

**POTENTIAL RADIATIVE IMPACT OF CONTRAIL COVERAGE
OVER CONTINENTAL USA ESTIMATED FROM AVHRR DATA**

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1. INTRODUCTION

Contrails are a potential factor in anthropogenic climate change because they often form in aircraft exhaust and can develop into persistent cirrus clouds. Air traffic is currently increasing at approximately 5%/year. Because they reflect solar radiation and absorb and emit thermal infrared radiation, contrail-induced cirrus produce a radiative forcing that depends on their microphysical properties and temperature, solar illumination, and the properties of the underlying surface. Whether this radiative impact is climatically important depends on many factors including contrail cloud persistence and coverage. In this paper, contrail coverage over the continental USA is derived from Advanced Very High resolution Radiometer (AVHRR) data using an automated method based on the linear shapes of contrails and their 11-12 μm brightness temperature differences. The data cover several months in 1993 and 1994 and are taken from the NOAA-11 and 12 AVHRR satellites. Surface observations are used to validate the satellite estimates of contrail occurrence. These linear contrail coverage results are used to estimate the potential longwave radiative impact on the USA using both a simple radiative transfer model of the Earth-atmosphere system and the observed radiances. Radiative forcing from contrails growing into cirrus clouds are also used to demonstrate the greater potential for contrails to affect climate.

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2. METHODOLOGY**2.1 Contrail detection**

An automated image processing method developed by Mannstein et al. (1999) is used to detect contrails. This technique exploits the linear structure of contrails and the emissivity difference between AVHRR channels 4 (10.8 μm) and 5 (12.0 μm) in fresh contrails compared to natural cirrus. The smaller ice crystals in young contrails cause a larger difference between the channel 4 and 5 brightness temperatures than found for the natural cirrus which generally have larger ice crystals.

2.2 Contrail radiative forcing

Contrails reflect shortwave (SW, 0.2–5 μm) radiation reducing the amount of energy absorbed by the Earth. Because they are cold like cirrus clouds, contrails absorb more longwave (LW, 5-50 μm) radiation than they emit to space. When considered over the entire diurnal cycle, contrails generally have an overall heating effect on the Earth-atmosphere system or positive radiative forcing.

Global radiative forcing by persistent contrails was estimated to be 0.02 Wm^{-2} in 1992 and 0.1 Wm^{-2} in 2050 in a study by Minnis et al. (1999). Much larger values were computed for regions with heavy air traffic. In that study, the contrail amount was estimated from aircraft fuel usage (Sausen et al. 1998, Gierens et al. 1999). Random overlap with existing clouds, defined by a satellite climatology, was assumed in the calculations. The contrails produced a negative SW forcing that was

countered by a positive LW forcing. The impact in the LW is about three times that of the SW.

Radiative forcing can also be calculated from observations or a combination of models and observations. For the former approach, the computed estimates of contrail coverage are replaced by direct observations of contrail amount. In the totally empirical approach, the contrails are identified and their forcing is computed directly from the observed radiances. For a given scene including contrails, the contrail forcing F is

$$F = (Q_{ncon} - Q_{con}) f_c \quad (1)$$

where Q is radiative flux, f_c is the fraction of the scene covered by contrails, and the subscripts *con* and *ncon* refer to observed fluxes including the contrails and fluxes that would have been observed in the absence of contrails, respectively. The broadband flux Q can be determined from the narrowband radiance observed by the satellite using the method of Minnis et al. (1995).

The purely empirical approach is most useful for estimating F in the absence of underlying clouds because it can be assumed that the radiances from clear areas adjacent to contrail-covered areas represent Q_{ncon} . Because clouds are so variable, such an assumption is less likely to hold. Here, the empirical approach is used by assuming that Q_{ncon} can be represented by the mean flux from all surrounding pixels that are 3 pixels distant from the contrail and contain no contrails. This distance factor is used to minimize contamination of the background radiance by partial contrail-covered pixels. The combined approach uses the theoretical estimation of F derived for two contrail coverage scenarios and linearly interpolates between the two scenarios using the actual satellite-derived contrail coverage.

3. DATA

This study uses NOAA-11 and 12 AVHRR data taken during April 1994 and July, October, and December 1993 from a receiving station in Austin, Texas. The domain, 25°N to 55°N, 130°W to 65°W is divided into a 30 X 65 1°-region grid. Images from all available satellite overpasses were analyzed with the algorithm of Mannstein et al. (1999) to determine the number of contrail pixels in each 1° box within the image to compute the average contrail amount. Only those regions having more than 90% of the expected number of pixels are used in the statistics. The location of the receiving station yields more observations over the central USA than over coastal areas.

