Contrail climatology over the USA from MODIS and AVHRR data

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1. INTRODUCTION

Persistent contrails have become a common feature in the skies over the United States. In addition to their reduction of clear skies, these man-made clouds may have a significant impact on climate through radiative processes. Like natural clouds, contrail cirrus reflect incoming solar and absorb outgoing infrared radiation. Current estimates of their overall effect suggest a global maximum warming effect equivalent to almost 0.24°C (Minnis et al. 1999). A more modest increase of less than 0.1 °C is more realistic. The uncertainties in such estimates are quite large, however, with estimates of contrail radiative forcing ranging over almost two orders of magnitude (Minnis et al. 1999; Meyer et al. 2002). The contrail effects depend on many factors including areal coverage, altitude, underlying background, optical depth, particle size, lifetime, and the time of day. To gain a better quantification of some of these parameters, this paper analyzes data taken over the USA from the Advanced Very High Resolution Radiometer (AVHRR) onboard the NOAA polar orbiting satellites and the Moderate Resolution Imaging Spectro-radiometer (MODIS) onboard the Terra (EOS-AM-1) satellite.

2. DATA AND METHODOLOGY

The datasets include the 1-km radiances from the mid-afternoon NOAA-16 AVHRR and the late morning Terra MODIS overpasses. Linear contrails are automatically detected by applying the method of Mannstein et al. (1999) to brightness temperature difference images created from the 11 and 12 µm channels on each satellite for viewing zenith angles less than 50°. The fractional areal coverage for each image is simply the number of contrail pixels divided by the total number of pixels within the domain between 25°N and 55°N and 65°W and 130°W. The visible optical depth τ is computed from the contrail emissivity ε as in Palikonda et al. (2001). Assuming the contrail temperature T_{con} = 224K (Meyer et al. 2002), the contrail emissivity for a given pixel with an 11-µm temperature T is

$$\varepsilon = \frac{\{B(T) - B(T_b)\}}{\{B(T_{con}) - B(T_b)\}}, \qquad (1)$$

where B is the Planck function and the background temperature T_b is computed from surrounding non-contrail pixels as in Palikonda et al. (2001). The contrail longwave radiative forcing *CLRF* is computed as in Palikonda et al. (1999). Each quantity is averaged over the entire domain for each month. The initial analyses were applied to NOAA-16 data taken during January, April, July, and September 2001.

3. RESULTS

Figure 1 shows the distribution of monthly mean contrail coverage over the domain. NOAA-16 data were unavailable over the southwestern corner of the domain during January (Fig. 1a). Maximum contrail coverage in Fig. 1a exceeds 2.0% over the southeastern states, New Mexico, west Texas, and Alberta, Canada with minima over western Colorado and the Atlantic Ocean. During April (Fig. 1b), maxima occur over North Dakota, Nevada, Washington, off the California and south-eastern US coasts, and over northern Mexico and the adjacent Pacific. Minima are seen over British Columbia, northern Colorado, Arizona, Florida, and the Atlantic. The number and areal coverage of contrails is substantially reduced during July (Fig. 1c) with a maximum of only 1.8% off the Delaware coast and a few relative maxima over Lake Superior, British Columbia, and the Pacific west of Oregon. Very few contrails were detected over the southern half of the USA and California. The broad area of negligible contrail coverage changes shape during September (Fig. 1d) and comprises a triangle extending from southern California to South Dakota and to the tip of Florida. Maximum coverage is increased up to 2% over British Columbia. Other relative maxima occur over Oregon, South Carolina, the Maine coast, Quebec, and Lake Winnipeg.

The results, including the mean values for *CLRF* and τ are summarized in Table 1. Contrail coverage peaks in January and is at a minimum during July, differing by a factor of 3. The mean contrail optical depths are relatively invariant with season. The summer maximum is 25% greater than the January minimum. Figure 2

