P4.33 CONTRAIL COVER AND RADIATIVE PROPERTIES FROM HIGH-RESOLUTION SATELLITE DATA

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1. INTRODUCTION

Increasing jet air traffic and the coincident rise in jet engine efficiency have resulted in the apparent increase in cirrus cloudiness through the formation of persistent contrails. Minnis et al. (2000) found that cirrus cloud amounts have increased over most air traffic regions with the strongest trends over the USA where cirrus coverage rose by an average of 0.027 between 1971 and 1996. In order to evaluate the potential impact of these contrails on climate, it is necessary to determine the coverage and the radiative properties of contrails. This paper presents recent results from a continuing study of contrails using satellite data to determine contrail coverage and optical properties. Results are presented for selected areas of the USA during 1998 and 2001.

2. DATA

Images from daytime USA overpasses of the Terra 1-km Moderate Resolution Imaging Spectroradiometer (MODIS) and the NOAA-14 1-km Advanced Very High Resolution Radiometer (AVHRR) are analyzed for contrail coverage, optical depth, effective particle size, and longwave (LW) radiative forcing. Terra has an equatorial crossing time ECT of 1030 LT, while the NOAA-14 had an ECT of 1630 LT by 1998. AVHRR data taken during April and December 1998 over 4° regions around New York (41° N, 72° W) and Norfolk, Virginia (36° N, 76° W) were selected for intensive study (Fig. 1).

European Center for Medium-range weather Forecasting (ECMWF) 6-hourly analyses provide surface skin temperatures and 1° atmospheric profiles for calculating top-of-atmosphere (TOA) clear-sky temperatures. A global 10' monthly mean map of VIS albedo, Minnis, et al (2001), is used to estimate clear sky reflectance.

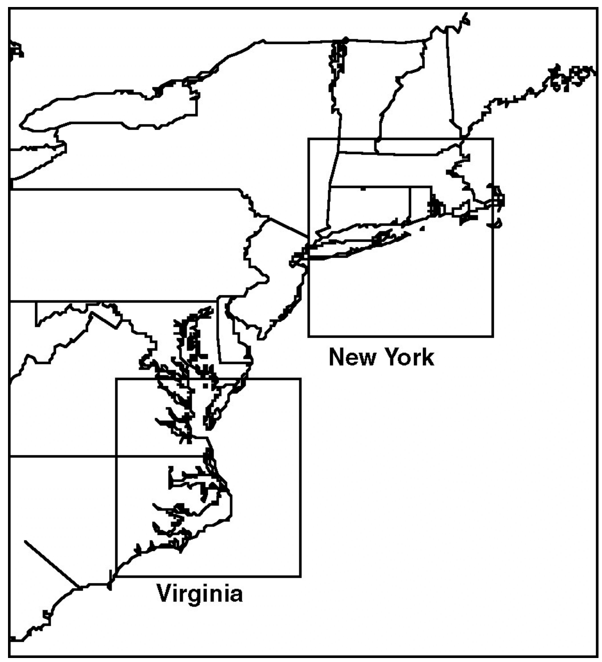

Fig. 1. Grid boxes for AVHRR analyses.

3. METHODOLOGY

3.1 Contrail Detection

Fresh linear contrails are detected using an image processing technique developed by Mannstein et al. (1999), which relies on the linear structure of contrails

