The importance of the diurnal and annual cycle of air traffic for contrail radiative forcing

Article *in* Nature · July 2006

DOI: 10.1038/nature04877 · Source: PubMed

4 authors, including:

Nicola Stuber
South Tees Hospitals NHS Foundation Trust

Piers Forster
University of Leeds

Gaby Rädel
Max Planck Institute for Meteorology

LETTERS

The importance of the diurnal and annual cycle of air traffic for contrail radiative forcing

Nicola Stuber[1], Piers Forster[1]†, Gaby Rädel[1] & Keith Shine[1]

Air traffic condensation trails, or contrails, are believed to have a net atmospheric warming effect[1], although one that is currently small compared to that induced by other sources of human emissions. However, the comparably large growth rate of air traffic requires an improved understanding of the resulting impact of aircraft radiative forcing on climate[2]. Contrails have an effect on the Earth's energy balance similar to that of high thin ice clouds[3]. Their trapping of outgoing longwave radiation emitted by the Earth and atmosphere (positive radiative forcing) is partly compensated by their reflection of incoming solar radiation (negative radiative forcing). On average, the longwave effect dominates and the net contrail radiative forcing is believed to be positive[1,2,4]. Over daily and annual timescales, varying levels of air traffic, meteorological conditions, and solar insolation influence the net forcing effect of contrails. Here we determine the factors most important for contrail climate forcing using a sophisticated radiative transfer model[5,6] for a site in southeast England, located in the entrance to the North Atlantic flight corridor. We find that night-time flights during winter (December to February) are responsible for most of the contrail radiative forcing. Night flights account for only 25 per cent of daily air traffic, but contribute 60 to 80 per cent of the contrail forcing. Further, winter flights account for only 22 per cent of annual air traffic, but contribute half of the annual mean forcing. These results suggest that flight rescheduling could help to minimize the climate impact of aviation.

Contrails form in the wake of aircraft only when the surrounding atmospheric conditions—in connection with the characteristics of the aircraft exhaust—are favourable[7]. In ice-supersaturated regions[8] contrails can exist for several hours. Flight management systems could be modified to reduce contrail radiative forcing. One way to reduce contrail coverage and forcing is by changing flight routes and/or cruising altitudes to avoid ice-supersaturated regions[9,10]. Another is to reduce the radiative forcing of contrails when they are present. Because of the compensation between positive longwave and negative shortwave forcings, shifting air traffic to times when the negative effects are largest would reduce the net contrail radiative forcing[11]. Our work aims to understand which parts of the diurnal and annual cycle of relevant parameters have the largest impact on the net radiative forcing of contrails.

We used AERO2k flightdata[12] over Herstmonceux (southeast England; longitude 0.32° E, latitude 50.90° N), a location for which vertical temperature and humidity profiles are available from radiosonde observations. AERO2k holds information on height-resolved distances flown in a 1° × 1° grid for each month in 2002 and for four six-hourly time periods—starting at midnight Greenwich Mean Time (GMT)—averaged over one week in June 2002. Using the size of the gridbox and the distance travelled in it, we first calculated the maximum possible contrail cover over Herstmonceux, initially assuming that all aircraft produce persistent contrails. In accordance with measurements[13] and model simulations[14] of line-shaped, persistent contrails, we assumed a contrail width of 2 km and a contrail lifetime of 2 hours. We scaled the data obtained using the monthly total air traffic over Herstmonceux to get diurnally resolved data for each month and assumed that these data for the year 2002 are also representative for the year 2003, for which Met Office radiosonde profiles were available. We corrected the systematic dry bias in the radiosonde humidity measurements[15], and applied the Schmidt–Appleman thermodynamic criterion for contrail formation[16,17] to determine the contrail cover. For contrail formation the mixture of aircraft exhaust and ambient air must reach water saturation; contrail persistency requires ice supersaturation.

