Contrail coverage over the North Pacific from AVHRR and MODIS data

Patrick Minnis[1]
Atmospheric Sciences, NASA Langley Research Center, Hampton, Virginia, USA

Rabindra Palikonda, J. Kirk Ayers
AS&M, Inc., Hampton, Virginia, USA

Abstract
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[1] *Corresponding author:* Patrick Minnis, MS 420, NASA Langley Research Center, Hampton, VA, USA 23681.
Email: p.minnis@nasa.gov

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Patrick Minnis[1]
Atmospheric Sciences, NASA Langley Research Center, Hampton, Virginia, USA

Rabindra Palikonda, J. Kirk Ayers
AS&M, Inc., Hampton, Virginia, USA

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ABSTRACT: An increase of air traffic over the North Pacific during the last 30 years has been accompanied by an increase in cirrus coverage. To help alleviate the uncertainty in the contribution of air traffic to the cirrus increase, an analysis of linear contrail coverage over the region has been initiated using afternoon NOAA-16 AVHRR data. Contrail coverage over the domain between 25° and 55°N and between 120° and 150°W was 0.51% and 0.67% in August 2002 and February 2003, respectively. These preliminary values are twice the average expected from theoretical considerations. Contrail optical depths for the 2 months average 0.26 resulting in a mean unit contrail longwave radiative forcing of 15.5 Wm^{-2}, a value that is comparable to that estimated over the USA from daytime analyses. The seasonal variation is smaller than that over land. The contrail optical depths are twice the mean value expected from theoretical estimates. Efforts are underway to estimate the uncertainties in the results and to analyze additional satellite datasets.

1 INTRODUCTION

Cirrus cloud cover has been increasing over the North Pacific since the 1970's. Although part of the increase may be due to a rise in relative humidity, some of the change is likely caused by contrails forming and spreading as a result of transoceanic air traffic. Analysis of high-resolution satellite data is required to determine the contribution by linear contrails to that increase. The air traffic passes through a region where mean cirrus cloud coverage is generally about half that observed over land, while the upper tropospheric humidity, as indicated by the NCEP reanalysis at 300 hPa, is roughly 10% greater than that over land (Minnis et al. 2003). Thus, the atmosphere over pristine oceanic regions should be more susceptible to contrail-cirrus cloud initiation than that over land areas. Additionally, transoceanic flights travel greater lengths at high altitudes than their continental counterparts and, therefore, should tend to produce longer contrails. The expected linear contrail coverage from theoretical considerations (Sausen et al. 1998) varies between 0% in the mid-Pacific and 1% near San Francisco Bay (Fig. 1a). The flight corridors are well defined in Figure 1. Cirrus coverage rose between 0 and 0.6%/year between 1971 and 1996 (Minnis et al. 2003) over the same area with a maximum increase over northern California (Fig. 1b). Over the ocean, a broad area with the greatest trends in cirrus coverage is centered near 45°N at the western edge of the domain in Figure 1. There is no apparent correlation between the cirrus trends and the theoretically derived contrail coverage. Understanding how the contrails relate to the changes in cirrus coverage necessitates the development of some empirical data on the linear contrail coverage. To begin that effort, this paper presents preliminary analyses of contrails as derived from satellite data over the North Pacific. The retrieved properties are compared to similar quantities derived from data over the continental United States of America (USA) to examine the differences between contrails formed over marine and continental areas. They are also compared to the theoretical results. Preliminary statistics are presented.

