A Case Study of the Radiative Forcing of Persistent Contrails Evolving into Contrail-Induced Cirrus

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Abstract

The radiative forcing due to a distinct pattern of persistent contrails that form into contrail-induced cirrus near and over the UK is investigated in detail for a single case study during March 2009. The development of the contrail-induced cirrus is tracked using a number of high-resolution polar orbiting and lower-resolution geostationary satellite instruments and is found to persist for a period of around 18 hours and, at its peak, it covers over 50,000km^2. The shortwave (SW) and longwave (LW) radiative forcing of the contrail-induced cirrus is estimated using a combination of geostationary satellite instruments, numerical weather prediction models, and surface observation sites. As expected, the net radiative effect is a relatively small residual of the much stronger but opposing SW and LW effects, locally totalling around 10Wm^{-2} during daylight hours and 30Wm^{-2} during night-time. A simple estimate indicates that this single localised event may have generated a global-mean radiative forcing of around 7% of recent estimates of the persistent contrail radiative forcing due to the entire global aircraft fleet on a diurnally-averaged basis. A single aircraft operating in conditions favourable for persistent contrail formation appears to exert a contrail-

induced radiative forcing some 5000 times greater (in Wm^{-2}/km) than recent estimates of the average persistent contrail radiative forcing from the entire civil aviation fleet. This study emphasizes the need to establish whether similar events are common or highly unusual for a confident assessment of the total climate effect of aviation to be made.

1. Introduction

The rapid growth and the forecast future expansion of the aviation industry mean that the potential climatic effects have received considerable attention over the past decade (e.g. *IPCC*, 1999; *Sausen et al.*, 2005*; Lee et al.* 2009). The civil aviation industry currently emits around 2-3% of all carbon dioxide emissions on a global basis, but the total impact upon the Earth radiation budget is thought to be higher primarily because of the radiative impact of persistent condensation trails (contrails) and aviation-induced cirrus. Aviation-induced cirrus can occur through two different pathways: via contrails spreading out, and by injection of aerosols into the upper troposphere to provide ice-nuclei that may subsequently form cirrus clouds (*Lee et al.*, 2009). Our study is restricted to the first of these, and we therefore refer to contrail-induced cirrus throughout this work. Contrails may form when emissions of hot, warm engine exhaust in the upper troposphere mix with the cool moist ambient atmosphere. Under certain atmospheric conditions (super-saturated with respect to ice), contrails can persist for several hours. If the atmospheric conditions are favourable for ice crystal growth these persistent contrails may grow and spread out to form contrail-induced cirrus clouds (e.g. *Fahey et al.*, 1999). Persistent contrails and contrail-induced cirrus exert a radiative forcing in both the SW solar spectrum and LW terrestrial spectrum (e.g. *Stuber et al.*, 2006; *Kärcher and Spichtinger*, 2009). They reflect incident sunlight back to space thereby brightening the planet and leading to a negative SW radiative forcing that is associated with a cooling. They also trap LW radiation within the Earth atmosphere system leading to a positive LW radiative forcing that is associated with a warming. The net radiative effect of persistent contrails and contrail-induced cirrus is the sum of the negative SW radiative forcing and positive LW radiative forcing, resulting in a net forcing that is believed to be positive but rather small in magnitude (e.g. *Myhre and Stordal*, 2001, *Stuber et al.*, 2006, *Rädel and Shine,* 2008).

The earliest comprehensive estimate of the impact of aviation emissions for aircraft operations in 1992 (*Prather et al.*, 1999; *IPCC*, 1999) suggested a radiative forcing of 20mWm^{-2} for the formation of persistent contrails with considerable uncertainty. The estimate of the radiative forcing from contrail-induced cirrus was thought to be so uncertain that it could not even be quantified. The radiative forcing of persistent contrails and contrail-induced cirrus has been estimated in more recent studies at 10mWm^{-2} by *Sausen et al.* (2005) and 30mWm^{-2} (range 10 to 80mWm^{-2}) by *Stordal et al.* (2005), respectively. This assessment of persistent contrails was adopted by *Forster et al.* (2007) and *IPCC* (2007) who assigned a 90% confidence interval of 6mWm^{-2} to 30mWm^{-2}. *Forster et al.* (2007) also point out the inherent ambiguity in trying to determine and separate aviation-induced cloudiness from persistent line shaped contrails: the line-shaped contrails typically shear and spread and lose their characteristic shape while evolving into contrail-induced cirrus (e.g. *Minnis et al.*, 1998). Thus estimates of the ratio of the RF from contrail-induced cirrus to persistent contrails are highly uncertain and range from about 1 to 8 (e.g. *Lee et al.* 2009). These estimates of the radiative forcing of contrail-induced cirrus typically are derived from satellite retrievals by considering the spatial correlation of the radiances in water vapour, infra-red, and/or solar channels with aviation traffic routes and by applying suitable threshold criteria (e.g. *Minnis et al.*, 1998; 2004; *Mannstein and Schumann*, 2005) but the difficulties in distinguishing contrail-induced cirrus from natural cirrus are severe (*Mannstein and Schumann* 2007).

The uncertainty in estimates of the radiative forcing of persistent linear contrails and the evolution into contrail-induced cirrus means that observational case studies are necessary to better understand their physical and radiative properties. *Minnis et al.* (1998) used geostationary satellite instruments to track distinctly-shaped contrails evolving into cirrus in three separate events during April-May

1996 and detailed the microphysical evolution of the cirrus particles together with the cirrus optical depth cloud top temperature and area extent. Essentially, we perform a similar study, but use polar orbiting satellite data that is available at higher frequency nowadays to track the evolution of a characteristic contrail shape as it evolved into cirrus. We extend the approach of *Minnis et al.* (1998) by utilising surface and satellite measurements in conjunction with operational numerical weather prediction (NWP) models to isolate both the SW and LW RF of the contrail-induced cirrus. Unlike other studies (e.g. *Rap et al.*, *submitted manuscript*), our methodology does not rely on explicit modelling of the persistent contrails/contrail-induced cirrus themselves. The radiative forcing is deduced by subtracting the irradiances from satellite observations of contrail-induced cirrus from the irradiances derived from the NWP model which does not include contrails.