We compared predictions of contrail-favourable conditions made on the basis of radiosonde data with our observations of the occurrence of persistent contrails. Data from the radiosonde ascent at Herstmonceux successfully predicted whether or not persistent contrails formed over Reading in 60 of the 81 cases analysed (see Table 1). Statistical tests of the resulting contingency table showed that these predictions were not due to chance (see the uncertainty analysis in Methods section 'Statistical significance of radiosonde contrail predictions' and Table 1).

Air traffic over Herstmonceux shows a distinct annual cycle (Fig. 1a) with a summer (June, July, August; JJA) maximum and a winter (December, January, February; DJF) minimum, with approximately 20% fewer flights. Flight restrictions at nighttime mean that approximately 75% of the total air traffic over Herstmonceux occurs between 06:00 and 18:00 GMT. Figure 1b shows the contrail frequency of occurrence, that is, the percentage of days each month when persistent contrails could occur. In mid-latitudes the upper tropospheric relative humidity has its lowest values during summer[18], so the contrail frequency is lowest in summer. The radiosonde data indicate that contrail formation over Herstmonceux is almost twice as likely in winter than in summer. Figure 1 shows that the peaks of air traffic and contrail-favourable conditions occur in different seasons.

Using the AERO2k data and only introducing a contrail if atmospheric conditions were favourable at the actual cruising altitudes, we calculated the instantaneous radiative forcing at the top of

Table 1 | Predicted and observed contrails over Herstmonceux

	Persistent contrails predicted	Either short-lived contrails or no contrails predicted
Observations of persistent contrails	24	18
No persistent contrails observed	3	36

Contingencies are shown for persistent contrails observed over Reading, and predicted from radiosonde data for Herstmonceux. Observations were made at Reading between July 2004 and June 2005 at least four times a day and compared to persistent contrail-favourable conditions predicted on the basis of radiosonde ascents made at Herstmonceux within about one hour of the observation at Reading.

[1]Department of Meteorology, The University of Reading, Reading RG6 6BB, UK. †Present address: School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK.

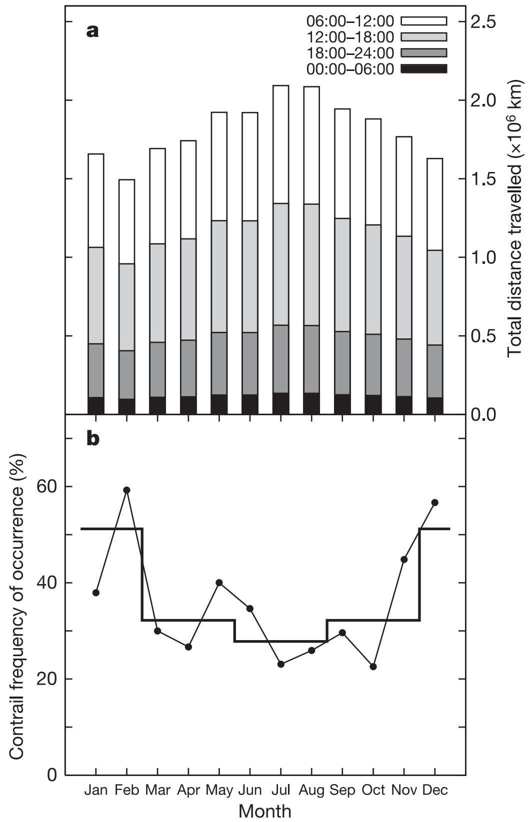

Figure 1 | **Air traffic and contrail occurrence over Herstmonceux.** **a**, Annual cycle of total column air traffic over Herstmonceux. Contributions of the four individual six-hour time periods are indicated by differently shaded bars. **b**, Annual cycle of the frequency of possible persistent contrail occurrence over Herstmonceux; that is, the number of days each month with persistent contrail-favourable conditions at one or more levels. This frequency is based solely on the meteorological conditions, indicating the potential percentage of contrail days. It does not take into account the actual vertical profile of air traffic. The heavy black line shows the seasonal mean.