[1] *Corresponding author:* Patrick Minnis, MS 420, NASA Langley Research Center, Hampton, VA, USA 23681. Email: p.minnis@nasa.gov

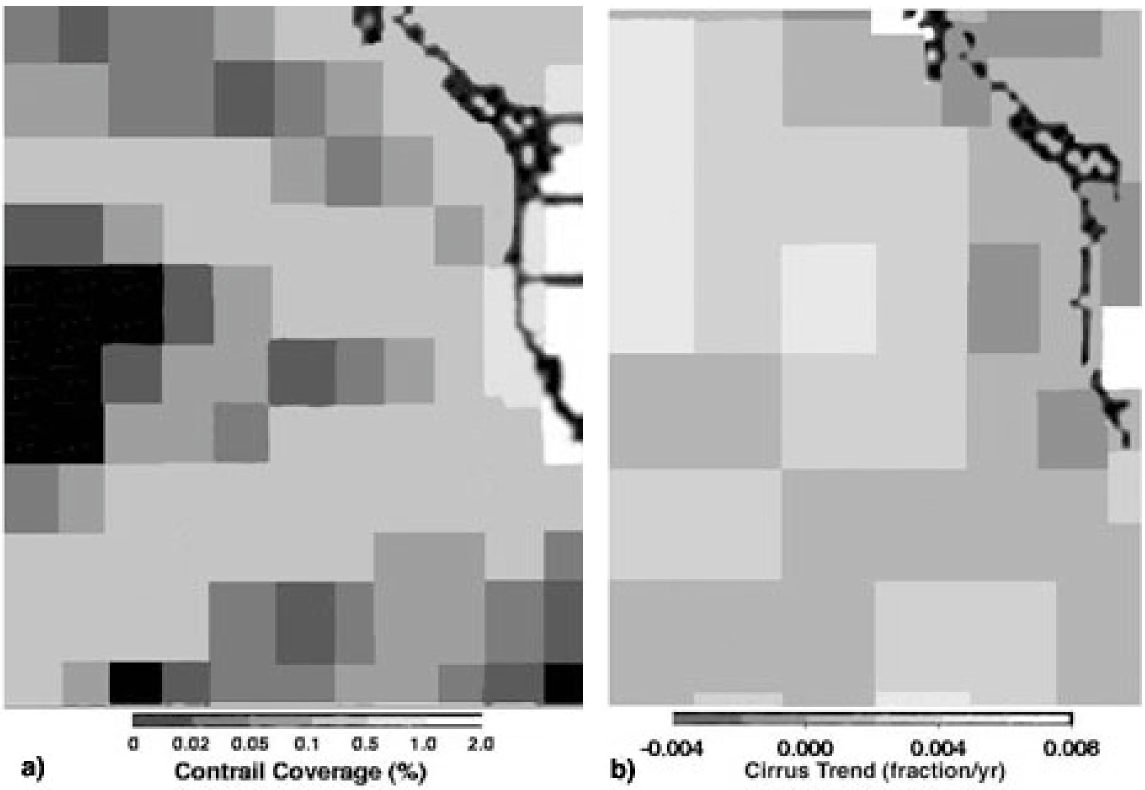

Fig. 1. Theoretical linear contrail coverage in 1992 (a) and trend in surface-observed 1971-1996 cirrus coverage (a), and

2 DATA AND ANALYSIS

Advanced Very High Resolution Radiometers (AVHRR) have been taking 1-km multispectral data from the NOAA satellites since the 1980's, but most of the archived and real-time data over the broad ocean areas are for the 4-km Global Area Coverage (GAC) dataset. The NASA Earth Observing System satellites, *Terra* and *Aqua*, have been operating since March 2000 and August 2002, respectively. Each carries the Moderate Resolution Imaging Spectroradiometer (MODIS) that takes and archives multispectral data globally at resolutions from 0.25 to 1 km. Figure 2 shows examples of large contrails evident in the NOAA-16 AVHRR GAC imagery off the coast of California. Some of the trails exceed 1000 km in length and 20 km in width and they are evident in both the channel-4 infrared (IR, 11 µm) image (Fig. 2a) and, in Figure 2a, the 11-12 µm brightness temperature difference (T4-T5), a parameter commonly used to differentiate contrails from cirrus clouds. Such lengthy, fat contrails are not uncommon as seen in Fig. 3. The contrails in the NOAA-15 T4-T5 image (Fig. 3a) are from jets approaching California from the northwest while those in the 1-km MODIS image (Fig. 3b) are from planes approaching southern California from the southwest.