A distinct coil-shaped contrail/cirrus (hereafter CCC) that is thought to have originated from manoeuvres performed by an Airborne Warning and Control System (AWACS) aircraft was observed in satellite imagery during March 2009 (Figure 1). Figure 1a shows that the CCC is difficult to detect in visible imagery owing to the presence of extensive stratocumulus cloud at lower levels. Indeed the shadow of the contrail on the lower stratocumulus clouds, which causes a reduction in reflectance, is more readily detectable than any increase in reflectance. Figure 1b shows that the CCC is however very readily discernable in the infra-red wavelengths because of the large difference in the emission temperature between the CCC and the low level stratocumulus. Both images show that while the CCC is by far the most distinguishable contrail occurring over the North Sea, several other contrails are also visible off the coast of Scotland and England and encroach over S.E. England.

In this study we analyse the meteorological conditions which are shown to favour persistent contrail formation between approximately 25,000-35,000ft (7.5 to 10.5km) (section 2). Polar orbiting satellite instruments that detect cloud at infra-red (10.8μm) wavelengths are used to record the evolution of the CCC over a ten hour period and an atmospheric dispersion model is used to verify the position of the coil-shaped contrail as it shears and spreads (section 3). The study also uses independent measurements from the geostationary Meteosat-9 satellite Spinning Enhanced Visible and InfraRed Imager (SEVIRI) instrument to track the CCC and other persistent contrails as they advect and evolve. Although analysis of the evolution of ice crystal effective radius and cirrus optical depth are hampered by the presence of low-level stratocumulus and the advection over variable land surfaces, retrievals are possible over ocean surfaces free from low level cloud (section 4). The advection of the contrail/cirrus over land means that instrumented meteorological observation sites may also be used to determine the SW radiative forcing at the surface (section 5). The SW and the LW top of the atmosphere radiative forcings are estimated by comparing the SW and LW irradiances derived from the Met Office high resolution (4km) UK4 operational NWP model (section 6.). A discussion and conclusion are then provided (section 7).

2. The prevailing meteorological conditions.

The synoptic surface analysis chart for 12:00 (all times refer to UTC) on 20 March 2009 is shown in Figure 2. A large anti-cyclone is centred on the UK with a central surface pressure of around 1034-1035hPa. The UK is in a stable warm sector with a weak frontal system approaching only very slowly from the west. The small pressure gradients mean that wind is slack across the UK. Figure 3 shows the tephigrams derived from radiosonde ascents from Met Office sites for 12:00 for Nottingham (53.00^{o}N, 1.25^{o}W), Albermarle (55.01^{o}N, 1.52^{o}W), and Ekofisk (56.53^{o}N, 3.21^{o}E) (see geographical positions marked on Figure 1). *Rädel and Shine* [2007] have shown that provided corrections are made to the relative humidity derived from these sondes, they can be used quite reliably to infer conditions necessary for the formation of persistent contrails. All three of the tephigrams show a strong subsidence temperature inversion indicating highly stable atmospheric conditions to around 900hPa. At low levels the atmosphere is dry with water vapour mass mixing ratios lower than 0.2-0.4gkg^{-1} evident in the Nottingham and Ekofisk ascents. The lack of moisture in the atmospheric column is reflected by the low total precipitable water values of 5.2mm, 8.5mm, and 6.7mm for the Nottingham, Albermarle, and Ekofisk ascents respectively. At upper levels, the Ekofisk sounding shows a similar temperature profile to the other two radiosonde ascents, but the water vapour mass mixing ratio is significantly higher between 250-500hPa indicating a moister upper troposphere. The relative humidity with respect to ice calculated from the profiles making the corrections to relative humidity recommended by *Rädel and Shine* [2007] based on *Vömel et al.* [2007] is shown in Figure 3b. At upper levels, the relative humidity only very slightly exceeds 100% for Nottingham, but exceeds 100% for Albermarle above about 275hPa. For the Ekofisk ascent a much greater altitude range (200-400hPa) is subject to ice supersaturation conditions meaning that persistent contrail formation and growth may therefore be expected near the Ekofisk oil platform provided that the ambient temperature is below the minimum temperature for contrail formation: the Ekofisk tephigrams reveals a temperature at 300hPa of around -50C which is sufficient for contrail initiation. Thus one might expect contrails to be initiated and spread around the Ekofisk region of the North Sea. This is consistent with visual inspection of the contrails shown in Figure 1.

Inspection of fields of the relative humidity with respect to ice from the operational UK4 model reveals that, although the relative humidity with respect to ice frequently approaches 100%, no areas of super-saturation are found over the North Sea between pressure levels of 300-350hPa over the period 12:00 on the 20 March 2009 to 06:00 on the 21 March 2009. In common with many of the current Met Office Numerical Weather Prediction models (e.g. *Newman et al.*, 2008) and the climate model (*Rap et al*., *submitted manuscript*), this deficiency in model performance appears to be linked to too dry a modelled upper troposphere. Not all operational NWP models exhibit this deficiency. Figure 4a shows the relative humidity with respect to ice determined from a 12 hour forecast of ECMWF operational model. The forecast relative humidity over the North Sea at 12:00 is seen to exceed 100% between levels of 25,000-35,000ft (7.5-10.5km), with peak values exceeding 130% above 32,500ft (~9.7km). Figure 4b shows the evolution of the ice-supersaturated region at 30,500ft

(9.2km). The region of ice-supersaturation is seen to persist throughout the period shown and drift southwards with the prevailing winds shown in Figure 4a.

Further efforts are obviously needed to improve the Met Office suite of models in terms of their upper tropospheric moisture, particularly if the Met Office is to improve its contrail forecasting capability from the model. However, here we turn this deficit to our advantage: because the model does not predict any significant ice super-saturation and hence no upper level cirrus, the difference between the modelled and observed radiative fluxes at the top of the atmosphere are essentially equivalent to the radiative forcing of the contrails/cirrus. This methodology assumes that the radiative effect of the moisture deficit is second-order compared to the radiative effect of the contrails, which radiative transfer calculations show to be a reasonable assumption. Such an approach has previously been used for determining the radiative effects of mineral dust over the Sahara desert (*Haywood et al.*, 2005). One particularly significant advantage of this approach is that it does not rely to any degree on accurate modelling of the detailed microphysics and spatial distribution of the contrails/cirrus: only radiative transfer in the absence of contrails/cirrus needs to be performed. This methodology will be considered in more detail in section 6.