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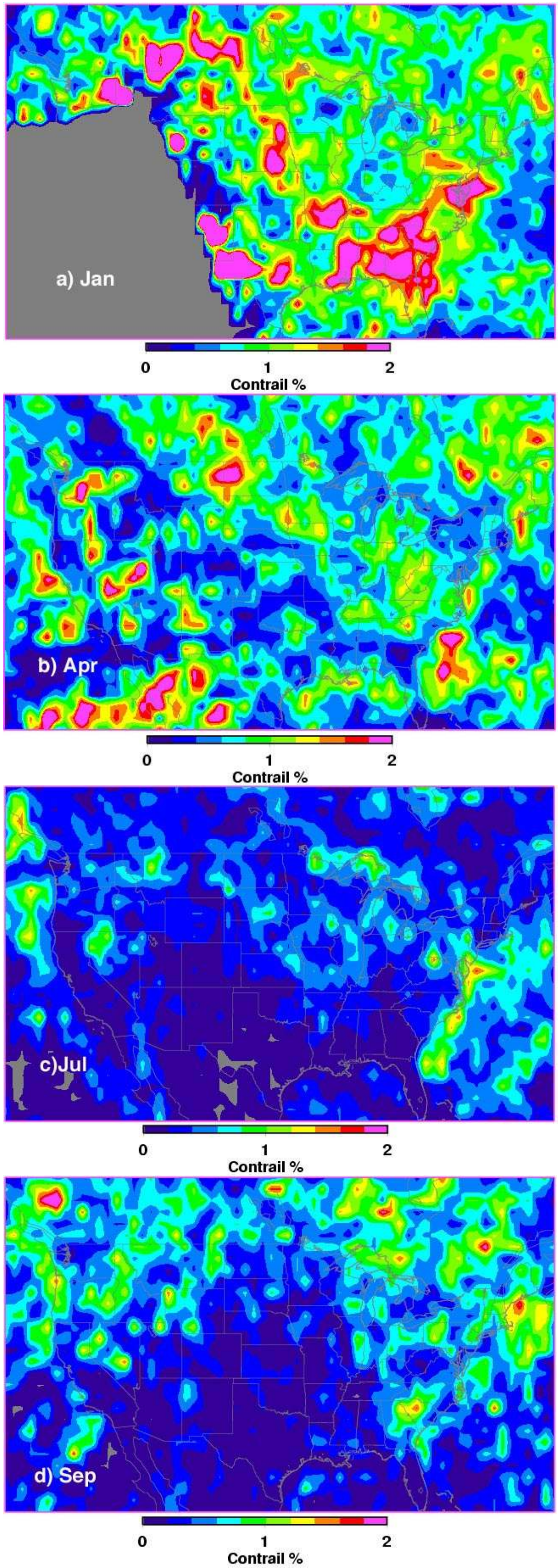

Fig. 1. Monthly mean contrail cover from NOAA-16, 2001.

Table 1. NOAA-16 daytime contrail properties, 2001.

Month	contrail cover (%)	τ	*CLRF* (Wm^{-2})
January	0.92	0.25	0.11
April	0.71	0.28	0.14
July	0.33	0.31	0.09
September	0.45	0.30	0.11

shows the frequency distribution of contrail optical depths for each month. More than 30% of the contrails had values of τ between 0.2 and 0.4 during all months. Optical depth exceeded 0.4 for 25% of the cases. Thicker contrails were observed more frequently during summer than during the winter and spring.

The radiative forcing (Table 1) was greatest during April and minimal during July when contrail coverage was least. *CLRF* depends on both the contrail coverage and the thermal contrast between the contrail and its background. Unit *CLRF*, the ratio of the CLRF to the fractional contrail coverage, varies from 12 Wm^{-2} in January to 27 Wm^{-2} during July indicating that the thermal contrast changed by a factor of 2 between winter and summer.

4. DISCUSSION

The results shown above are subject to a number of error sources that especially affect the contrail coverage and, therefore, the properties derived from the resulting contrail pixels. The contrail detection algorithm is highly sensitive to the particular filter characteristics of the 11 and 12-µm channels (Mannstein et al. 2000). Thus, the same algorithm applied to the same scene viewed by two different AVHRRs or by an AVHRR and a MODIS imager may yield two different contrail amounts. One might systematically overestimate the coverage, while the other could underestimate it. The impact of stationary (e.g., coastlines, river valleys) and non-stationary (e.g., cirrus streaks, cloud streets) features on the contrail detection algorithm have been discussed by Meyer et al. (2002). These features will affect the retrieval differently for each satellite type. A possible source of bias caused by cirrus streaks is the maximum in contrail coverage over the Pacific west of Mexico during April (Fig. 1b). The subtropical jet is often located over this area during the Spring and produces many cirrus streaks in an area with minimal jet traffic. Similarly, cirrus streamers emanating from the tops of hurricanes can also resemble contrails in the satellite imagery.