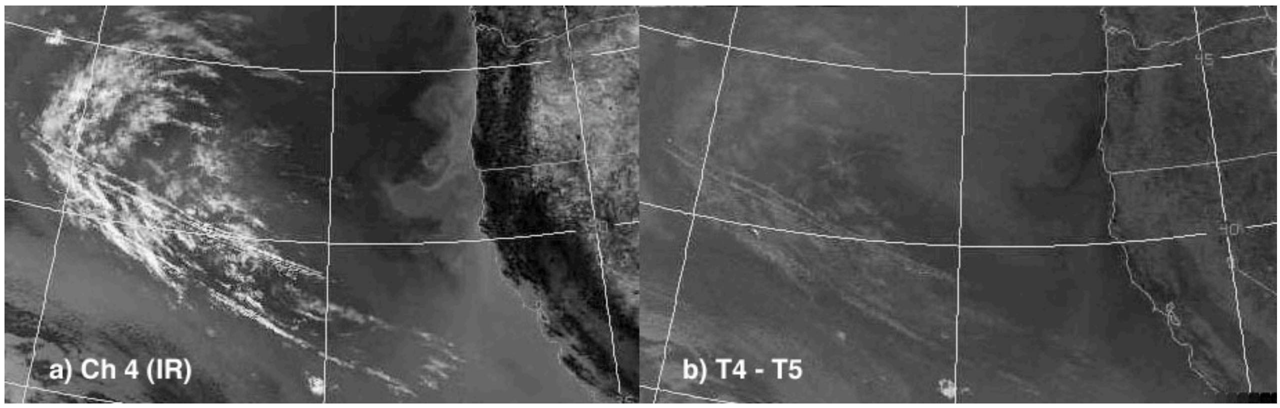

Fig. 2. NOAA-16 AVHRR imagery at 1056 UTC, 13 August 2002: Infrared brightness temperature (a) and channel 4-5 brightness temperature difference.