3. Evolution of the contrails into cirrus.

As shown in Figure 1, the CCC is most readily distinguished from the low-level stratocumulus cloud using infra-red (10.8μm) wavelengths. Figure 5 shows the evolution of fresh, linear contrails and the CCC.

The majority of the fresh, relatively narrow, linear contrails appear to be initiated between about 08:30 and 12:00. The satellite imagery suggests that prior to around 12:00, the majority of contrails that are growing into contrail-induced cirrus appear to be initiated over the North Sea although a few also appear over the SE of the UK. After 12:00 the area of contrail-induced cirrus is advected over land areas of the UK which is in reasonable agreement with the ECMWF forecast model fields of supersaturation shown in Figure 4b.

The earliest image that shows the presence of the CCC is at 10:06 where five complete orbits are shown. By 11:30 the CCC has advected to the south but retains its characteristic shape which now contains 10 full orbits. Thus 1 orbit takes approximately 17mins. By 12:02, the CCC is becoming more difficult to identify owing to shear and diffusion smearing the characteristic shape of the CCC and by the mixing with other contrails. By 15:26 all initial resemblance to the coil shape has all but vanished and the casual observer would be forgiven for thinking that the resulting cirrus was an entirely natural feature; indeed, we are unable to definitively rule out the possibility that entirely natural cirrus could have formed anyway. The contrail-induced cirrus then persists over the UK until at least 19:48 and is advected southwards over the Isle of Wight as shown by the final frame of Figure 5. Further imagery from 03:32 on 21 March 2009 (not shown for reasons of brevity) suggests that contrail-induced cirrus is still present over SW England, although this cirrus was likely generated from contrails forming to the north and west of the distinctively shaped CCC.

By considering the time evolution of the CCC we can deduce that the first orbit would have been started at around 08:30 and that the contrail formation from the aircraft ceased around 11:50. To show beyond reasonable doubt that the CCC is still over the UK by 19:48, we initiate the Met Office Numerical Atmospheric-dispersion Modelling Environment (NAME) model. NAME is a Lagrangian particle model (*Ryall and Maryon*, 1998) in which emissions from pollutant sources are represented by parcels released into a model atmosphere driven by the meteorological fields from the Met Office global, North Atlantic Environment, or UK4 NWP models. Each parcel carries mass of one or more pollutant species. The mass can change due to various physical and chemical processes during its lifespan. Although originally designed as an emergency-response nuclear accident model, subsequent development has greatly enhanced NAME's capabilities so that it is now used in a wide range of applications (*Jones*, 2004). The NAME model was initiated using UK4 model data and emission rate of particulate mass of 1g/second at an altitude of 30,000ft (9km) in a fixed circle centred on 55.3^{o}N, 1^{o}E with a radius of 20km. The emission rate is entirely arbitrary, and bares no resemblance to engine particulate or water vapour emissions. In addition, the specific microphyscial evolution of contrail-induced cirrus is not modelled. While dynamical processes of turbulent diffusion and shear are included, the microphysical process of gravitational sedimentation of cirrus particles is not parameterised. As gravitational sedimentation is the major mechanism for the spreading of contrails in the vertical (e.g. *Burkhardt and Kärcher*, 2009), this deficiency is likely to result in the NAME simulations underestimating the geometric thickness of the resulting contrail-induced cirrus. The size and location of the circular orbit were determined by visual inspection of the satellite images. The results from the dispersion model are shown in Figure 6. Figure 6a-c show that, as in the satellite images shown in Figure 5, the modelled CCC is stretched in the N-S direction and by 12:02, the southernmost extent of the CCC is just over the coast of the UK near the Humber estuary. Between 13:42 and 15:26 the CCC is directly over the Cardington field site (see Figure 1 for the location). By 17:08 the modelled CCC lies broadly between the Wash and the Isle of Wight and is roughly centred on the Isle of Wight by 19:48.

Throughout the first part of the period, the coherence of the CCC modelled by the NAME model and that observed by satellites is excellent which suggests that, even when the CCC becomes indistinct in the observations, the origin of the cirrus over the UK appears to be from persistent contrails. Tests with the NAME model, but with emissions now at 35,000ft (10.5km), reveal that the position of the modelled CCC is quite similar, with a similar spread and trajectory but ends in a slightly more easterly location (less than 50km difference from that shown in Figure 6h) by 19:48. Similarly, initiating the emissions at 25,000ft (7.5km) again leads to a more easterly position with the CCC being centred over London. Thus, although we cannot be certain, an emission height of 30,000ft or

9km appears to result in the best agreement between the model and satellite observations of the CCC.

This choice of emission height can be validated by independent measurements made by the Doppler lidar at the Chilbolton Observatory (for location see Figure 1). Doppler lidar attenuated backscatter is shown in Figure 7. Any cirrus signature is entirely absent from the retrievals until around 13:00, in agreement with what might be expected from the satellite observations of Figure 5. By 15:00 what we believe to be tenuous persistent contrails/contrail-induced cirrus other than those formed from the CCC are evident. The CCC is forecast to influence the retrievals from around 17:00 (see Figure 6g and 6h), and continuous cirrus is indeed detected between 7.5km and 9.5km between 17:00 and 24:00.

4. Determination of the contrail-induced cirrus optical depth and effective radius.

Minnis et al. (1998) were able to assess the evolution of the contrail-induced cirrus particle radii, as small contrail particles grow to become indistinguishable from natural cirrus. Our efforts are hampered by the presence of low-level stratocumulus clouds below the contrails which make unique solutions to satellite inversion algorithms extremely challenging for operational retrievals, meaning that the particle size evolution cannot be evaluated when these low-level clouds are present. However, there are enough contrail/cirrus influenced pixels over otherwise cloud-free oceanic areas to perform a limited set of retrievals. These retrievals make use of reflectance measurements at a pair of solar wavelengths (in this case the SEVIRI channels centred at 0.8 μm and 1.6 μm), following techniques developed by *Nakajima and King* (1990), and are produced routinely at the Met Office for every 15-minutes during daylight hours.