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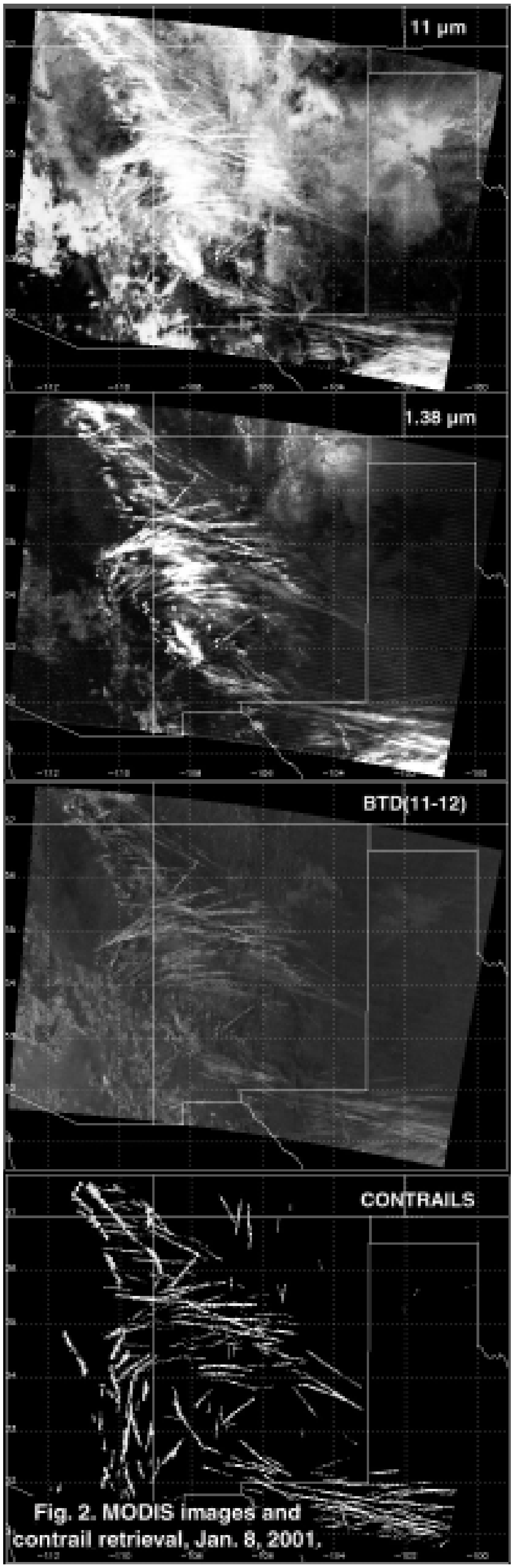

Fig. 2. MODIS images and contrail retrieval, Jan. 8, 2001.

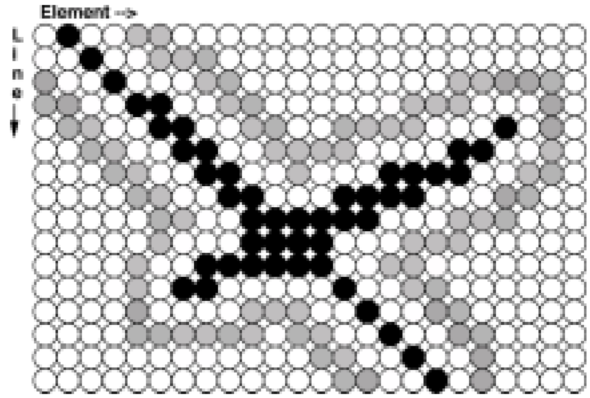

Fig. 3. Schematic of pixels used for computing background radiances. Black - contrail; Gray - background; white - unused.

and the emissivity difference between channel 4 (10.8 µm) and channel 5 (12.0 µm) for small ice crystals. The algorithm is applied to images of channel-5 brightness temperatures and the brightness temperature difference BTD between channels 4 and 5.

Figure 2 shows an example of MODIS images that were analyzed with this approach. The data were taken around 1742 UTC, January 8, 2001 over the southwestern USA. The 11-µm image shows a variety of cloud (white or gray) and surface (black or gray) including some linear structures. The 1.38 µm image, which is sensitive to reflecting surface in the upper atmosphere, shows a large number of linear features that were not evident in the 11-µm image. Similar features are also quite distinct in the BTD picture. The analysis algorithm applied to the BTD image yields the contrails in the bottom panel. Nearly all of the contrails are correctly identified in this case. A few contrails with N-S orientation are actually mountaintops, while some of the thicker contrails are too thin in the result.

3.2 Contrail Microphysical Properties

Cloud and contrail properties are derived using the Visible Infrared Solar-Infrared Split Window Technique (VISST), Minnis et al. (2001), to determine the microphysical properties. VISST is a 4 channel model-matching method for plane parallel clouds. It utilizes parameterizations of theoretical radiance calculations for 7 water and 9 ice crystal size distributions. The cloud properties, cloud height, temperature, emissivity, optical depth, phase, and effective particle size D_e are obtained by matching the model calculations to observations. Particle sizes are typically invalid for overlapped thin-over-thick clouds.

Additionally, for the contrail pixels the effective emissivity is calculated,

$$\varepsilon = [B(T) - B(T_b)] \,/\, [B(T_c) - B(T_b)], \qquad (1)$$

following the approach of Meyer et al. (2001), where B is the Planck function at 10.8 µm, T is the observed channel 4 temperature, T_b is the background temperature, and T_c is the contrail temperature. In this case T_c is assumed to be 224 K, a typical temperature suitable for contrail formation. The background radiance is calculated as the average radiance of all pixels at a distance of 2 pixels horizontally, vertically, or diagonally from a contrail pixel that is not adjacent to any other contrail pixels. The background pixels for a hypothetical pair of crossing contrails are shaded gray in Fig. 3. To ensure that the background pixels are below the contrail, $T_b > T_c$. Otherwise, T_b is invalid. If no pixels meeting these criteria are found, the mean background radiance, calculated for all other contrail pixels within the local 10' grid box, is used.