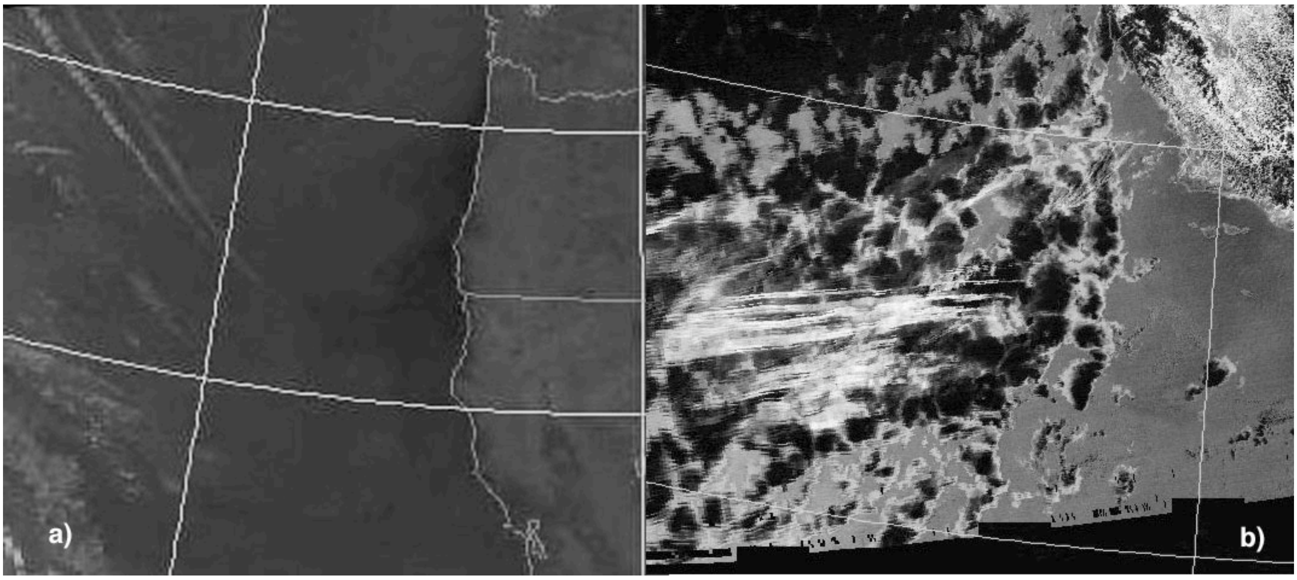

Fig. 3. Contrails in the northeastern Pacific. (a) NOAA-15 AVHRR GAC T4-T5, 0230 UTC, 14 August 2002. (b) Aqua MODIS 1-km, 2054 UTC, 3 May 2003, T31-T32.

To quantify the contrail properties over the North Pacific, an automated algorithm (Mannstein et al. 1999) can be applied to 1-km AVHRR data from *NOAA-16* and to MODIS data from *Terra* and *Aqua* to derive contrail areal coverage. Contrail optical depth is computed with the method of Meyer et al. (2002) assuming that the contrail temperature is 224 K and that the contrail emissivity varies with optical depth (*OD*) according to the model of Minnis et al. (1993) for small ice crystals. Contrail longwave radiative forcing (CLRF) and the background temperature were computed using the methods of Palikonda et al. (2002, 2003). The initial analyses are performed on 1-km NOAA-16 AVHRR data taken from afternoon orbits during August 2002 and February 2003. The domain extends from 25°N to 55°N and from 120°W to 150°W corresponding to the plots in Figure 1.

3 RESULTS AND DISCUSSION

Figure 4 shows the distribution of contrail coverage over the domain for the two months. It is obvious that the derived contrail coverage in February (Fig. 4b) exceeds that found in August (Fig. 4a). During August, the greatest contrail coverage occurred around 47°N, 142°W with a secondary maximum near the west-southwest approach to San Francisco. Minimum coverage is seen in the southwestern corner of the domain, off the Oregon coast and inland. A general increase in contrail coverage during February is accompanied by a shift in the areal maximum to 42°N, 147°W. The southwestern corner remained relatively free of contrails. However, the contrail coverage is greatly increased over all of the approaches to the west coast cities. Overall, the mean contrail amounts during August 2002 and February 2003 are 0.51 and 0.67%, respectively.

The corresponding mean contrail optical depths for the domain are 0.27 and 0.26. The mean CLRF for both months is 0.09 Wm^{-2}. However, during February the unit or normalized CLRF (NCLRF) is 13.5 Wm^{-2} compared to 17.4 Wm^{-2} during August. The frequency distributions of *OD* and NCLRF are plotted in Figure 5. Optical depths vary according to a slightly skewed Gaussian distribution with a mode value around 0.20. The NCLRF distribution is highly skewed with a mode near 8 Wm^{-2}. This domain includes inland desert areas in Oregon and Washington that can become very warm during the afternoon even during winter. The large variability in NCLRF arises from the large range in background radiating temperatures. Contrails mixed with other cirrus clouds will tend to have small values of NCLRF while over clear areas NCLRF will be much larger, especially over land during the afternoon.

The contrail coverage values for both months are roughly twice the annual mean (0.30) from the results of Sausen et al. (1998). This difference could be due to a number of factors including the restricted sampling of the NOAA-16 afternoon orbit, a potential bias in the satellite retrievals (e.g.,