Figure 8 shows images of the cloud optical thickness and effective radius retrieved from SEVIRI data for 14:00. The large area of liquid water stratocumulus cloud over the northern part of the North

Sea is apparent, and it is this optically thick low cloud that the retrieval scheme has identified, rather than the overlying optically thin ice cloud. The areas free of low-level water cloud off the east coast of England are identified as ice cloud made up of aggregate particles having optical thicknesses generally less than around 2. Because of the thin nature of the ice cloud, the retrieval scheme encounters problems over land, and incorrectly identifies much of the thin cloud over eastern England as being water cloud. For this reason, all land pixels identified as being water cloud with an optical thickness less than 4 have been classed as ice cloud in Figure 8a when used in subsequent calculations and the corresponding effective radius pixels have been flagged as invalid data in Figure 8b.

Frequency histograms of the optical thickness and effective radius are shown in Figure 9, the data here being restricted to only ice cloud retrievals over sea. Two areas are considered, the small area 52.25^{o}N to 54.6^{o}N, 0.7^{o}W to 1.4^{o}E associated with the CCC in Figures 5 and 6 (and shown as a cyan box in Figure 8a), and the larger (L) area 50^{o}N to 58^{o}N, 3^{o}W to 5^{o}E to tie in with the main area of ice cloud shown in Figure 8a, where this area is shown as a magenta box. Figure 9a shows a distribution of optical thicknesses in the CCC (dotted line) ranging between 0.4 and 1.95, with a mean value of 1.06, whereas the distribution of optical thicknesses for the residual (i.e. L minus CCC) area (solid line) shows significantly lower values, the mean value being 0.74. Corresponding effective radius distributions are shown in Figure 9b, and these indicate that the values in the CCC area (dotted line) are generally lower than those in the residual area (solid line), with a mean value of 27.9 μm for the CCC area and a mean value of 35.2 μm for the residual area. The ice water path retrievals (not shown) suggest a mean value of 17.8gm^{-2} for the CCC area and a mean value of 15.7gm^{-2} for the residual area. If we assume that the contrail-induced cirrus is of 1-2km thickness (as in the lidar profile shown in Figure 7), then an ice water content of 8-18mgm^{-3} is derived which corresponds to values between the median and the upper quartile measured in mid-latitudes of the Northern hemisphere at temperatures between -43C and -53C during the Interhemispheric Differences in

Cirrus Properties From Anthropogenic Emissions (INCA) measurement campaign (*Gayet et al.*; 2004).

A scatter plot of the optical thickness versus the ice effective radius is shown in Figure 9c for the CCC (red dots) and the residual area (black dots). Smaller ice effective radii are associated with optically thicker cirrus of the CCC. *Minnis et al.* (1998) report a change in contrail-induced cirrus cloud effective radius from around 10 μm at contrail formation to around 30 μm after approximately 7.5 hours. In our analysis, the oldest cirrus particles are around 5-6hours old; our values of around 28 μm are in reasonable agreement, although the rate of increase of particle size will be strongly dependent on the atmospheric conditions (*Fahey et al.*, 1999). The cause of the difference in the microphysical properties of the CCC is not investigated here, but could be due to the higher concentration of ice nuclei emitted owing to circling nature of the aircraft flight pattern or the lower estimated air-speed of the AWACS operations (estimated from the time taken to complete one complete circle of radius 20 km as around 440 km/hour) compared to aircraft operating at faster cruising speeds.

5. Determination of the solar SW radiative forcing from the contrail-induced cirrus at the surface

The radiative forcing of the contrail-induced cirrus is determined from the Cardington field site (location shown in Figure 1) using standard Eppley solar pyranometers. Detection of the radiative effects of the contrail-induced cirrus at infra-red wavelengths is not considered here because the variation in water vapour dominates the infra-red signal. Figure 5 shows that Cardington will be affected both by the CCC and by contrail-induced cirrus from other sources. However, the NAME modelling of the CCC suggests that Cardington will become directly influenced by the CCC sometime between 14:10 and 14:30. We estimate the radiative forcing in two separate ways:-

a) Determining the down-welling solar irradiance including contrail-induced cirrus from 20 March 2009 ($SW_{\downarrow 20\ obs}$) and using simple radiative transfer modelling to determine the surface irradiance in the absence of contrail-induced cirrus ($SW_{\downarrow 20\ model}$). The surface SW radiative forcing by contrail-induced cirrus, ΔF_{SW}, is then given by:-

$$\Delta F_{SW\ obs\ \&\ model} = SW_{\downarrow 20\ obs} - SW_{\downarrow 20\ model} \tag{1}$$

Because the radiative transfer modelling only needs to account for Rayleigh scattering and gaseous absorption, only a very simple radiative transfer parameterisation scheme is used. Rayleigh scattering and gaseous absorption by ozone and water vapour are accounted for using the parameterisations for atmospheric transmission developed by *Lacis and Hansen* (1974) including a magnification factor to account for the curvature of the Earth and refraction of incident radiation (*Rodgers*, 1967). Ozone is estimated from the Ozone Mapping Imager (OMI) to be around 325DU, while the precipitable water vapour is from the nearby Nottingham radiosonde.

b) Determining the down-welling SW irradiance including contrail-induced cirrus from 20 March 2009 ($SW_{\downarrow 20\ obs}$) and using observations from a cloud and contrail-free day (18 March 2009) to determine the surface irradiance from observations in the absence of contrail-induced cirrus ($SW_{\downarrow 18\ obs}$). The surface SW radiative forcing by contrail-induce cirrus, ΔF_{SW}, is then given by:-

$$\Delta F_{SW\ obs} = SW_{\downarrow 20\ obs} - SW_{\downarrow 18\ obs} \tag{2}$$

The precipitable water vapour varies from 8.3mm on 18 March 2009 at 12:00 to 5.2mm on 20 March at 12:00 for the Nottingham ascent. This change in water vapour can contribute significantly to differences in the SW radiation reaching the surface: calculations using the parameterisations of *Lacis and Hansen* (1974) indicate a maximum difference at local noon of around $16 Wm^{-2}$. This change in down-welling SW irradiance due to changes in column water vapour loading is accounted for in our calculations.

