A Regional Contrail Climatology Developed from MODIS Data

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1. **INTRODUCTION**

Several research programs including ACCRI (Aviation-Climate Change Research Initiative) have recognized the importance of reducing the significant uncertainty in current estimates of the regional and global contributions of contrails and contrail-generated cirrus clouds to climate change. Before we can predict their potential effects in the future, it is necessary to characterize their past effects accurately. One of the recommendations of the ACCRI research program is to develop a global climatology of line-shaped contrails detectable with remote sensing methods with information on the associated optical properties of the contrails. Such a database would be a valuable first step towards a more realistic representation of contrails and cirrus within climate models.

An automated contrail detection algorithm and a multi-spectral cloud property retrieval method are used to determine the optical properties of linear persistent contrails over the contiguous United States (domain: 25°-55°N, 130°W-65°W), and to compute radiative forcing within the detected contrails. The contrail detection algorithm is an extension of the Mannstein et al. (1999) method, and uses several channels from Terra and Aqua MODIS data to reduce the occurrence of false positive detections. Results from 2 months of satellite observations will be presented, representing a regional climatology of contrail properties over the selected domain including contrail coverage, optical depth, and longwave radiative forcing.

The goal of this research is to create a dataset of contrail coverage, optical depth and radiative forcing (RF) over the contiguous United States (CONUS) from Terra MODIS radiances. This dataset serves as a case study for developing a globally homogeneous dataset of contrail coverage and cloud properties necessary for quantifying global contrail RF more accurately.

2. **CONTRAIL MASK**

Mannstein et al. (1999) developed an automated 2-channel contrail detection algorithm (CDA) to detect linear contrails in AVHRR thermal IR imagery. Contrails appear as bright lines in 11 minus 12 μm brightness temperature difference (BTD) images. An important advantage of the CDA is that it requires only brightness temperatures $T_{11}$ and $T_{12}$; no auxiliary information is needed and it can be applied to both day and night scenes. The CDA uses a scene-invariant threshold to detect cloud edges.

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produced by contrails, and 3 binary masks to determine if the detected linear features are truly contrails. However, these masks are not always sufficient to remove all non-edge features. To reduce the number of false positive detections due to lower cloud streets and surface features, we add observations from other IR radiance channels (6.7, 8.6 and 13.3 µm) available on the MODerate-resolution Imaging Spectroradiometer (MODIS) on Terra and Aqua. The new modified method uses additional masks derived from the added thermal infrared channels to screen out linear cloud features that appear as contrails in the original method. Also, the additional channels sometimes allow better discrimination of contrails than BTD_{11-12}.

2.1 Quality control of MODIS data

The MODIS instrument consists of an array of independent scanning sensors that may induce striping in raw images. The striping is especially apparent in BTD imagery. To reduce the impact of striping, a two-step correction is applied to the images. First, data from the two failing detectors on Terra MODIS (detectors 1 and 6) are replaced by interpolated data from neighboring lines. Next, the image is processed as a series of overlapping blocks of pixels. For each block, the Fourier frequency spectrum is corrected to suppress frequencies that are multiples of 10. The processed image has almost no striping noise, while the contrail features remain mostly intact.

To reduce effects of image distortion at large (> 50°) viewing angles, including MODIS “bow-tie” effects), each granule of data is reprojected onto a standard map (Lambert Azimuthal Equal-Area projection). The reprojected data allow more accurate contrail detections at viewing angles greater than 50 degrees.

2.2 Determining confidence of contrail detection

Global aircraft emissions waypoint data provided by FAA (Wilkerson et al., 2010) allow comparison of detected contrails with commercial aircraft flight tracks. A pixel-level product based on the advected flight tracks defined by the waypoint data and the U-V wind component profiles from the NASA GMAO GEOS-4 reanalyses has been developed to assign a confidence of contrail detection for the contrail mask. The product computes a flight track “strength” value for each pixel in a MODIS granule determined from the number, age, and bearing of the advected flight tracks passing over each pixel. This product is currently being tested and improved to act as a validation/screening mask in the contrail detection algorithm. At present, tracks as old as 4 hours before image time are considered. Figure 1 shows an example of the confidence of detection product. Several contrails are visible in the brightness temperature difference (BTD_{11-12}) image (Fig. 1a). Figure 1b shows the contrail mask color-coded to represent the confidence of detection for each pixel in the mask. The blue pixels represent areas with the highest confidence of accurate detection based on the proximity of recent flight tracks, while the yellow and red pixels represent pixels with moderate and poor confidence of detection, respectively. The region of blue contrails at top of Fig. 1b correspond to air traffic passing over Portugal towards the Atlantic Ocean, while the detected contrails near the bottom of the image lie nearly perpendicular to most of the other contrails (and the typical flight corridors), and have been properly labeled with a low confidence of detection.