Despite the potential errors, both the seasonal variation and geographic distribution of contrail coverage appears reasonable. From surface observations of persistent contrails during 1993/94 and 1998/99, Minnis et al. (2002) found that, for the 4

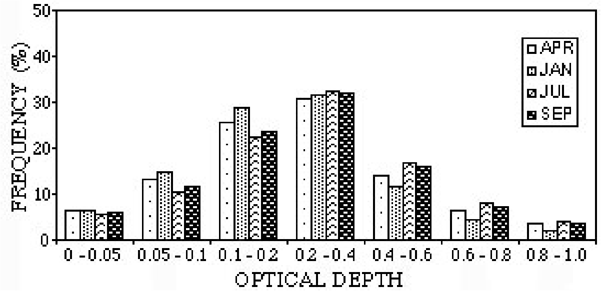

Fig. 2. Histogram of contrail optical depths over USA, 2001.

months of the year used in the current study, the maximum contrail frequency occurred during January with decreasing amounts during April, September, and July as in Table 1. Except for September, the ratio of coverage during January to that during another month is within the range of values for the same ratio computed using domain-mean contrail frequencies from the two surface observation datasets. During September, the contrail coverage for the domain might have been greater than expected from the surface observations because of the relatively large contributions from the Canadian Provinces and from the adjacent ocean areas where no surface observations were taken. Also, a hurricane that passed the east coast during September may have contributed to the contrails over the Atlantic.

Figure 3 shows the distribution of commercial air traffic above 25,000 ft (7.6 km) over the continental USA and its adjacent waters, and southern Canada for 10 September 2001. No data were available for Mexico or from any military flights. The available data were compiled from 2 and 5 minute aircraft position data from the FlyteTrax dataset (FlyteComm, Inc., San Jose, CA). The results in Fig. 3 are typical for a weekday prior to 11 September 2001. Weekend traffic can be reduced by as much as 20% from that in Fig. 3. After 15 September 2001, the commercial air traffic above 25,000 ft was diminished by 11%. The heaviest air traffic occurred over the middle Atlantic and lower midwestern states with up to 800 flights passing through a given 1°x1° latitude-longitude box. The heaviest traffic in the western USA is found over the Arizona-California border and north of Los Angeles, CA with more than 600 flights. More than 200 flights pass over Oregon each day. During July and September, few contrails were observed over the southwestern USA and Florida, areas with relative maxima in flight density. Significant maxima in contrail coverage are found over the southwest during April and over Florida during January. Other patterns in the contrail coverage correlate with the air traffic, while some, such as the minimum in contrail coverage over Colorado is coincident with more than 400 flights per day.

Two conditions are necessary for contrail formation: air traffic and suitable conditions. Duda et al. (2002) derived the distribution of potential contrail frequency from numerical weather prediction (NWP) reanalyses for the period 5 - 30 September 2001. Their results, shown in Fig. 4, are similar in many respects to the September

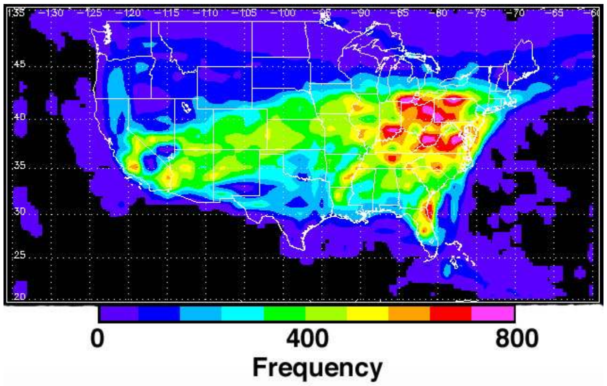

Fig. 3. Number of commercial flights above 25,000 ft in each 1° box, 10 September 2001.

contrail coverage in Fig. 1. For example, the model results suggest a minimum in contrails for a roughly triangular area extending from the Pacific off southern California to eastern Montana and to the central Gulf of Mexico. This area is similar to that mentioned earlier for the minimum in contrail coverage during September. The three contrail maxima noted for Canada in Fig. 1d closely correspond to the relative maxima in Fig. 4. A relative maximum in potential contrail frequency is also found over South Carolina. The minimum in contrail potential off southern California, however, corresponds to a relative maximum in Fig. 1d that correlates with the axis of air traffic in the same area. Whether this discrepancy is due to shortcomings in the atmospheric model or to the contrail retrieval algorithm is not clear. Given the correlation between the air traffic and the location of the relative maximum and the fact that the humidity data west of the continent is sparse, it is more likely that the model estimates are under-predicting the potential for contrails in this case. Other areas where the contrail coverage and potential are in qualitative agreement include the northwestern USA and the upper Midwest, except for West Virginia. Also, the relative maximum off the coast of New England in Fig. 1d is inconsistent with both the flight traffic and potential contrail data. This possible overestimate by the retrieval algorithm might be the result of mistaking cirrus streamers from hurricanes Erin, Gabrielle, and Humberto that passed south of Nova Scotia during September. Areas with heavy cirrus coverage would preclude detection of contrails with the method of Mannstein et al. (2000), so that, over areas like Florida that show a large potential for contrail occurrence, few contrails are detected because the suitable conditions usually occur in conjunction with cirrus anvils or other thick cirrus clouds.