Figure 10a shows the ratio of the diffuse to the direct fluxes between 14:00 to 18:00 for 18 March 2009 (contrail and cloud free) and 20 March 2009 (affected by contrail-induced cirrus but otherwise cloud free). The effect of contrail-induced cirrus can clearly be seen on 20 March 2009 with a significant increase in the diffuse/total radiation at the surface. The more variable nature of the diffuse/total radiation caused by the varying contrail-induced cirrus optical depth and viewing geometries can also be seen in the data from 20 March when compared to 18 March.

Figure 10b shows $\Delta F_{SW\ obs}$ and $\Delta F_{SW\ obs\ \&\ model}$ determined from the two methods described above which show reasonable agreement. The peak ΔF_{SW} is determined to be stronger than -150Wm^{-2} (the minus sign indicating a reduction in SW radiation at the surface). Subsequently ΔF_{SW} is weaker, ranging from around zero to -50Wm^{-2}. Between 14:00 and 17:00 the mean $\Delta F_{SW\ obs}$ is -44Wm^{-2} and the mean $\Delta F_{SW\ obs\ \&\ model}$ is -47Wm^{-2}. Although the modelling method tends to give a slightly higher mean estimate for ΔF_{SW}, no consistent bias is found (e.g. the period between 15:00 and 16:00), and either method may be thought of as a reasonable approximation. A standard deviation of 14 Wm^{-2} is found for both methods, when considering one minute averages, leading to a standard error of around 1Wm^{-2}. The real error is considerably higher owing to potential systematic uncertainties in the total column water vapour and ozone fields and variations in the aerosol optical depth and is estimated as ±10Wm^{-2}.

6. Determination of the SW and LW radiative forcing of contrail induced cirrus at the top of the atmosphere.

The radiative forcing is determined at the top of the atmosphere by using a methodology similar to that used in *Haywood et al.* (2005). *Haywood et al.* (2005) compared the LW top of the atmosphere clear-sky irradiances derived from the Meteosat-7 instrument with those predicted by the Met Office global NWP model. Differences in the irradiances of up to 50 Wm^{-2} were clearly identified over the Sahara. This feature was shown to be due the omission of the radiative effects of mineral dust in the NWP model. Here we perform a similar exercise; because the NWP model does not accurately represent the ice super-saturation observed between approximately 25,000ft-35,000ft (7.5 to 10.5km) (Figure 3b), no cirrus cloud is modelled in these regions. Just as the study of *Haywood et al.* (2005) does not rely on explicit modelling of the radiative effects of mineral dust, the simulations that we perform here do not rely on explicit modelling of the radiative effects of contrail-induced cirrus. The estimates presented here are therefore independent of the retrievals derived in section 4.

6.1. Definition and diagnosis of the radiative forcing

The radiative forcing at the top of the atmosphere, ΔF_{SW_TOA}, of the contrail-induced cirrus can be simply diagnosed as:-

$$\Delta F_{SW\_TOA} = SW_{\uparrow no\ contrails} - SW_{\uparrow contrails} \quad (3)$$

or

$$\Delta F_{SW\_TOA} = SW_{\uparrow model} - SW_{\uparrow satellite} \quad (4)$$

Similarly the long-wave radiative forcing, ΔF_{LW_TOA}, can be diagnosed from:-

$$\Delta F_{LW\_TOA} = LW_{\uparrow no\ contrails} - LW_{\uparrow contrails} \quad (5)$$

or

$$\Delta F_{LW\_TOA} = LW_{\uparrow model} - LW_{\uparrow satellite} \quad (6)$$

Previous studies have derived top of the atmosphere irradiances from radiance data from either the Meteosat-7 instruments (*Haywood et al.*, 2005) or the Geostationary Earth Radiation Budget (GERB) instrument (*Allan et al.*, 2007). In this study we diagnose $SW_{\uparrow satellite}$ and $LW_{\uparrow satellite}$ from the SEVIRI instrument. Broadband irradiance is routinely estimated from narrow-band channels of the

SEVIRI instrument by the Royal Meteorological Institute of Belgium in the processing of GERB data. Processing is conducted on 3x3 SEVIRI pixels at an approximate pixel resolution over the UK of 15km. Conversion of narrow to broad-band radiances is achieved using a regression technique combined with detailed calculations from line-by-line radiative transfer simulations (*Clerbaux et al.* 2008a) and are converted to irradiance using a set of angular distribution models; this is essentially the same method as described in *Haywood et al.* (2005) for Meteosat-7 but exploiting the greater number of channels supplied by SEVIRI. For the shortwave region of the spectrum, a similar approach is adopted, using 3 shortwave channels from SEVIRI in the regression and applying angular dependence models from the Clouds and the Earth's Radiance Energy System (CERES) dataset to estimate broadband shortwave irradiance (*Clerbaux et al.* 2008b).

Since GERB data was only produced between 02:00 and 07:00 during the period of interest, we use the SEVIRI-based estimates of $SW_{\uparrow satellite}$ and $LW_{\uparrow satellite}$. To reduce the effect of slight timing differences between the model and the SEVIRI data, $SW_{\uparrow satellite}$ is scaled by the ratio of the incoming shortwave radiation for the model and the satellite data.

Interpolating SEVIRI $LW_{\uparrow satellite}$ to the GERB grid, comparisons were conducted over 140 grid points over the UK region for 03:00 and 06:00 on the 20 and 21 March 2009. A mean bias of 0.7 Wm^{-2} and root mean squared difference of 3.2 Wm^{-2} between SEVIRI and GERB estimates are apparent. Based on the expected SEVIRI calibration and the processing described in *Clerbaux et al.* (2008a,b) we propose a conservative estimate of uncertainty of order 5%, which corresponds to ±12.5 Wm^{-2} for an irradiance of 250 Wm^{-2}: a similar uncertainty is assumed for $SW_{\uparrow satellite}$.

