Geophysical Research Letters

RESEARCH LETTER
10.1029/2018GL080899

Key Points:
- Weather largely controlled diurnal temperature range variations during the 2010 Eyjafjallajökull eruption-related UK flight disruption
- Evidence is consistent with a ~1.1 °C contrail effect on DTR in high flight density region
- Using rare observational data, this study broadly corroborates previous estimates of the contrail effect on DTR

Correspondence to:
J. U. L. Baldini,
james.baldini@durham.ac.uk

Citation:
Sandhu, A. S., & Baldini, J. U. L. (2018). Evaluating the significance of the contrail effect on diurnal temperature range using the Eyjafjallajökull eruption-related flight disruption. *Geophysical Research Letters*, *45*. https://doi.org/10.1029/2018GL080899

Received 15 JUN 2018
Accepted 18 NOV 2018
Accepted article online 21 NOV 2018

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

Ajvir S. Sandhu[1,2] and James U. L. Baldini[1]

[1]Department of Earth Sciences, Durham University, Science Laboratories, Durham, UK, [2]Deceased 30 April 2016

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-CO_2 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 & Burkhardt, 2016; Burkhardt & 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

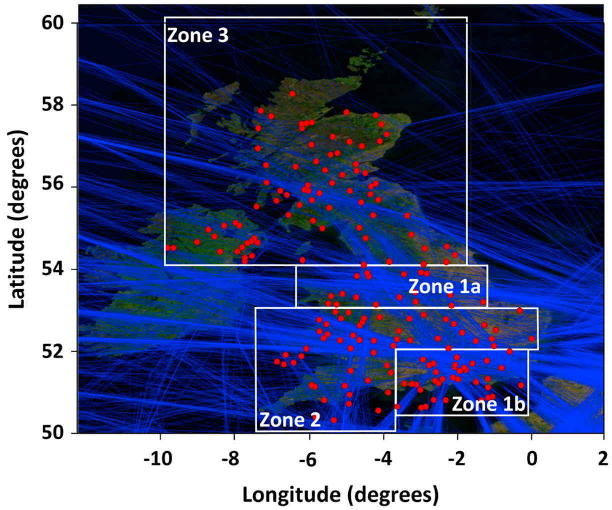

Figure 1. Distribution of UK meteorological stations used in this study (red filled circles). Overlain is the zone allocation according to flight path location (zone 1 = high, zone 2 = moderate and zone 3 = low), identified using information on the locations of high-altitude flight routes over the United Kingdom from the UK's aeronautics information data unit (AIDU, 2012). This information was then broadly confirmed using the contrail flight map tool found at: http://contrailscience.com/map/. The blue lines represent the flight paths of aircraft over the United Kingdom on the oldest available date (30 September 2012) on the contrail flight map, but these flight paths should not differ significantly from those characteristic of April 2010. Only flight paths over 30,000 feet are shown, the altitude at which temperatures are most conducive to the formation of contrails, although some minor variability in threshold altitude based on aircraft propulsion efficiency, amount of sunlight, and humidity is possible (Sausen et al., 1998). These contrail maps are only used to confirm the contrail density of the three zones identified using the Aeronautics Information Data Unit data. The base map is adapted from output generated by the contrail flight map tool.

the flight grounding of 11–14 September 2001. The 3 days of the event and the 3 days before and after were compared to the same calendar dates in previous years, demonstrating that a 1.1 °C DTR increase from the 1971–2000 mean over the same calendar days existed during the grounding period, whereas adjacent periods had almost no deviation from the mean. Additionally, the grounding period had a 1.8 °C larger range than the adjacent 3-day intervals, and Travis et al. (2002) concluded that mean DTR across the United States increased during the grounding period due to the absence of contrails. A more recent study using meteorological sites with similar characteristics but differing contrail coverage also suggested that contrails reduce DTR (Bernhardt & Carleton, 2015), supporting the earlier results (Travis et al., 2002).