4. RESULTS AND DISCUSSION

4.1 Contrail distributions

The distribution of mean contrail coverage for April 1993 is shown in Fig 1a. The average over the entire domain is 2.1%. Heaviest contrail coverage is evident over the northeastern USA, around northern Montana and the northwest part of the domain. Minimum coverage is found over the Pacific southwest of California. Over the well-traveled air corridor extending from New York through Chicago to San Francisco, the mean contrail coverage ranges from 2 to 3%. The contrail distributions for July and December are shown in Figs. 1b and 1c, respectively. During July, the average contrail coverage is 1.3%. Even though the air traffic increases during summer, the temperatures and humidities at flight altitudes are often too warm or dry, respectively, to support development of persistent contrails. This is especially true for the southern USA, where few contrails were seen during July. During December, the average is 2.0%. Areas with heavy coverage include northern sections of the Great Plains and California as well as Florida. A relative minimum occurs over northern Kansas throughout the year. Peak coverage occurs at 1430 LT for April and July. Minimum coverage is seen at 0730 or 1930 LT, but the diurnal range is only 0.5% for both months.

Initial subjective visual analysis of the satellite data indicates that the error rate is roughly 20% to 25%. If contrails are present at the image resolution, the technique usually detects them. Other cloud features like certain natural cirrus or lines of strato- or altocumulus clouds are occasionally misclassified as contrails leading to an overestimate of the coverage. The misclassification of contrails increases at high viewing zenith angles VZA, because frontal systems and cirrus clouds more often appear linear. On average, the April contrail amount increased from 2.1% for VZA < 50° to 2.5% for VZA < 60° to 2.9% for VZA < 70°. While part of the increase is due to improved sampling at some locations along the coast, most of it is the result of viewing more linear features. Results are reported here only for data taken at VZA < 50°.

Other sources of error arise from the sampling times of the NOAA satellites. For example, air traffic increases between sunrise and noon, yet the early morning NOAA-12 overpass at 0700 local time (LT) will miss many of the morning flights in most areas. Furthermore, many late afternoon flights will also be missed because of the 5-hr gap between the 1430 LT NOAA-11 and 1900 LT NOAA-12 overpasses. Differences in the relative

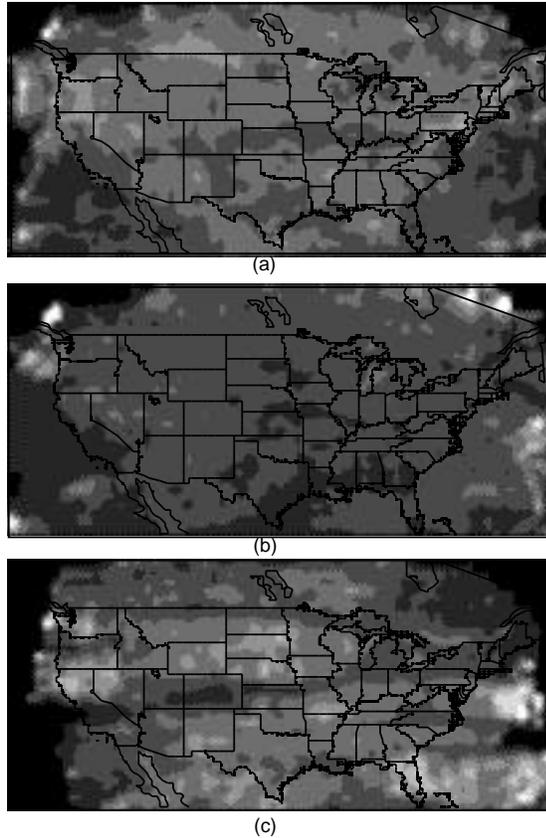


Fig 1 Percentage contrail coverage over continental USA for April, 1994 (a), July (b) and December (c), 1993 from AVHRR data.

behavior of channels 4 and 5 on NOAA-11 and 12 may also induce some errors. NOAA-11 appears to yield greater temperature differences than NOAA-12. Contrails that are not wide enough, that have developed beyond their linear structure, or that have matured rapidly to produce larger cirrus-sized ice crystals are not detected with this approach. The magnitude of these effects is unknown.

Nevertheless, the results found here appear quite reasonable. The seasonal cycle is similar to that found in the frequency of contrail occurrence from coincident surface observations (Minnis et al. 1997) and from theoretical estimates by Sausen et al. (1998). The results from Sausen et al. (1998) for 1992 yield an average of 2.0, 0.5, and 1.6% over the USA.

4.2 Radiative forcing

The LW radiative forcing due to contrails calculated using (1) for April 1994 is shown in Fig.