To diagnose $SW_{\uparrow model}$ and $LW_{\uparrow model}$ we use the TOA fluxes from the high resolution operational UK4 model (*Lean et al.*, 2008) which has a spatial resolution of 4km in the horizontal and contains 70 model levels. The model is initialised at 00:00 and is run forward with no data assimilation for a period of 36hours. Data assimilation is turned off to prevent the model from moistening the upper troposphere via assimilation of observational data sets and hence we deliberately inhibit any cirrus cloud formation. The model time-step is 100seconds with radiation being called every 9 timesteps (15 minutes). The model contains a basic aerosol climatology (*Cusack et al.*, 1998). The SW surface reflectance is determined from the combined reflectance of 9 representative surface types as described in the Met Office Surface Exchange Scheme II (MOSES II, *Essery et al.*, 2003) and the surface emissivity is uniformly set to a spectrally independent value of 0.97. The radiation scheme in the model is the *Edwards and Slingo* (1996) radiation code which is configured to treat the absorption and scattering of SW and LW radiation by gases, aerosols, and water and ice clouds. The radiation code contains 5 bands in each of the SW and LW regions of the spectrum and the 2-stream approximation is used. Note here that the irradiances derived from the UK4 model are very similar to those from the global model: we chose to present the analysis of the UK4 model only as this model has superior spatial resolution.

Sources of error in $SW_{\uparrow model}$ and $LW_{\uparrow model}$ come from errors in both the parameterisation of radiation (e.g the two-stream approximation and the relatively coarse spectral resolution used in the operational model, *Edwards and Slingo,* 1996) and from errors in the horizontal and vertical spatial distribution of gases that absorb radiation in the SW and LW region of the spectrum. One specific potential error relating to the latter is the low bias in the upper tropospheric water vapour in the model fields which may bias $SW_{\uparrow model}$ and $LW_{\uparrow model}$. Calculations with a stand-alone version of the *Edwards and Slingo* (1996) radiation code where the upper troposphere between 200-500hPa is moistened from the sub-saturated profile from the Nottingham ascent (Figure 3b) to that of the super-saturated Ekofisk ascent reveal a negligible effect on $SW_{\uparrow model}$, but a bias of up to +5Wm^{-2} for $LW_{\uparrow model}$. However, we shall see that a bias of this magnitude is a second-order effect when we isolate the ΔF_{TOA_LW} of contrails.

6.2. Approach to cloud screening

The cloud screening approach that is used here differs when applied to satellite and the model data.

Low lying stratocumulus clouds have less impact on LW radiation than SW radiation at the top of the atmosphere because the temperature of the top of the low level liquid water clouds is only a few degrees different from the surface of the ocean whereas the change in the SW reflectivity change can be significant. Consider the tephigrams in Figure 3, particularly the Ekofisk ascent in the North Sea. Although no stratocumulus cloud was present at this location, the relative humidity was 88% at 993hPa. The difference between the temperature at 993hPa and 1026hPa (the highest recorded pressure approximately corresponding to 29m altitude) was less than 4K. Calculations show that differences of 4-6K at temperatures of around 280K correspond to flux differences of around 6-9% or 13-20Wm^{-2} for TOA fluxes of 220Wm^{-2}. Thus, in terms of TOA LW irradiances, areas where stratocumulus cloud is forecast in the model but not present in the observations (or vice versa) will lead to an error estimated as approximately ±20Wm^{-2}. We therefore assign an error estimate of ±20Wm^{-2} over areas where cloud is present in either the model or the satellite retrievals.

For $SW_{\uparrow satellite}$ over oceans, areas where the cloud retrievals described in section 4 reveal the influence of low level water cloud are screened out of the analyses. Over land, for optically thin clouds, the retrievals fail (section 4) and liquid water cloud is diagnosed. This problem is overcome by applying a threshold that removes all areas of liquid cloud with optical thickness at 0.55µm greater than 2. For $SW_{\uparrow model}$, areas with significant liquid water cloud are screened out from the data. While it is recognised that these masking thresholds have some degree of subjectivity associated with them, the results presented in 6.3 appear entirely reasonable.

6.3. Results

The resulting $LW_{\uparrow satellite}$, $LW_{\uparrow model}$, and ΔF_{LW_TOA} with no cloud screening applied are shown for 14:00 in Figure 11a, b, and c respectively. Figure 11a shows $LW_{\uparrow satellite}$ of greater than 260Wm^{-2} over land areas of the UK and the continent. Lower values of around 250Wm^{-2} are evident in clear skies over the ocean owing to the lower surface temperature. The lowest values of all are apparent over the North Sea and over eastern areas of England where a $LW_{\uparrow satellite}$ of less than 220Wm^{-2} is evident; these areas correspond to the presence of either thick low level stratocumulus clouds, or thin high level contrail-induced cirrus. Figure 11b indicates that $LW_{\uparrow model}$ shows many similar features to $LW_{\uparrow satellite}$: the highest values over land regions, lower values over clear-sky ocean regions, and the lowest values over thick modelled stratocumulus regions are all present. The feature that is clearly absent is the low values (< 220-230 Wm^{-2}) associated with the optically thin contrail-induced cirrus. ΔF_{LW_TOA} obtained from equation (6) shows strong positive values which exceed +40Wm^{-2} in the vicinity of the CCC (see area labelled (i) on Fig 11c). The strong spatial correlation between ΔF_{LW_TOA} and the polar orbiting satellite image of the CCC shown in Figure 5e and the modelled position of the CCC shown in Figure 6e is clearly evident. A second area where ΔF_{LW_TOA} exceeds +40Wm^{-2} is also shown in Figure 11c (labelled (ii)) which appears to correspond to contrails initiated off the east coast of Scotland (see Figure 5). There are several areas where ΔF_{LW_TOA} is diagnosed as being negative; areas of SW England, Wales, northern Scotland and the continent all exhibit ΔF_{LW_TOA} as strong as -15Wm^{-2}. Interestingly, no significant biases are evident over clear sky ocean areas. The biases over land areas are likely related to a cold bias in the surface temperature in the UK4 model (*J.M. Edwards, personal communication*) which is currently under investigation, but beyond the scope of the present work.