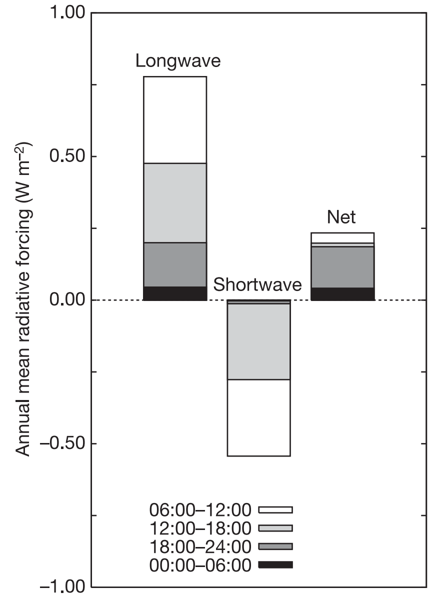

Figure 2 | **Annual mean longwave, shortwave, and net radiative forcing due to persistent contrails over Herstmonceux.** The contributions of flights occurring during different time periods to the diurnal mean values are indicated by differently shaded bars.

the atmosphere due to contrails over Herstmonceux, using a sophisticated radiative transfer model[5,6]. We allowed for the full diurnal cycle of shortwave insolation but used a single radiosonde atmospheric profile at all times of day—the choice of a single background profile was found to have a negligible impact on the radiative forcing. We complemented the radiosonde data with climatological profiles providing information on ozone, higher level temperatures and humidities, and surface albedo. We assumed a contrail visible optical depth of 0.1, standard-sized contrail particles[19] and random overlap for contrails at different altitudes. As the radiosonde data gives no information on natural clouds, the calculations were performed for otherwise clear-sky conditions. However, we investigated the effect of this assumption through sensitivity studies (see the uncertainty analysis in Methods section 'Effect of natural clouds on contrail radiative forcing').

The diurnal, annual mean radiative forcings (Fig. 2) are 0.78 and $-0.54\,\mathrm{W\,m^{-2}}$ in the longwave and shortwave, respectively, resulting in a net forcing of $0.23\,\mathrm{W\,m^{-2}}$. The locally large net forcing is due to the location of Herstmonceux in the entrance to the North Atlantic flight corridor. The diurnal variation in longwave radiative forcing reflects the daily variation in air traffic (Fig. 1a). Each of the two time periods 06:00–12:00 GMT and 12:00–18:00 GMT contributes roughly 50% to the diurnal, annual mean shortwave radiative forcing. Strikingly, because of the near cancellation between shortwave and longwave forcings for these time periods, almost 82% of the annual mean net radiative forcing is due to flights between 18:00 and 06:00 GMT, even though these night flights are responsible for only 25% of the air traffic.

The annual cycle of forcings (Fig. 3) reveals the complex interaction and competition of different effects: Time-averaged shortwave forcings are affected by daylength and solar zenith angle. With all other parameters held fixed, the shortwave effect will increase with solar zenith angle and the duration of sunlight. The effect of these two factors is superimposed on the annual variation in meteorological conditions and air traffic. Daytime shortwave forcings are smallest in summer because the combination of low solar zenith angles and smaller chances of forming a contrail dominates the effect of comparably higher summertime air traffic and longer daytime hours.

The annual cycle of longwave radiative forcing shows the dominant role of variations in meteorological conditions and hence contrail frequency of occurrence, compared to variations in air traffic. The cancellation between longwave and shortwave forcings is large throughout the year and the net forcing can sometimes be negative (Fig. 3b). The seasonal cycle of the diurnal mean radiative forcing (heavy black line in Fig. 3b) emphasizes the importance of winter (DJF) flights, which contribute 50% to the annual mean contrail radiative forcing despite being responsible for only 22% of the flights.

The net forcing is the residual from subtracting two comparatively large numbers, so its magnitude and sign are very sensitive to uncertainties in input parameters. Important sources of uncertainty are the contrail's ice crystal size and optical depth (see the uncertainty analysis in Methods section 'Sensitivity of radiative forcing to

Table 2 | **Percentage contribution of night flights to radiative forcing over Herstmonceux**

	Relative size 0.5	Relative size 1.0	Relative size 2.0
Optical depth 0.05	116	81	63
Optical depth 0.1	113	82	62
Optical depth 0.3	115	81	64
Optical depth 0.5	123	87	67

The perecentage contribution of flights between 18:00 and 06:00 to the diurnal, annual mean net radiative forcing over Herstmonceux is shown. Percentages are given for different contrail particle sizes and contrail visible optical depths.