However, other research has challenged this view (Hong et al., 2008), arguing that the DTR increase observed across the United States over the 2001 flight grounding interval was controlled by low-altitude clouds, winds, and humidity. Hong et al. (2008) suggested that some contrail influence may have existed but was essentially overprinted by weather on key days (Kalkstein & Balling, 2004). Furthermore, simulations using the ECHAM4 model with a contrail parameterization found no DTR response to contrails and concluded that low-level clouds were mainly responsible for the observed DTR shifts (Dietmüller et al., 2008), consistent with the results of Hong et al. (2008). Similarly, van Wijngaarden (2012) used meteorological data to argue that the DTR shifts observed by Travis et al. (2002) actually reflected the migration of weather systems across North America rather than the removal of contrails. Regardless, it has been argued that an observed 1.8 °C increase in DTR compared to the mean shift during the adjacent 3-day periods is extremely rare in the meteorological record and that the temporary lack of contrails was responsible (Travis et al., 2002, 2004).

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., Huszar 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_{max} and T_{min}) at meteorological stations across the United Kingdom. At the time of acquisition for this study, the data set 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

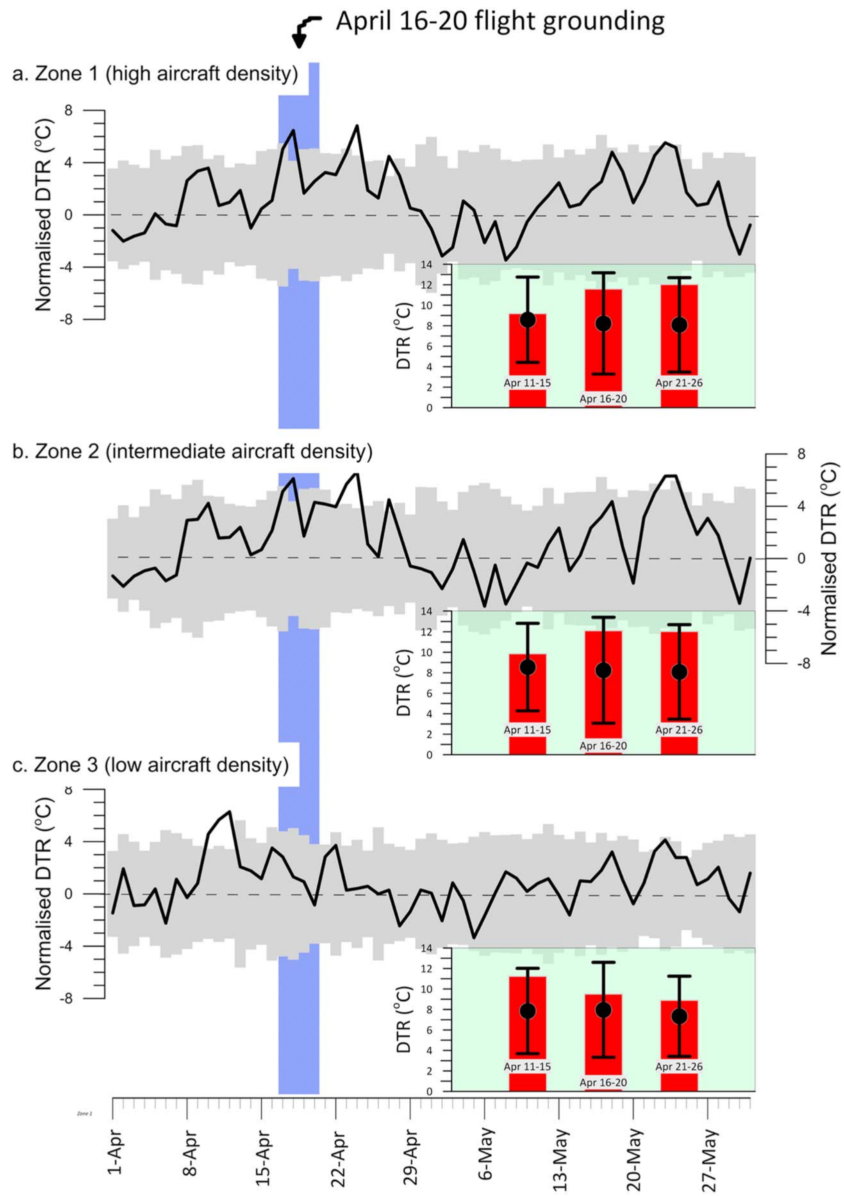

Figure 2. Mean diurnal temperature range (DTR) anomalies from 1 April to 31 May 2010 for the three zones of flight density discussed here (a-c). Values are normalized by subtracting value for that station and day from mean values across 1991–2009 for that same station and day, and then averaging all 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).