The resulting $SW_{\uparrow satellite}$, $SW_{\uparrow model}$, and ΔF_{SW_TOA} with no cloud screening applied are shown for 14:00 in Figure 11d, e, and f respectively. It is immediately apparent that the differences between the modelled and measured irradiances over the stratocumulus clouds in the North Sea are far larger in the SW region of the spectrum than in the LW region, with SEVIRI generally diagnosing brighter clouds by in excess of $150Wm^{-2}$ in many areas. The liquid water cloud mask for SEVIRI (sections 4 and 6.2) are encompassed by the thick contour intervals on Figure 11d surrounding the extensive stratocumulus in the North Sea and another less extensive area of stratocumulus over SW Scotland. Liquid water cloud present in the model is encompassed by the thick contour line shown in Figure 11e. Generally, the model does a reasonable job of predicting the presence and areal extent of the stratocumulus regions in both the North Sea and SW Scotland. There are areas where the model contains cloud where the SEVIRI retrieval does not or vice-versa. For example the model extends the stratocumulus sheet in the North Sea further south than the SEVIRI retrieval and SEVIRI shows more extensive stratocumulus to the extreme north west of the images shown. The composite cloud mask determined in Figure 11f contains all areas where liquid water cloud is diagnosed in either the SEVIRI retrieval or the model and is indicated once more by areas falling within the thick contour line. This composite cloud screening algorithm is used henceforth in screening data for liquid water cloud via a simple cloud mask.

ΔF_{LW_TOA} and ΔF_{SW_TOA} including the cloud mask are shown in Figure 12 for the period 12:00 to 18:00. No ΔF_{SW_TOA} is shown for 18:00 because the sun had set. The areas of maximum ΔF_{LW_TOA} and ΔF_{SW_TOA} associated with the contrail-induced cirrus are shown to drift southwards in agreement with the observations in Figure 5 and the modelling in Figure 6. ΔF_{LW_TOA} has values stronger than $45Wm^{-2}$ throughout the period (Figure 12a-d). On the other hand, ΔF_{SW_TOA} shows values stronger than $-75Wm^{-2}$ in the predicted position of the CCC at 14:00 (Figure 12f). As a consequence, there is significant cancellation of ΔF_{LW_TOA} and ΔF_{SW_TOA} as is clearly shown in ΔF_{net_TOA} (Figure 12h-j). The temporal evolution of the mean ΔF_{LW_TOA}, ΔF_{SW_TOA} and ΔF_{net_TOA} over the domain encompassed by the thick contour on Figure 12 are shown in Figure 13a.

Figure 13a shows that, during daylight hours ΔF_{LW_TOA} is significantly offset by ΔF_{SW_TOA} leading to a ΔF_{net_TOA} of around $+10Wm^{-2}$ during the period 11:00 – 15:00. ΔF_{net_TOA} becomes negative when the solar zenith angle increases towards sunset owing to the stronger contribution from the SW component as expected from detailed radiative modelling of the SW and LW radiative effects (*Myhre and Stordal*, 2001). At sunset ΔF_{net_TOA} is simply equal to ΔF_{LW_TOA}. Note that ΔF_{SW_TOA} becomes more negative during afternoon until immediately before sunset, at a rate that is faster than the ΔF_{LW_TOA} becomes more positive. This is consistent with the increase in SW forcing, due to the dependence of the contrail albedo on solar zenith angle, as was discussed in, for example, *Myhre and Stordal* (2001).

The areal extent of the contrail-induced cirrus is defined as areas where ΔF_{LW_TOA} is greater than twice the standard deviation of ΔF_{LW_TOA} in the domain shown in Figure 12 for each time-frame. Alternative thresholds based on the standard deviation or even a single threshold could be applied, but our method has the advantage of factoring in the temporal variability of ΔF_{LW_TOA}. Figure 13b shows the area extent of the contrail-induced cirrus is shown to steadily increase from around 28,000km^2 at 11:00 to 52,000km^2 by 17:00 after which it decays. Note that no areas outside the domain shown are classified as contrail-induced cirrus throughout the sequence shown indicating that the cirrus has not simply advected out of the domain. Thus, the area of the contrail-induced cirrus approximately doubles in size over a 6 hour period. We also calculate the areal extent of the CCC from the NAME model results: these are also shown on Figure 13b. The CCC covers approximately 9,000km^2 at 11:00, growing to approximately 34,000km^2 by 20:00 and is on average 23,000km^2. The rate of increase in the area is similar between the contrail-induced cirrus derived over the entire domain and that derived for the CCC until around 17:00. After 17:00 the areal extent of the CCC derived from NAME continues to grow while the area of contrail-induced cirrus over the domain starts to diminish. This indicates that conditions for continued contrail-induced cirrus growth cease around this time. The reasons for this transition from conditions of contrail-induced cirrus growth to conditions of contrail-induced cirrus decay are unclear but could be due to a combination of a reduction in the magnitude and/or extent of the supersaturated area, sedimentation of ice crystals (e.g. *Burkhardt and Kärcher*, 2009) and the expected diurnal reduction in the air traffic activity in the area which could reduce new contrail formation (e.g. *Stuber et al.*, 2006).

ΔF_{LW_TOA}, and ΔF_{SW_TOA} may also be calculated for the Cardington site. Because the scattering of visible radiation by contrail-induced cirrus should be essentially conservative, ΔF_{SW_TOA} should be roughly comparable to ΔF_{SW} determined at the surface (see section 5, and Figure 10). This comparison will be affected by the amount of absorption of near-IR by water vapour in the column between the CCC and the surface. ΔF_{SW_TOA} is evaluated from the 7 grid-boxes closest to Cardington, for 12:00 and at each hour through to sunset at around 18:00; the mean value for ΔF_{SW_TOA} over the period 14:00-17:00 is -36.5Wm^{-2}, which is in reasonable agreement with the surface ΔF_{SW} of between -44.4Wm^{-2} to -47.3Wm^{-2} ± 10Wm^{-2} determined from the in-situ measurements. As in the calculations over the entire domain (Figure 12), ΔF_{LW_TOA} for the same period for the Cardington site reveals an almost complete cancellation of the SW and LW effects with ΔF_{LW_TOA} being computed as +35.3Wm^{-2}.