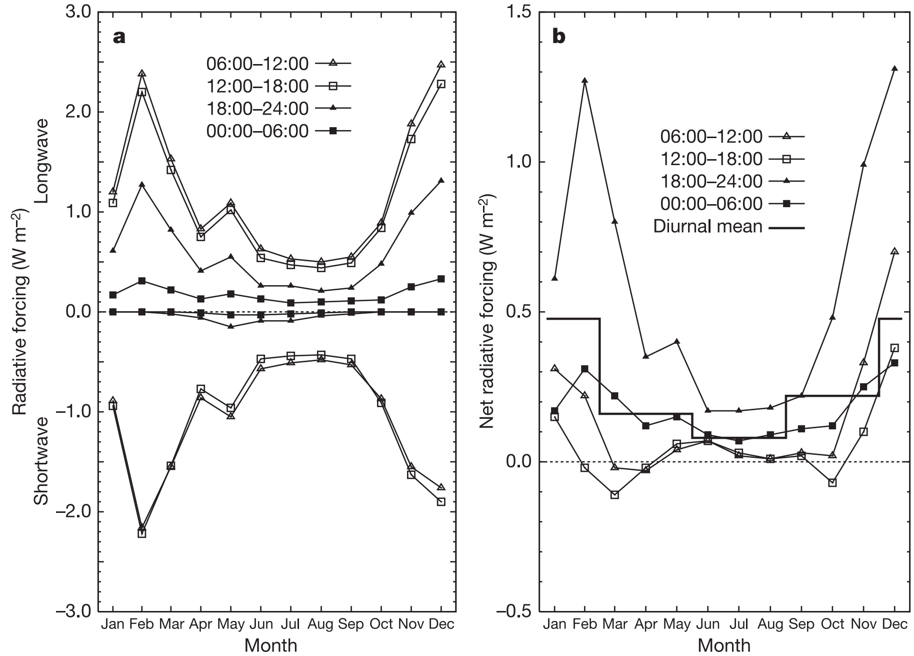

Figure 3 | Annual cycle of the diurnal-mean contrail radiative forcing over Herstmonceux for the four time periods. a, Longwave (positive) and shortwave (negative) radiative forcing. **b**, Net radiative forcing. The heavy black line shows the seasonally averaged diurnal-mean radiative forcing.

contrail optical depth and particle size' and Table 2). We found that the contribution of night-time flights to the total forcing decreased when crystal sizes were increased. However, even for the largest ice crystals, night-time flights were still found to contribute at least 62% to the daily mean forcing, depending on the contrail optical depth. Decreasing particle sizes implies a decrease in net forcing. However, this decrease in absolute forcing is accompanied by a further increase in the relative importance of night-time flights, as daytime net forcings become negative.

Natural clouds were omitted in the calculations described above because cloud data was not available from the radiosondes. In sensitivity calculations using climatological cloud distributions (see the uncertainty analysis in Methods section 'Effect of natural clouds on contrail radiative forcing') we found that natural clouds reduce both the shortwave and longwave contrail radiative forcing. However, their effect on the net forcing is variable, increasing daytime net forcings and decreasing night-time net forcings. As a consequence, the contribution of night-time flights to the diurnal mean net radiative forcing was smaller for cloudy (59%) than for clear-sky (82%) conditions. However, given their comparably small share of daily total air traffic (25%), night-time flights still contribute disproportionately to the diurnal mean forcing.

The sensitivity studies showed that changing contrail optical properties or the presence of natural clouds did not have an appreciable effect on the relative importance of the winter season for the annual mean contrail radiative forcing.

In summary, flights between 18:00 and 06:00 GMT have a disproportionate effect on the daily mean radiative forcing over Herstmonceux. Given the current flight schedules, these flights account for only 25% of total air traffic, yet they contribute 60 to 80% to the net radiative forcing. Flights during winter (DJF) are almost twice as likely to form a contrail as are summer (JJA) flights and contribute 50% to the annual mean radiative forcing.