The optical depth τ for the contrails is also derived from the emissivity using the parameterization of Minnis et al (2001),

$$\varepsilon = 1 - \exp[\, a\,(\tau / \mu)^b], \qquad (2)$$

which accounts for the infrared scattering. In (2), μ is the cosine of the viewing zenith angle, and the coefficients, a = -0.458 and b = 1.033, are for an axi-symmetrical 20-µm hexagonal ice column. To minimize false detections, all contrails with $\tau > 1$ were eliminated from the processing. Although some actual contrails were observed with $\tau > 1$, the number eliminated is negligible.

3.3 Contrail Longwave LW Radiative Forcing

After the contrails are detected using the image processing technique, their LW forcing is computed directly from the observed radiances. The contrail LW forcing is given by

$$F = (Q_b - Q_c)\, f_c, \qquad (3)$$

where f_c is the contrail fraction and Q_c and Q_b are the LW fluxes for contrails and the background respectively. Broadband LW fluxes are calculated from the 10.8-µm radiances as described by Minnis and Smith (1998).

4. RESULTS

The contrails in Fig. 2 covered 22,644 km^2, or 5.8% of the region shown in the image. The distribution of contrail optical depths derived from (1) and (2) is shown in Fig. 4. Most of the contrails have τ between 0.05 and 0.2, although contrails with optical depths as large as 1.0 were observed. On average, τ = 0.14. In this case, F = 0.42 Wm^{-2}, which gives a unit forcing, $F_o = F / f_c$, of only 7.3 Wm^{-2}. The histogram of τ (Fig. 5) for the entire 1742-UTC MODIS image (~2.5 x 10^6 km^2) over the USA during Jan. 8, 2001 is nearly identical to that in Fig. 4 for the southwestern USA. The total contrail coverage was 9 x 10^4 km^2, or 3.6% of image. The mean τ and unit LW forcing are 0.13 and 4.9 Wm^{-2} for the entire image.

The distributions of optical depths from the AVHRR analyses in Figs. 6 and 7 show little seasonal and only slight regional differences. The histograms show more contrails with $\tau > 0.2$ than those from MODIS. In these cases, the mean optical depths over the New York and Virginia regions were 0.21 and 0.19 during April 1998 and 0.18 and 0.15 during December 1998, respectively

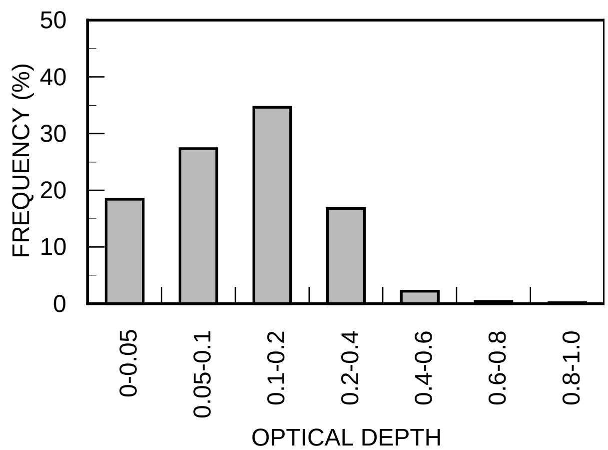

Fig. 4. Histogram of τ for contrails in Fig. 2.

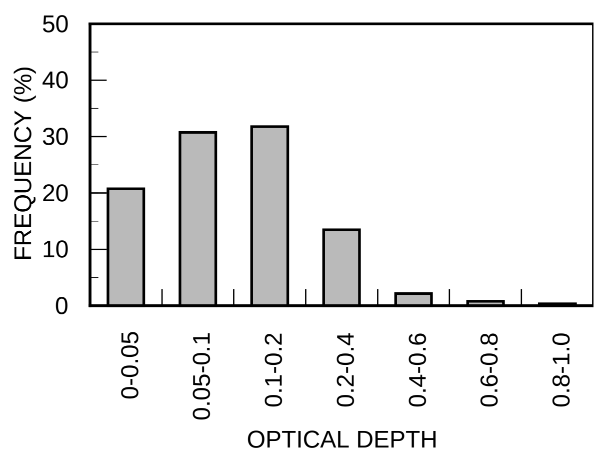

Fig. 5. Histogram of τ for contrails detected over USA in MODIS image taken at 1800 UTC, Jan. 8, 2001.