7. Discussion and conclusions.

The formation of persistent contrails and their evolution into contrail-induced cirrus clouds are illustrated. While it is not possible to be 100% certain that cirrus clouds would not have formed in the absence of aviation activity, the balance of evidence, which includes the spatial coherence of the contrail-induced cirrus and modelling its position, very strongly suggests that the cirrus cloud is of aviation origin.

The persistence of the contrails and contrail-induced cirrus is remarkable. The persistent contrail formed at ~08:30 on the 20 March 2009 (Figure 5 and Figure 6) is still clearly evident as contrail-induced cirrus some 12 hours after formation. In fact, as noted in section 4, contrail-induced cirrus initiated during daylight hours of the 20 March are clearly present in satellite imagery at 03:32 on 21

March 2009. The recent global modelling study of *Burkhardt and Kärcher* (2009) suggests that contrail-induced cirrus coverage is dominated by a few major events, and that contrail-induced cirrus coverage scales with ice-supersaturation rather than contrail coverage. Our study documents one such major event, which at its peak covers more than 50,000km^2.

Our study confirms the fact ΔF_{net_TOA} from contrail-induced cirrus is the relatively small residual derived from strong ΔF_{LW_TOA} and ΔF_{SW_TOA} components of opposite signs which has been known for some time (e.g. *Fahey et al.*, 1999 *and references therein, Stuber et al.,* 2006). However, to our knowledge, this is the first time that this has been proved without relying on explicit modelling of contrail-induced cirrus microphysics. While the results from this study have to be considered to be a specific case study, it does question the merits of rescheduling aircraft flights from night to day flights which have been suggested to make maximum benefit of the negative radiative forcing owing to the reflection of solar radiation (e.g. *Myhre and Stordal*, 2001, *Stuber et al*., 2006). If contrails spread into contrail-induced cirrus and the cirrus has a lifetime of some 18 hours as in this study, then initiating the contrail between 00:00 and 06:00 on the 20 March 2009 would maximise the exposure of the contrail-induced cirrus to solar radiation. While, this calculation must be considered very speculative given our current understanding of the complexities of contrail-induced cirrus, the recent idealised global modelling study of *Burkhardt and Kärcher* (2009) supports the significant lag of contrail-induced cirrus behind aircraft operations. *Burkhardt and Kärcher* (2009) model emissions from trans-Atlantic air traffic and find that contrail-induced cirrus peaks some 9hours subsequent to cessation of flying. Figure 5 suggests that the majority of fresh contrails in the study presented here were initiated between 08:30 to 12:00 and the peak contrail-induced cirrus areal coverage (Figure 13b) is around 17:00 or some 5-9hours subsequent to initiation.

It is interesting to ask to what degree the radiative forcing from aviation is enhanced owing to the formation of the contrail-induced cirrus in this episode: here we make a simple estimate by considering solely the influence of the CCC that we presume is formed by the AWACS aircraft. We chose to compare our estimate of the radiative forcing against that from persistent contrails from the entire aviation fleet, as to compare against the radiative forcing from other emissions such as carbon dioxide would be misleading because of the disparate residence times of contrail-induced cirrus and carbon dioxide. The approximate area influenced by the CCC (Figure 6 and Figure 13) is estimated to be 23,000km^2, and the radiative forcing ΔF_{net_TOA} is assumed to be +10Wm^{-2} during daylight hours and +30Wm^{-2} during night-time hours (Figure 13), acting from approximately 09:00 until 03:00 the next day. We assume that sunlight hours extend from 06:00 until 18:00, then the SW and LW effects act together for the first 9 hours and LW effects act alone for the remaining 9 hours, so that the *local* mean forcing is about 20 Wm^{-2} for an 18 hour period or 15Wm^{-2} for a 24 hour period. This is equivalent to a *global* mean radiative forcing in the 24hour period of ~0.7mWm^{-2}. Hence, this *single* event may have caused a forcing which is an appreciable fraction (7%) of the diurnally averaged global-mean persistent contrail forcing (10 mWm^{-2}). Alternatively, when averaged over a year, the event generated by the AWACS aircraft contributes approximately 2μWm^{-2} or 0.02% of the annual global mean radiative forcing from persistent contrails from the entire fleet of civil aircraft: 5000 such events/year would need to occur to generate a global annual mean radiative forcing of 10 mWm^{-2}.

We can also estimate the distance flown by the AWACS aircraft (10 complete circles of 40km diameter ~ 1250km) and the distance flown by the entire civil aviation fleet (3.3x10^{10}km, on an annual basis, *Eyers et al.*, 2004). If we consider the best estimate for the global mean radiative forcing due to persistent contrails to be 10mWm^{-2} then the entire civil fleet contributes a radiative forcing/km due to persistent contrail formation of around 3x10^{-13}Wm^{-2}/km. The AWACS aircraft exerts a global annual mean forcing of approximately 2μWm^{-2} for a distance travelled of 1250km leading to a radiative forcing/km due to contrail-induced cirrus of 1.6x10^{-9}Wm^{-2}/km: this is over

5000 times greater indicating that aviation operations that generate contrail-induced cirrus could exert a disproportionately high radiative forcing and hence warming of the climate system.

Of course, it is possible that natural cirrus could have been generated in the absence of the AWACS and other aircraft operations. The very high supersaturation with respect to ice in this specific case study mean that other meteorological 'triggers' causing the downstream evolution of natural cirrus cannot be ruled out. To establish that natural cirrus would not have formed in the absence of the aircraft operations would require very accurate modelling of processes that are only crudely represented in current numerical weather prediction models.

These calculations emphasize the importance of obtaining a reliable estimate of the global role of contrail-induced cirrus, and understanding the extent to which they add to natural cirrus cover. In this particular instance, because of the distinct pattern of the original contrails, it has been possible to follow, with some degree of confidence, the causal sequence from contrails to contrail-induced cirrus. In normal circumstances this would not be possible and it will be important to ascertain whether the sequence of events, and the size of the effect, that we have inferred is a regular occurrence.

This work indicates that a confident assessment of the total effect of aviation on climate, and the efficacy of possible mitigation options (for example, changing flight routing or altitudes to avoid contrail formation, with the possibility that CO_2 which has a radically longer lifetime will increase as a result) is heavily dependent on reducing the uncertainty in the size of the contrail-induced radiative forcing.

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