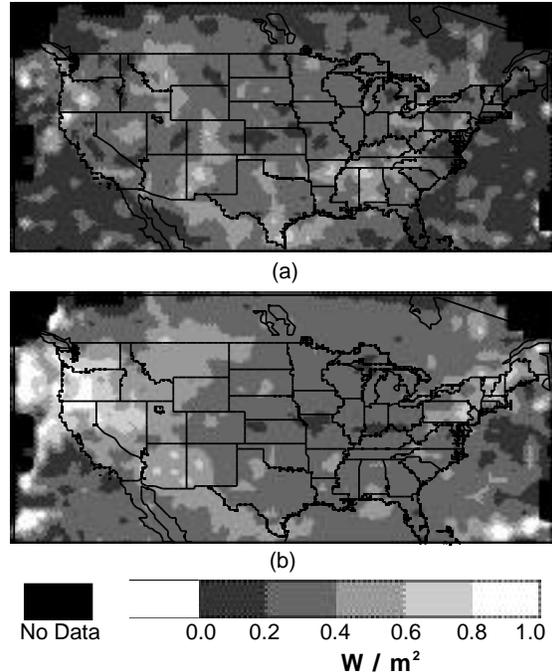


Fig 2 Longwave radiative forcing due to contrails over continental USA for April 1994 from (a) AVHRR data and (b) from theoretical calculations.

2a with the results interpolated from the model calculations of Minnis et al. (1999). The empirical average over the domain for April is $0.26 Wm^{-2}$ compared to $0.37 Wm^{-2}$ from the theoretical results. Even though f_c is similar to or smaller over the southern than over the northern USA, F_{LW} is greater because of the warmer background. The greater forcing by the model calculations may be due to the assumption of random overlap. Because contrails tend to form in areas with existing cirrus clouds, they may overlap clouds more often than assumption used in the model. Also, the calculation of Q_{ncon} from the data requires further study as the contrails may be forming in the otherwise clear space between existing cirrus clouds leading to an underestimate of Q_{ncon} . Despite the magnitude of the differences, the spatial distributions are similar with the stronger forcings in the western and southern USA and the minimum over Kansas. For the July AVHRR results, F_{LW} is $0.22 Wm^{-2}$ compared to $0.24 Wm^{-2}$ from the theoretical calculations. This remarkable agreement arises because the observed contrail coverage is more than twice that used in the calculations.

4.3 Case Study

The estimates produced above rely on the coverage by distinct linear contrails that can be easily identified during particular overpass times.

Time, LT	0745	0845	0915
F_{LW} , Wm^{-2}	10.1	15.4	30.3
F_{SW} , Wm^{-2}	7.7	5.9	4.2
F_{net} , Wm^{-2}	3.4	9.5	26.1
Area, km^2	2,580	36,950	46,750

Table 1. Contrail areal coverage and radiative forcing for March 5, 1999 over eastern Virginia.

Contrails only form when the planes are in the sky, so that the observation times may not be optimal. Furthermore, contrails often spread and change shape rather quickly so that they are no longer distinct lines, yet they cover considerably more area than the observable contrails (e.g., Minnis et al., 1998). To examine how this phenomenon of contrail spreading and the sampling times may affect the estimates of contrail forcing, a case study involving contrails observed during March 5, 1999 over eastern Virginia is considered.

Visible and infrared data from the Geostationary Operational Environmental Satellite (GOES-8) were used to observe the formation of linear contrails and their subsequent advection for several hours. They were initially detected in the 1245 UTC 1-km visible image near 36°W, 77°W. This corresponds to 0745 LT, approximately 45 min past the nominal NOAA-12 sampling time. The contrail areal coverage, LW, SW, and net forcing were derived from the 4-km GOES-8 as the contrails spread and advected to the east over the Atlantic Ocean where additional contrails formed during the following 2 hours. The results of this analysis are summarized in Table 1 where the forcing is reported as the unit forcing

$$F = Q_{con} - Q_{cor}$$

The initial contrail coverage and forcings are relatively small at 0745 LT. Because of the rapidly increasing number of flights along the Atlantic corridor and the contrail spreading, the areal coverage explodes within an hour to include more 36,000 km^2 . The land surface is heating up and some of the contrail clouds advect over the warm Gulf Stream dramatically increasing the unit contrail LW forcing F_{LW} . The contrails continue growing for several more hours and gradually dissipate off the coast. This type of event appears to be relatively frequent. Thus, the contrail forcing based strictly on the linear contrails at the NOAA overpass times may significantly underestimate the actual contrail-induced forcing.

5. CONCLUDING REMARKS

The results from the AVHRR analysis are relatively consistent with the theoretical calculations of contrail coverage and longwave radiative forcing. Because the approach used here considers only easily identified linear contrails, the results represent a minimum for contrail forcing. It is clear from the example presented here and previous studies that the coverage by contrail-induced clouds is much greater than estimated from the AVHRR data. Additional research is needed to complete the estimation of the annual cycle of linear contrails, determine the extent of contrail-induced cirrus, and formulate an accurate assessment of the background radiation fields underneath contrails.

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