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

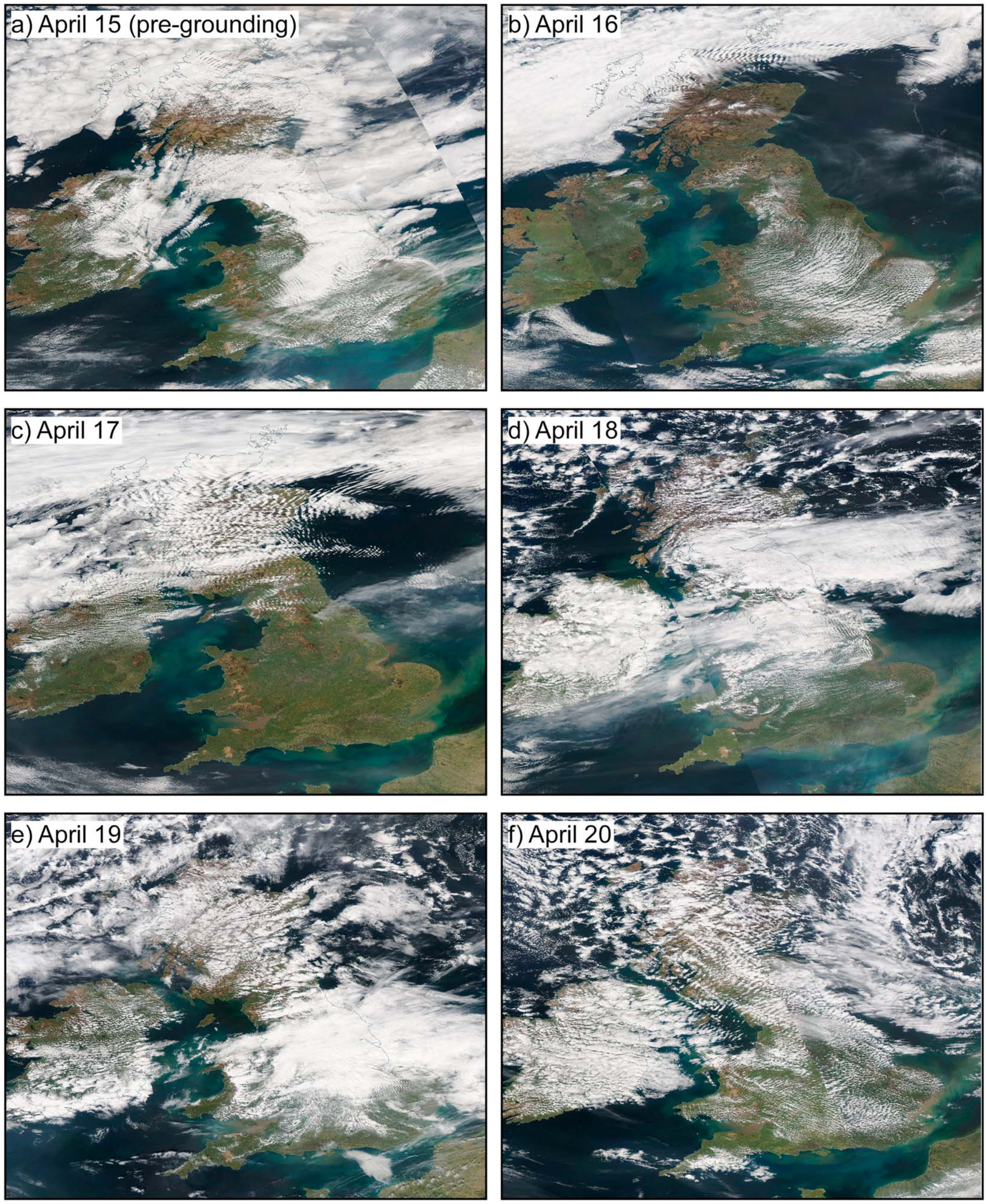

Figure 3. Daily Aqua Moderate Resolution Imaging Spectroradiometer corrected reflectance imagery for the United Kingdom from 15 to 20 April 2010, including the flight disruption interval (b-f) and the preceding day (a). Images courtesy of the National Aeronautics and Space Administration Earth Observing System Data and Information System Land Processes Distributed Active Archive Center, United States Geological Survey/Earth Resources Observation and Science center.

contrail effect during the grounding interval of approximately the same magnitude as that reported in Travis et al. (2002).

Examining T_{max} and T_{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_{min} reductions (−1.5 °C) and T_{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_{min} decreases compared to much larger T_{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

