by normal synoptic-scale weather systems moving across the United Kingdom. However, detailed analysis of our data is broadly consistent with the results of Travis et al. (2002), and we tentatively identify an approximately −1 °C contrail effect in the region with the highest contrail density. These results suggest that previous difficulties in identifying the effects of contrails on DTR may have resulted from the masking of a relatively small contrail forcing by much more substantial weather-related effects. Future empirical studies should consider that large spatial-scale studies, if permitted by data set length, are more likely to successfully capture a contrail effect through averaging of weather effects.

References


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