Emissions from aircraft affect climate in numerous ways[1,2]. However, the radiative properties of contrails and their short lifetime make them the only mechanism for which a rescheduling of flight times can significantly change the radiative forcing. Our results show that, in terms of radiative forcing, the southeast of England already benefits from night-flying restrictions. At locations without such restrictions the contribution of night-time flights to daily mean contrail radiative forcing could be even larger than at Herstmonceux. For example, for South-East Asia, the AERO2k data set indicates that 40% of flights occur during night, and we find that these flights contribute 73% to the diurnal, annual mean forcing (see the uncertainty analysis in Methods section 'Effect of natural clouds on contrail radiative forcing'). In view of this, we argue that shifting air traffic from night-time to daytime would help to minimize the climate effect of contrails.

METHODS

Statistical significance of radiosonde contrail predictions. We predicted persistent contrail-favourable conditions by applying the Schmidt–Appleman thermodynamic criterion to the radiosonde data. An error in the prediction of whether a contrail could occur might be introduced either by errors in the threshold values of temperature and humidity given by the Schmidt–Appleman criterion and/or by errors in the radiosonde data. False decisions would have a direct impact on the contrail cover and hence on the radiative forcing.

The Schmidt–Appleman criterion has been tested and verified in experimental studies[20,21]. We therefore assume that any false decisions are due solely to errors in the radiosonde data. We compared predictions of contrail-favourable conditions made on the basis of Herstmonceux radiosonde data with observations of persistent contrails over Reading. The distance between Reading and Herstmonceux is smaller than the typical spatial scale of contrail clusters[22,23] and the mean extension of ice-supersaturated regions[24,25]. We statistically tested the resulting contingency table (Table 1) using different tests. The 'odds ratio'[26] compares the odds of making a true forecast with those of making a false one. It is 1 if there is no correlation between observations and predictions, and larger or smaller than 1 for a positive or negative correlation. For our case we get an odds ratio of 16. The probability that there is a positive correlation between observing persistent contrails over Reading and predicting contrails from Herstmonceux radiosonde ascents exceeds 99.5%.

In addition, we calculated the significance of the Peirce skill score, which gives a measure of accuracy for both the 'yes' and 'no' events and compares the hit rate with the false alarm rate. The score takes values between −1 and 1, being zero in case of a random forecast and greater than zero if there is some forecasting skill. We calculated a score of 0.49.

Sensitivity of radiative forcing to contrail optical depth and particle size. In view of the uncertainties associated with contrail optical properties, in addition to the reference experiment described above we conducted a number of sensitivity experiments in which we changed both the contrail particle size and the contrail optical depth. Increasing the particle size results in an increase in the magnitude of the shortwave forcing, and vice versa, while the longwave forcing is practically unaffected. In contrast, with increasing optical depths the magnitude of both the shortwave and the longwave radiative forcing increases.

The IPCC's estimate of contrail radiative forcing[1] relied on an optical depth of 0.3. However, as typical values are now believed to be lower[27,28] we adopted a value of 0.1 in our reference experiment, decreasing it to 0.05 and increasing it to 0.5 in the sensitivity experiments. Additionally, we varied the contrail particle size. The standard size used in the reference experiment is based on contrail ice-crystal size distributions derived from both *in situ* measurements and a temperature-dependent parameterisation[19]. We conducted experiments with relative contrail particle sizes of 0.5 and 2.0. These are equivalent to halving or doubling the standard width as well as the standard length of the hexagonal ice particles, respectively. Table 2 gives the percentage of diurnal mean contrail radiative forcing that is due to flights between 18:00 and 06:00 GMT for different contrail optical depths and particle sizes.

Effect of natural clouds on contrail radiative forcing. It has been shown[11] that the presence of natural clouds has a negligible effect on the global mean, annual and diurnal mean net contrail radiative forcing. However, the study did not give details on the effects of clouds on the diurnal and annual cycle of contrail radiative forcing.