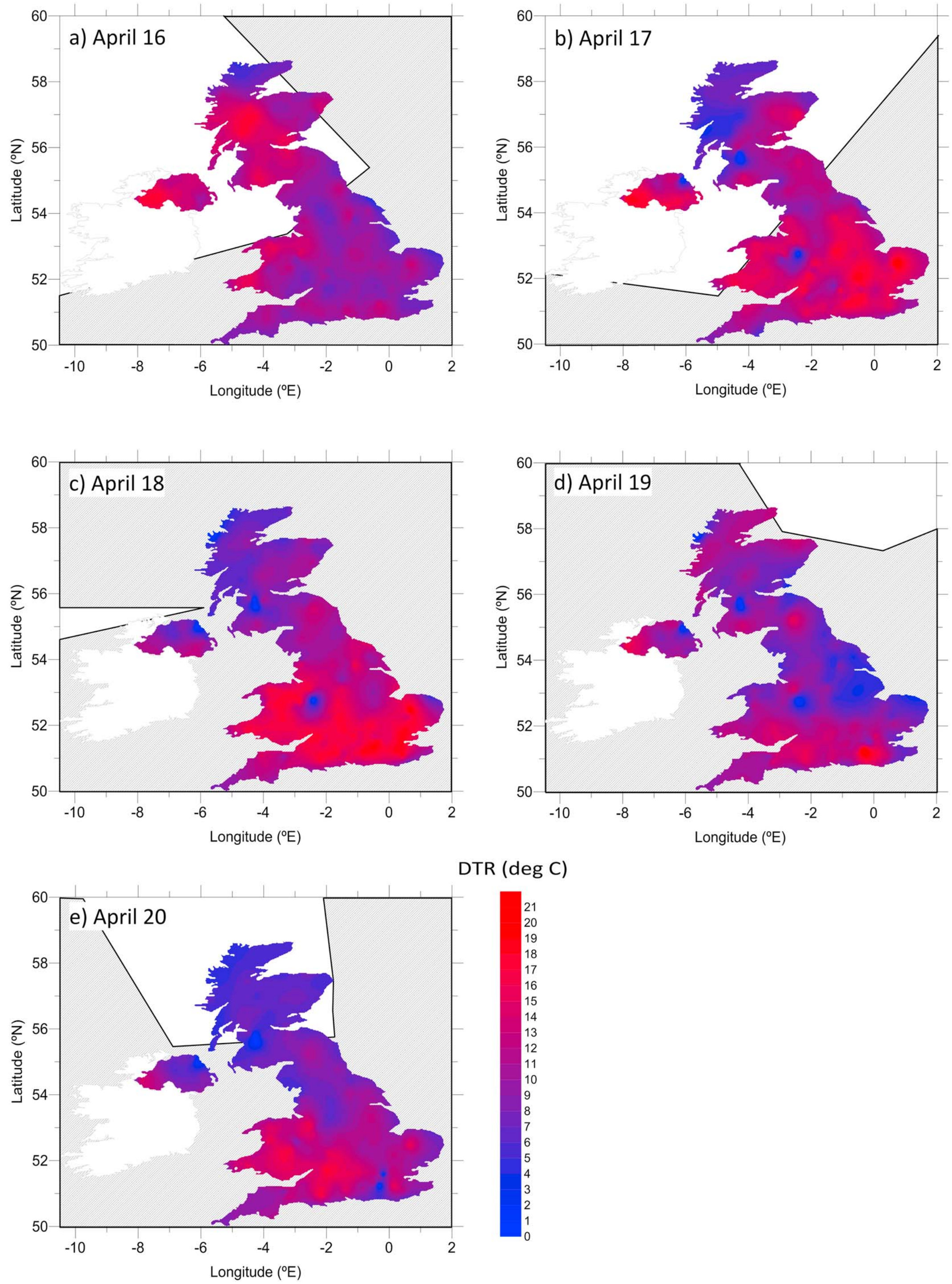

Figure 4. Diurnal temperature range daily values for each of the 199 meteorological stations from across the United Kingdom (shaded contours) and the Eyjafjallajökull ash cloud coverage (light gray overlay) (panels a-e). White regions are areas unaffected by the ash cloud. Ash cloud limits are based on the United Kingdom Met Office's London Volcanic Ash Advisory Centre for flight level 200 (20,000 feet).

(Schumann & Mayer, 2017) and (ii) the nature of the daily aviation cycle (Stuber et al., 2006). This same pattern of somewhat lower T_{min} and substantially higher T_{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