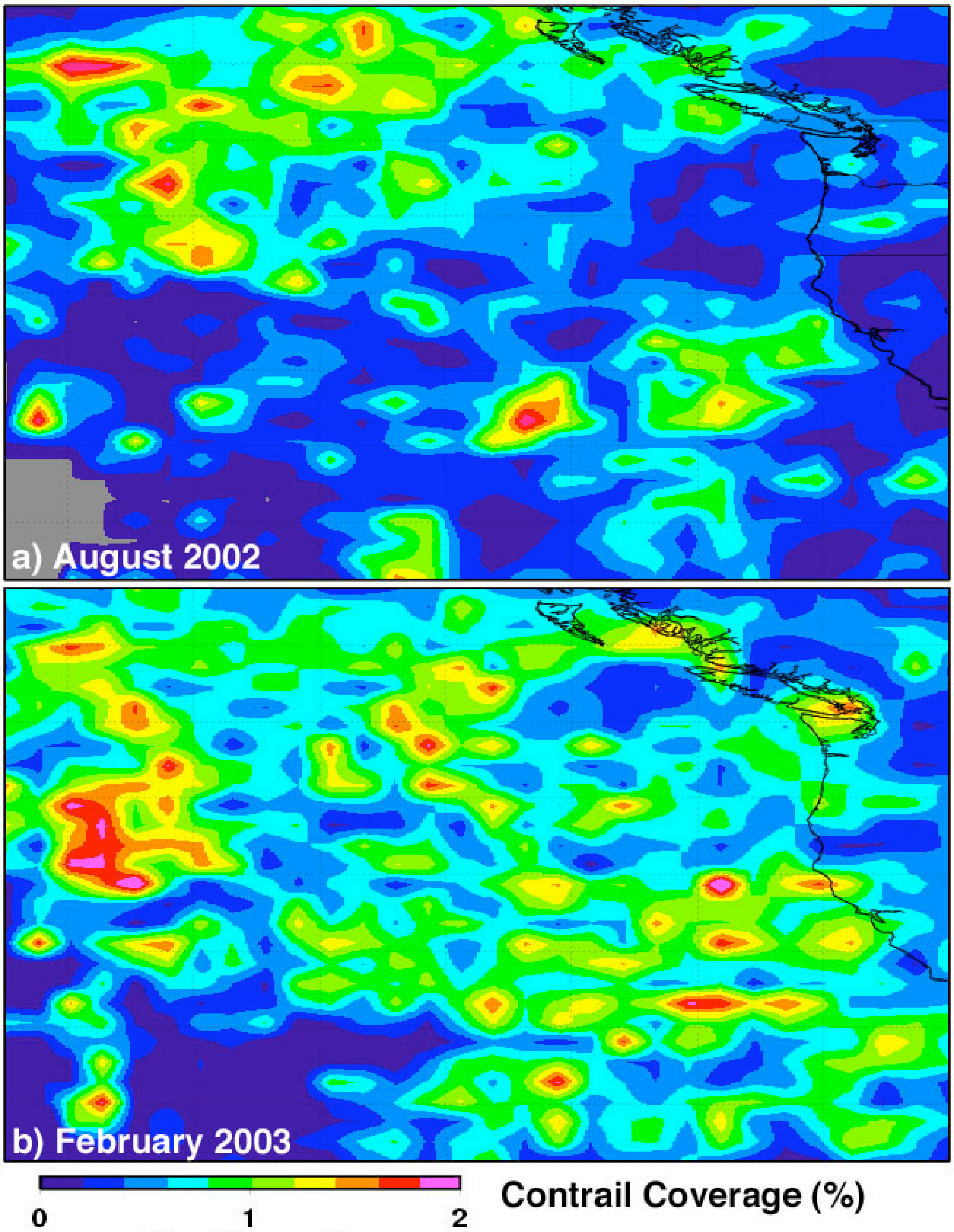

Figure 4. Mean contrail coverage derived from afternoon (1430 LT) NOAA-16 AVHRR data.