To determine the effects of natural cloudiness on contrail radiative forcing we combined AERO2k data with analysis data from the integrated forecast system of the European Centre for Medium-Range Weather Forecasts to calculate global contrail cover and calibrated the contrail cover to an annual and diurnal area mean value of 0.375% (ref. 29) in the Bakan area[22]. As input for the radiative transfer model we derived atmospheric profiles using a three-dimensional climatology compiled at the University of Reading. This climatology is based on satellite, aircraft and ground-based observations and provides long-term monthly mean profiles of temperatures and the mixing ratios of water vapour and ozone extending up to 1 hPa. Information is also given about the surface albedo and the amount, optical depth and height of low, mid- and high-level clouds. Cloud information is based on ISCCP C2 data[30].

We analysed the results for selected locations. For western Europe (Herstmonceux), clouds reduce the contribution of night-time flights to annual, diurnal mean contrail radiative forcing to 59% (from 82% for cloud-free conditions). For the East Coast of the United States, 36% of flights occur during the night, contributing 53% to the diurnal, annual mean radiative forcing. For South-East Asia night flights (40%) contribute 73%, and in the North Atlantic flight corridor (48%) they contribute 58%.

Received 3 August 2005; accepted 5 May 2006.

1. The IPCC Working Group *Aviation and the Global Atmosphere—A Special Report of IPCC Working Groups I and III* (eds Penner, J. E. *et al.*) (Cambridge Univ. Press, Cambridge, UK, 1999).
2. Sausen, R. *et al.* Aviation radiative forcing in 2000: An update on the IPCC (1999). *Meteorol. Z.* **14,** 555–561 (2005).
3. Hartmann, D. L., Ockert-Bell, M. E. & Michelsen, M. L. The effect of cloud type on Earth's energy balance: global analysis. *J. Clim.* **5,** 1281–1304 (1992).
4. Minnis, P., Schumann, U., Doelling, D. R., Gierens, K. M. & Fahey, D. W. Global distribution of contrail radiative forcing. *Geophys. Res. Lett.* **26,** 1853–1856 (1999).
5. Fu, Q. & Liou, K. N. On the correlated k-distribution method for radiative transfer in nonhomogeneous atmospheres. *J. Atmos. Sci.* **49,** 2139–2156 (1992).
6. Fu, Q. & Liou, K. N. Parameterization of the radiative properties of cirrus clouds. *J. Atmos. Sci.* **50,** 2008–2025 (1993).
7. Schumann, U. On conditions for contrail formation from aircraft exhausts. *Meteorol. Z.* **5,** 4–23 (1996).
8. Gierens, K., Schumann, U., Helten, M., Smit, H. G. J. & Marenco, A. A distribution law for relative humidity in the upper troposphere and lower stratosphere derived from three years of MOZAIC measurements. *Ann. Geophys.* **17,** 1218–1226 (1999).
9. Sausen, R., Nodorp, D., Land, C. & Deidewig, F. *Ermittlung optimaler Flughöhen und Flugrouten unter dem Aspekt minimaler Klimawirksamkeit* 96–13 (DLR-Forschungsbericht, Cologne, Germany, 1996).
10. Williams, V. & Noland, R. B. Variability of contrail formation conditions and the implications for policies to reduce the climate impacts of aviation. *Transp. Res. Part D* **10,** 269–280 (2005).
11. Myhre, G. & Stordal, F. On the tradeoff of the solar and thermal infrared radiative impact of contrails. *Geophys. Res. Lett.* **28,** 3119–3122 (2001).
12. Eyers, C. J. *et al. AERO2k Global Aviation Emissions Inventories for 2002 and 2025* (QinetiQ Ltd, Farnborough, UK, 2004).
13. Schumann, U. On the effect of emissions from aircraft engines on the state of the atmosphere. *Ann. Geophys.* **12,** 365–384 (1994).