10.1029/2018GL080899

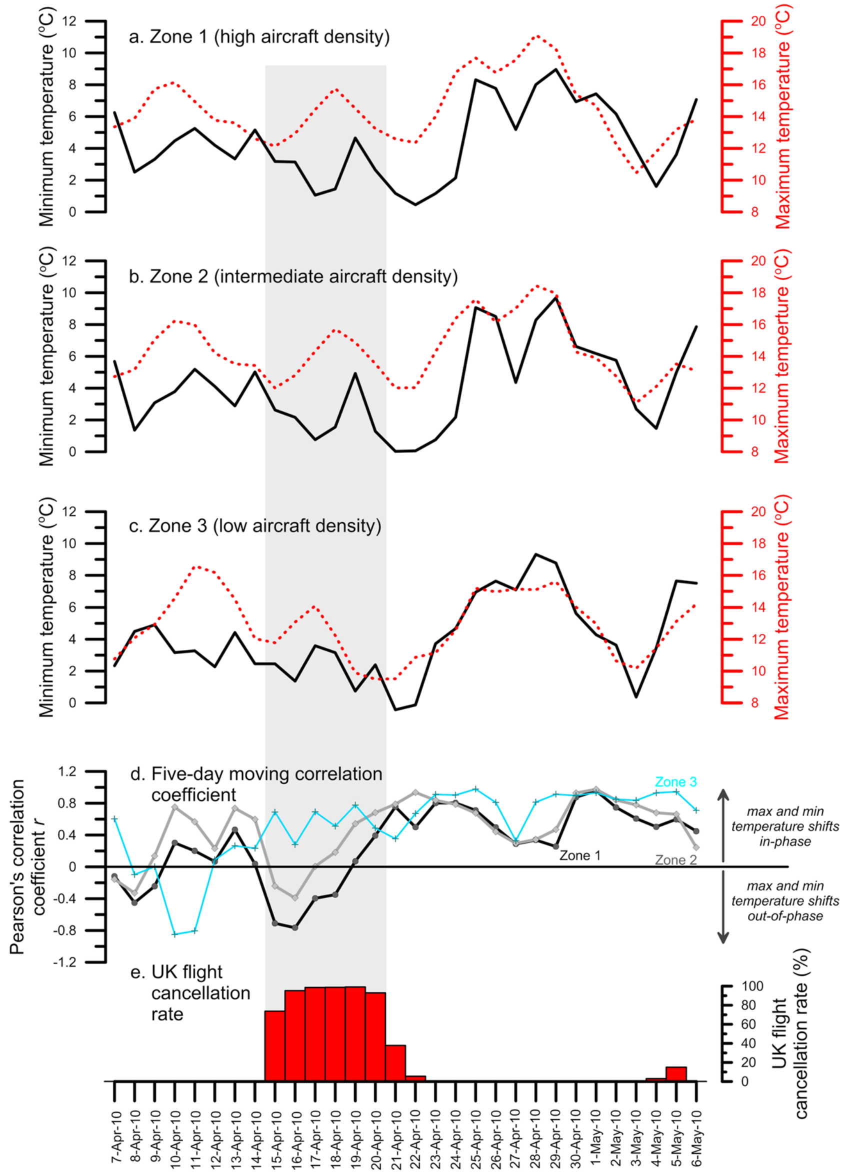

Figure 5. T_{max} and T_{min} from 7 April to 6 May 2010, averaged over zones of differing flight density (a–c). Panel d illustrates the 5-day moving correlation between T_{max} and T_{min}, where negative values indicate that the values are anticorrelated (diurnal temperature range increases caused by the divergence of T_{max} and T_{min}) and positive values indicate that the values are correlated. Zones 1 and 2 (high to intermediate flight density) flight grounding interval show an anticorrelation, indicating that T_{max} and T_{min} are diverging in those zones, whereas this same pattern is not apparent in zone 3. The bottom panel (e) shows the flight cancelation rates through the interval.

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_{max} and T_{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, 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_{min} decreases and T_{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.

Acknowledgments
We thank the UK Met Office for providing access to the MIDAS data. We are grateful to two reviewers for their helpful comments and suggestions that significantly improved the manuscript. We are also grateful for Hui Su's editorial handling of the manuscript. We would like to thank Eirene Williams for useful discussions and also Shivani Patel for her involvement in the early stages of this project. The MODIS satellite images were retrieved from the online EOSDIS Worldview tool, courtesy of the NASA EOSDIS Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota, https://worldview.earthdata.nasa.gov/. The estimated contrail distributions over the United Kingdom were estimated using the Contrail Flight Map tool, http://contrailscience.com/map/.