2.3 Visual analysis of contrail mask

Following Palikonda et al. (2005), visual analyses of the contrail mask over several overpasses by trained analysts are used to estimate error in CDA contrail
coverage using enhanced interactive software. Figure 2 shows an example of the visual analysis. Fig 2a shows a typical BTD image used to find contrails visually, while Fig. 2b highlights the pixels identified by the CDA (red), as well as the pixels the analyst determines to be additional contrails missed by the CDA (green), and the pixels expected to be false positives (dark blue). Because the visual inspection of persistent linear contrails by humans is subjective, as many as four analysts are used to produce a consensus analysis that will minimize overall analyst error. Analysis of MODIS imagery from January, April, July and October 2006 are being completed so that uncertainty bounds as a function of all seasons can be determined.

3. OPTICAL DEPTH AND LONGWAVE RADIATIVE FORCING

The visible optical depth of the contrails (COD) is derived from the contrail emissivity assuming a typical contrail temperature ($T_{con}$) of 224 K (Meyer et al., 2002).

$$
e = \frac{B(11 \mu m) - B(T_{back})}{B(T_{con}) - B(T_{back})}$$

where $B$ is the Planck function and the background temperature ($T_{back}$) is computed from the surrounding non-contrail pixels as in Minnis et al. (2005). The visible optical depth is then computed from emissivity (Minnis et al., 1993).

$$
e = 1 - \exp\left[a(\tau / \mu)^b\right]$$

Contrail longwave (LW; 5-50 µm) radiative forcing (CLRF) is defined as CLRF = ($Q_{back} - Q_{con}$) $f_{con}$, where $Q$ is the radiative flux and $f_{con}$ is the fraction of the scene covered by contrails, and the subscripts con and back are the observed fluxes including the contrails and the fluxes estimated that would be 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). Additional contrail optical properties (e.g., optical depth, effective particle size, solar radiative forcing) will be computed using the CERES cloud product retrieval system (Minnis et al., 2008, 2010).

The computer code to produce the contrail coverage, cloud optical and radiative property data at the pixel level was run for 4 sample days of Terra MODIS morning overpasses (2 each from July and October 2006) as a test of the code. Figure 3 shows the results of the run. The normalized probability distributions of contrail optical depth (COD) derived with the assumption that the contrail temperature is 224 K are shown, along with the mean longwave radiative forcing (LW RF) and average contrail coverage computed for all overpasses during the sample days. The COD histograms are similar for both months, with a peak for COD between 0.1 and 0.2, and almost no contrail pixels identified with optical depths greater than 1.0. The average COD for July and October 2006 is 0.17 and 0.19, respectively, ~25% less than earlier studies over the CONUS. The mean LW RF for both months is near 11 Wm$^{-2}$, also smaller than results from earlier studies. In the future, we plan to use the results of the visual analysis to determine not only the uncertainty in the contrail coverage derived from the CDA, but by applying the analysts’ composite correction to the contrail mask, to determine the uncertainty in the contrail optical properties derived from the CDA mask.
4. FUTURE WORK

Two years of *Terra* MODIS imagery over the CONUS will be processed to create a climatology of contrail coverage and optical properties. The results will be averaged into 1x1 degree bins and made available publicly in netCDF format.

5. REFERENCES


Figure 1. Contrails and flight tracks near Portugal and Spain, 1135 UTC, 12 March 2006. (a) Terra MODIS 11 – 12 µm brightness temperature difference (BTD) showing contrails. (b) BTD image overlaid with contrail mask with high confidence of detection (blue) moderate confidence (green, yellow) and low confidence (orange, red).
Figure 2. Contrails and flight tracks from Terra MODIS over United States, 1658 UTC, 2 October 2006. (a) BTD(11-12) image. (b) CDA contrails overlaid BTD image in red, contrails added by analyst in green and contrails deleted by analyst in blue.
Figure 3. Probability distribution of contrail optical depth, LWRF and mean optical for contrails during July 2006 (a) and October 2006 (b).