14. Gierens, K. M. Numerical simulations of persistent contrails. *J. Atmos. Sci.* **53,** 3333–3348 (1996).
15. Wang, J., Cole, H. L., Carlson, D. J., Miller, E. R. & Beierle, K. Corrections of humidity measurement errors from the Vaisala RS80 radiosonde—Application to TOGA COARE Data. *J. Atmos. Oceanic Technol.* **19,** 981–1002 (2002).
16. Schmidt, E. Die Entstehung von Eisnebel aus den Auspuffgasen von Flugmotoren. *Schr. deutsch. Akad. Luftfahrtforsch.* **44,** 1–15 (1941).
17. Appleman, H. The formation of exhaust condensation trails by jet aircraft. *Bull. Am. Meteorol. Soc.* **34,** 14–20 (1953).
18. Kley, D. *et al.* (eds) *SPARC Assessment of Upper Tropospheric and Stratospheric Water Vapour* WCRP-113, WMO/TD-No. 1043 (SPARC, Verrières le Buisson Cedex, 2000).
19. Strauss, B., Meerkötter, R., Wissinger, B., Wendling, P. & Hess, M. On the regional climatic impact of contrails: microphysical and radiative properties of contrails and natural cirrus clouds. *Ann. Geophys.* **15,** 1457–1467 (1997).
20. Jensen, E. J. *et al.* Environmental conditions required for contrail formation and persistence. *J. Geophys. Res.* **103** (D4), 3929–3936 (1998).
21. Schumann, U. Influence of propulsion efficiency on contrail formation. *Aerosp. Sci. Technol.* **4,** 391–401 (2000).
22. Bakan, S., Betancor, M., Gayler, V. & Grassl, H. Contrail frequency over Europe from NOAA-satellite images. *Ann. Geophys.* **12,** 962–968 (1994).
23. Mannstein, H., Meyer, R. & Wendling, P. Operational detection of contrails from NOAA-AVHRR-data. *Int. J. Remote Sens.* **20,** 1641–1660 (1999).
24. Detwiler, A. & Pratt, R. Clear-air seeding: opportunities and strategies. *J. Weath. Modif.* **16,** 46–60 (1984).
25. Gierens, K. & Spichtinger, P. On the size distribution of ice-supersaturated regions in the upper troposphere and lowermost stratosphere. *Ann. Geophys.* **18,** 499–504 (2000).
26. Stephenson, D. B. Use of the "odds ratio" for diagnosing forecast skill. *Weath. Forecast.* **15,** 221–232 (2000).
27. Meyer, B., Mannstein, H., Meerkötter, R., Schumann, U. & Wendling, P. Regional radiative forcing by line-shaped contrails derived from satellite data. *J. Geophys. Res.* **107** (D10), 4104, doi: 10.1029/2001JD000426 (2002).
28. Ponater, M., Marquart, S. & Sausen, R. Contrails in a comprehensive climate model: Parameterization and radiative forcing results. *J. Geophys. Res.* **107** (D13), 4164, doi: 10.1029/2001JD000429 (2002).
29. Marquart, S., Ponater, M. & Sausen, R. Future development of contrail cover, optical depth, and radiative forcing: Impacts of increasing air traffic and climate change. *J. Clim.* **16,** 2890–2904 (2003).
30. Rossow, W. B., Garder, L., Lu, P.-J. & Walker, A. *International Satellite Cloud Climatology Project (ISCCP) Documentation of Cloud Data* WMO/TD 266 (World Climate Research Programme, Geneva, 1988).

Acknowledgements We thank Q. Fu for providing the basic radiative transfer code and C. Eyers for the AERO2k data. Radiosonde data was provided by the British Atmospheric Data Centre (BADC). A. Tompkins (ECMWF) provided us with analysis data. N.S. was supported by the Department for Transport, and G.R. by the Department of Trade and Industry, and Airbus.

Author Contributions N.S. was the principal researcher. G.R. performed analysis of contrail observations. P.F. led the research with significant contributions from K.S.

Author Information Reprints and permissions information is available at npg.nature.com/reprintsandpermissions. The authors declare no competing financial interests. Correspondence and requests for materials should be addressed to N.S. (n.stuber@reading.ac.uk).