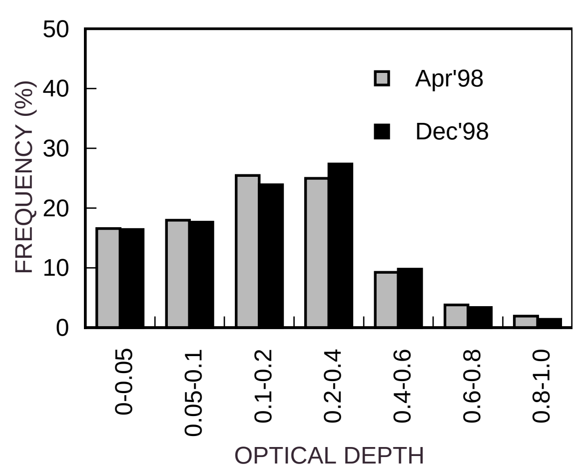

Fig. 6. Histogram of τ for contrails in New York region.

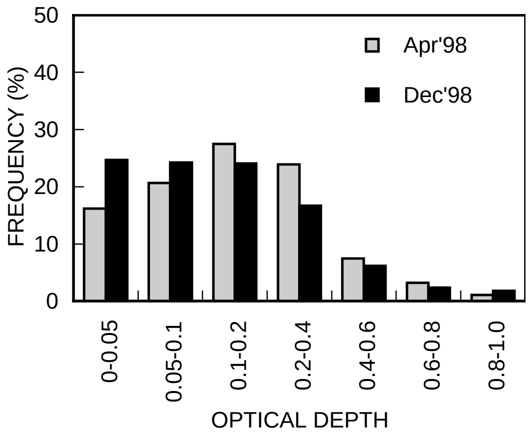

Fig. 7. Histogram of τ for contrails in Virginia region.

The respective mean contrail amounts are 0.50% and 0.26% during April and 0.52% and 1.05% during December. For all four datasets, the unit LW forcing is 8.8 Wm^{-2}. D_e was computed for the New York region using only those contrail pixels occurring over an otherwise cloud-free background. The resulting mean value is 37 µm.

5. DISCUSSION AND CONCLUSIONS

The contrail optical depths computed here are 20 to 90% larger than those from Meyer et al. (2001) for contrails over Europe, but are 50 to 70% less than those derived by Minnis et al. (2000) over the USA and the value of 0.3 used by Minnis et al. (1999) to simulate global contrail radiative forcing. The latter value was selected based on early estimates of τ that were derived from a few selected cases. Similarly, Minnis et al. (2000) only used contrails over clear backgrounds and a few selected days over the east coast of the USA. They derived τ using the visible channel, an approach that may bias the retrieval. The infrared method, which assumes a value of T_c, is a more reliable technique than the visible retrieval because of large uncertainties in the contrail scattering properties. The larger value relative to the Meyer et al. (2001) results is supported by model calculations (Ponater et al. 2001) that find τ over the USA is greater than over Europe because of temperature and moisture differences. The mean value of D_e is remarkably close to the 34-µm value used by Meyer et al. (2001).

The mean contrail coverage over the Virginia and New York regions, which is lower than expected from theoretical estimates, is probably underestimated. Using the same technique with NOAA-14 data, Meyer et al. (2001) estimated the contrail detection efficiency at 40%. If true for the AVHRR data used here, the average contrail coverage over the New York and Virginia regions respectively would be 1.3% and 1.6%, values that are closer to the January theoretical estimates of Ponater et al. (2001). The detection efficiency for these regions needs further examination. Visual examination of the MODIS retrievals indicate that the detection efficiency is much better than found for the AVHRR. The only contrails that were not detected appeared to be those that had already spread significantly.

The mean values of F_o are significantly less than the 28.7 Wm^{-2} from Minnis et al. (1999), primarily, because of the reduced optical depths. Adjusting for differences in τ yields global theoretical estimates of 12.4 and 16.6 Wm^{-2} for the MODIS and AVHRR results, respectively. These values are roughly twice those derived from the data. Remaining differences are likely due to the specific ambient cloud conditions, time of day, location, and the assumed model value of T_c.

The preliminary results shown here provide additional evidence that contrail radiative impacts are smaller than previously estimated. However, complete multi-seasonal analyses of both AVHRR and MODIS data taken over the USA are needed to determine the spatial and temporal distribution of contrails, their optical properties and shortwave and LW forcings as well as their relationships to the ambient conditions. Results from such studies are essential for confirming or improving predictions of future air traffic climate effects.

Acknowledgments
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