References

AIDU (2012). *Aeronautics information data unit*. British Isles: Flight Information Publication: En Route High Altitude.

Bernhardt, J., & Carleton, A. M. (2015). The impacts of long-lived jet contrail 'outbreaks' on surface station diurnal temperature range. *International Journal of Climatology*, *35*(15), 4529–4538. https://doi.org/10.1002/joc.4303

Bock, L., & Burkhardt, U. (2016). Reassessing properties and radiative forcing of contrail cirrus using a climate model. *Journal of Geophysical Research: Atmospheres*, *121*, 9717–9736. https://doi.org/10.1002/2016JD025112

Burkhardt, U., & Karcher, B. (2011). Global radiative forcing from contrail cirrus. *Nature Climate Change*, *1*(1), 54–58. https://doi.org/10.1038/nclimate1068

Dai, A., Trenberth, K. E., & Karl, T. R. (1999). Effects of clouds, soil moisture, precipitation, and water vapor on diurnal temperature range. *Journal of Climate*, *12*(8), 2451–2473. https://doi.org/10.1175/1520-0442(1999)012<2451:EOCSMP>2.0.CO;2

Dietmüller, S., Ponater, M., Sausen, R., Hoinka, K. P., & Pechtl, S. (2008). Contrails, natural clouds, and diurnal temperature range. *Journal of Climate*, *21*(19), 5061–5075. https://doi.org/10.1175/2008JCLI2255.1

Duda, D. P., Minnis, P., Khlopenkov, K., Chee, T. L., & Boeke, R. (2013). Estimation of 2006 Northern Hemisphere contrail coverage using MODIS data. *Geophysical Research Letters*, *40*, 612–617. https://doi.org/10.1002/grl.50097

Flemming, J., & Inness, A. (2013). Volcanic sulfur dioxide plume forecasts based on UV satellite retrievals for the 2011 Grímsvötn and the 2010 Eyjafjallajökull eruption. *Journal of Geophysical Research: Atmospheres*, *118*, 10,172–110,189. https://doi.org/10.1002/jgrd.50753