The mean contrail coverage is considerably less than that computed by Sausen et al. (1998) based on 11 years of global NWP analyses and that estimated by Palikonda et al. (1999) over the USA from NOAA-11 AVHRR data. Although the seasonal cycle from the latter study is similar to the current results, the mean contrail coverage is 2 to 3 times greater than that found

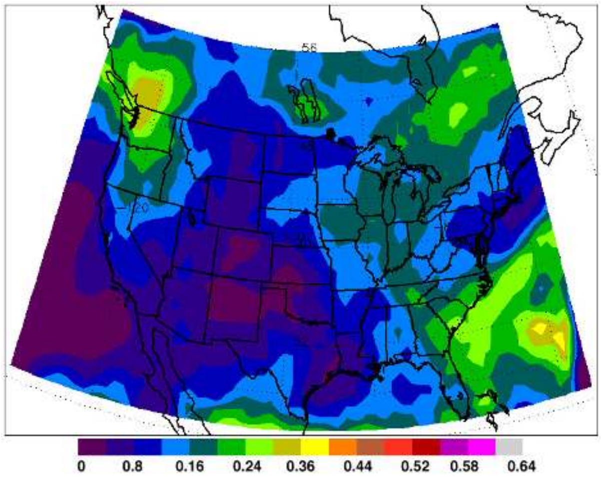

Fig. 4. Frequency of potential contrail conditions between 150 and 400 hPa during September 2001 from RUC-2 data. Frequency greater than 0.12 in stippled areas.

here. This difference is surprising because air traffic increased at a rate of ~5%/year during the 1990's. Part of this apparent decrease in contrail coverage between 1993-94 and 2001 may be due to differences in the sensitivities of the AVHRR thermal channels on NOAA-11 and NOAA-16 as discussed earlier. Some of the difference may be a result of changes in the atmospheric conditions. From the National Center for Environmental Prediction (NCEP) analyses, Minnis et al. (2002) found that during the 1993-94 period, the mean relative humidity (RH) at 300 hPa over the USA was 45.5%, a value close to the 30-year maximum. That same dataset yields a mean 300-hPa RH of 39.4% for 2001. Because the RH is a crucial factor in formation of persistent contrails, it is likely that a reduction in the mean RH would lead to a decrease in the contrail coverage. It is not clear how much of the differences in contrail coverage between the current results and the earlier analysis can be explained by the RH reduction between 1993-94 and 2001.

The contrail coverage in Fig. 1 over the two 4° regions analyzed by Palikonda et al. (2001) was 1.09 and 0.94 during January and 0.53 and 0.61 during April for the Norfolk, VA (ORF) and New York City (NYC) regions, respectively. During December 1998, the coverage was 1.05 and 0.52 over ORF and NYC, respectively. The corresponding values during April 1998 were 0.54 and 0.26. This apparent increase in contrail coverage over those areas since 1998 may be due to differences in local time sampling by the two satellites or in the AVHRR filters

The mean optical depths computed here are slightly greater than those estimated by Palikonda et al. (2001) and nearly three times larger than those from Meyer et al. (2002) over Europe. Examination of the distribution of τ and the imagery in conjunction with the retrievals is needed to determine if the larger values in Fig. 2 are systematically occurring in areas of cirrus streamers. Excluding $\tau > 0.4$ in Fig. 2 would result in histograms that are very similar to those of Palikonda et al. (2001).

The unit *CLRF* values are comparable to the global values of 12.2 Wm^{-2} for $\tau = 0.1$ and 27 Wm^{-2} for $\tau = 0.3$ computed by Minnis et al. (1999) using a combination of theoretical contrail cover and empirical cloud cover in a radiative transfer model. The smaller value of *CLRF* during January is probably due to the colder background and, possibly, to more frequent occurrence in extant cirrus clouds.

5. CONCLUDING REMARKS

Additional analysis of NOAA-16 and MODIS data, including estimation of shortwave radiative forcing will provide a more complete assessment of contrail coverage and its climatic effects during 2001. Further study of the error sources will be used to determine the uncertainties in the derived products, which will be valuable for modeling contrail formation and persistence to determine the impact of air traffic on climate.

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