Hong, G., Yang, P., Minnis, P., Hu, Y. X., & North, G. (2008). Do contrails significantly reduce daily temperature range? *Geophysical Research Letters*, *35*, L23815. https://doi.org/10.1029/2008GL036108

Huszar, P., Teyssèdre, H., Michou, M., Voldoire, A., Olivié, D. J. L., Saint-Martin, D., Cariolle, D., et al. (2013). Modeling the present and future impact of aviation on climate: An AOGCM approach with online coupled chemistry. *Atmospheric Chemistry and Physics*, *13*(19), 10027–10048. https://doi.org/10.5194/acp-13-10027-2013

Jensen, E. J., Toon, O. B., Kinne, S., Sachse, G. W., Anderson, B. E., Chan, K. R., Twohy, C. H., et al. (1998). Environmental conditions required for contrail formation and persistence. *Journal of Geophysical Research*, *103*(D4), 3929–3936. https://doi.org/10.1029/97JD02808

Kalkstein, A. J., & Balling, R. C. (2004). Impact of unusually clear weather on United States daily temperature range following 9/11/2001. *Climate Research*, *26*(1), 1–4.

Karcher, B. (2018). Formation and radiative forcing of contrail cirrus. *Nature Communications*, *9*(1), 1824. https://doi.org/10.1038/s41467-018-04068-0

Kästner, M., Meyer, R., & Wendling, P. (1999). Influence of weather conditions on the distribution of persistent contrails. *Meteorological Applications*, *6*(3), 261–271. https://doi.org/10.1017/S1350482799001231

Lee, D. S., Fahey, D. W., Forster, P. M., Newton, P. J., Wit, R. C. N., Lim, L. L., Owen, B., et al. (2009). Aviation and global climate change in the 21st century. *Atmospheric Environment*, *43*(22–23), 3520–3537. https://doi.org/10.1016/j.atmosenv.2009.04.024

Lee, D. S., Pitari, G., Grewe, V., Gierens, K., Penner, J. E., Petzold, A., Prather, M. J., et al. (2010). Transport impacts on atmosphere and climate: Aviation. *Atmospheric Environment*, *44*(37), 4678–4734. https://doi.org/10.1016/j.atmosenv.2009.06.005

Marquart, S., Ponater, M., Mager, F., & Sausen, R. (2003). Future development of contrail cover, optical depth, and radiative forcing: Impacts of increasing air traffic and climate change. *Journal of Climate*, *16*(17), 2890–2904. https://doi.org/10.1175/1520-0442(2003)016<2890:FDOCCO>2.0.CO;2

Minnis, P., Ayers, J. K., Nordeen, M. L., & Weaver, S. P. (2003). Contrail frequency over the United States from surface observations. *Journal of Climate*, *16*(21), 3447–3462. https://doi.org/10.1175/1520-0442(2003)016<3447:CFOTUS>2.0.CO;2

Minnis, P., Ayers, J. K., Palikonda, R., & Phan, D. (2004). Contrails, cirrus trends, and climate. *Journal of Climate*, *17*(8), 1671–1685. https://doi.org/10.1175/1520-0442(2004)017<1671:CCTAC>2.0.CO;2

Minnis, P., Bedka, S. T., Duda, D. P., Bedka, K. M., Chee, T., Ayers, J. K., Palikonda, R., et al. (2013). Linear contrail and contrail cirrus properties determined from satellite data. *Geophysical Research Letters*, *40*, 3220–3226. https://doi.org/10.1002/grl.50569

Myhre, G., & Stordal, F. (2001). On the tradeoff of the solar and thermal infrared radiative impact of contrails. *Geophysical Research Letters*, *28*(16), 3119–3122. https://doi.org/10.1029/2001GL013193

Penner, J. E., Lister, D. H., Griggs, D. J., Dokken, D. J., & McFarland, M. (1999). Aviation and the global atmosphere: Summary for policymakers, IPCC Special Report, 373.

Petersen, G. N. (2010). A short meteorological overview of the Eyjafjallajökull eruption 14 April–23 May 2010. *Weather*, *65*(8), 203–207.

Ponater, M., Marquart, S., Sausen, R., & Schumann, U. (2005). On contrail climate sensitivity. *Geophysical Research Letters*, *32*, L10706. https://doi.org/10.1029/2005GL022580

Rap, A., Forster, P. M., Haywood, J. M., Jones, A., & Boucher, O. (2010). Estimating the climate impact of linear contrails using the UK Met Office climate model. *Geophysical Research Letters*, *37*, L20703. https://doi.org/10.1029/2010GL045161

Sassen, K. (1997). Contrail-cirrus and their potential for regional climate change. *Bulletin of the American Meteorological Society*, *78*(9), 1885–1903. https://doi.org/10.1175/1520-0477(1997)078<1885:CCATPF>2.0.CO;2

Sausen, R., Gierens, K., Ponater, M., & Schumann, U. (1998). A diagnostic study of the global distribution of contrails part I: Present day climate. *Theoretical and Applied Climatology*, *61*(3–4), 127–141. https://doi.org/10.1007/s007040050058

Schumann, U., & Mayer, B. (2017). Sensitivity of surface temperature to radiative forcing by contrail cirrus in a radiative-misxing model. *Atmospheric Chemistry and Physics*, *17*(22), 13,833–13,848. https://doi.org/10.5194/acp-17-13833-2017

Schumann, U., Penner, J. E., Chen, Y. B., Zhou, C., & Graf, K. (2015). Dehydration effects from contrails in a coupled contrail-climate model. *Atmospheric Chemistry and Physics*, *15*(19), 11,179–11,199. https://doi.org/10.5194/acp-15-11179-2015

Stuber, N., Forster, P., Radel, G., & Shine, K. (2006). The importance of the diurnal and annual cycle of air traffic for contrail radiative forcing. *Nature*, *441*(7095), 864–867. https://doi.org/10.1038/nature04877

Travis, D. J., Carleton, A. M., & Changnon, S. A. (1997). An empirical model to predict widespread occurrences of contrails. *Journal of Applied Meteorology*, *36*(9), 1211–1220. https://doi.org/10.1175/1520-0450(1997)036<1211:AEMTPW>2.0.CO;2

Travis, D. J., Carleton, A. M., & Lauritsen, R. G. (2002). Contrails reduce daily temperature range. *Nature*, *418*(6898), 601–601. https://doi.org/10.1038/418601a

Travis, D. J., Carleton, A. M., & Lauritsen, R. G. (2004). Regional variations in US diurnal temperature range for the 11–14 September 2001 aircraft groundings: Evidence of jet contrail influence on climate. *Journal of Climate*, *17*(5), 1123–1134. https://doi.org/10.1175/1520-0442(2004)017<1123:RVIUDT>2.0.CO;2

UKMO (2012). UK daily temperature data, part of the Met Office Integrated Data Archive System (MIDAS), in http://catalogue.ceda.ac.uk/uuid/1bb479d3b1e38c339adb9c82c15579d8, edited by NCAS_British_Atmospheric_Data_Centre.

van Wijngaarden, W. A. (2012). Examination of diurnal temperature range at coterminous U.S. stations during sept. 8–17, 2001. *Theoretical and Applied Climatology*, *109*, 1–5.

Walker, J. C., Carboni, E., Dudhia, A., & Grainger, R. G. (2012). Improved detection of sulphur dioxide in volcanic plumes using satellite-based hyperspectral infrared measurements: Application to the Eyjafjallajokull 2010 eruption. *Journal of Geophysical Research*, *117*, D00U16. https://doi.org/10.1029/2011JD016810

Wild, M. (2009). How well do IPCC-AR4/CMIP3 climate models simulate global dimming/brightening and twentieth-century daytime and nighttime warming? *Journal of Geophysical Research*, *114*, D00D11. https://doi.org/10.1029/2008JD011372