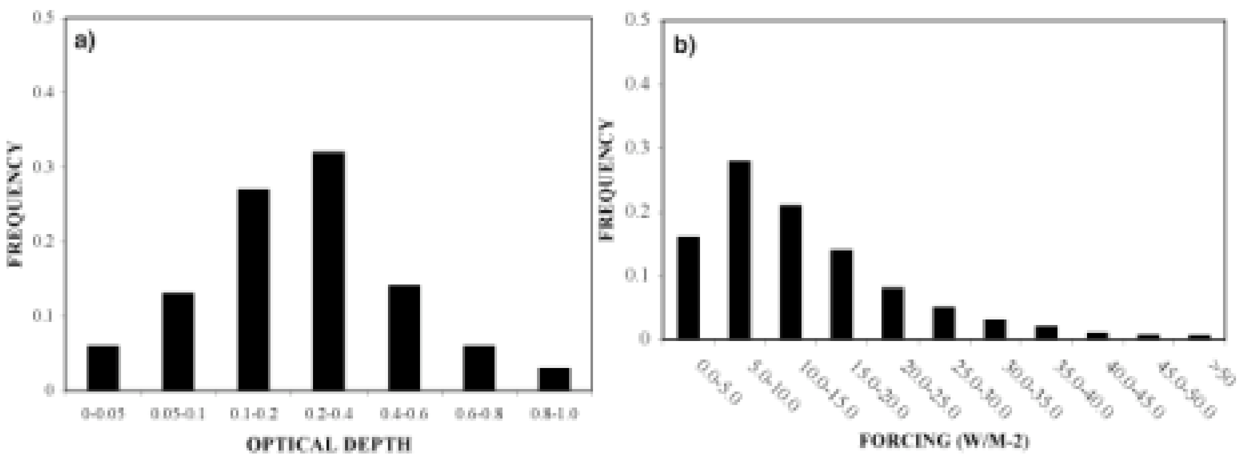

Figure 5. Frequency distributions of (a) contrail optical depth and (b) unit CLRF during February 2003.

Palikonda et al. 2003), an increase in trans-Pacific air traffic since 1992, differences in the upper tropospheric humidity between the model and the actual atmosphere, and a variety of other reasons. From the theoretical calculations of Ponater et al. (2002), it appears that summertime contrail coverage over the area should be larger than that during winter. This discrepancy with the current observations may arise form the same sources causing the differences in absolute contrail coverage. For instance, during winter, cirrus clouds are more abundant over the domain due to the more frequent passage of baroclinic disturbances. The opportunity for mistaking cirrus clouds during winter is enhanced at the same time as the potential for forming contrails. The overall effect may be that the overestimate of contrail coverage from the satellite analysis is greater during winter than during summer.

The afternoon NOAA-16 sampling may not be representative of the air traffic over the Pacific. While the air traffic over the USA is nearly constant for half of the day (Garber et al. 2003), scheduling of transoceanic flights differs from transcontinental traffic. Thus, the number of flights may be greater or less at other hours than at 1430 LT. Additional satellite overpass times should be analyzed.

The wwestern maxima in contrail coverage (Fig. 4) are generally consistent with the maximum in cirrus trend (Fig. 1b) although the theoretical contrail coverage minimum extends into the same area. The flight tracks used in the Sausen et al. (1998) study are highly idealized and may not accurately represent the actual distribution of flight locations during the 2002-2003 period. Given the greater number of contrails in the northwestern part of the domain, it is likely that the conditions for contrail and cirrus formation are most favourable in that area. Thus, the errors in contrail detection may be greater in the same region. This issue requires further study.

The contrail optical depth distributions and mean values are nearly identical to those derived over the USA by Palikonda et al. (2003). The means are almost twice the magnitude found over Europe by Meyer et al. (2002) and estimated by Ponater et al. (2002) from theoretical calculations. The differences again may be related to mistaken cirrus clouds that are deeper than the average contrail or to an underestimate of contrail depth by the theoretical models. The February NCLRF mean is 5 Wm-2 greater than the wintertime mean for NOAA-16 results over the USA while the August NCLRF is 2 Wm-2 less than the corresponding USA summertime mean (Palikonda et al. 2003). This seasonal difference in the CLRF is likely due to the relatively stable background temperatures over the ocean. Over land, the contrast between the contrail and surface temperatures is much greater in summer than in winter.

4 CONCLUDING REMARKS

The results presented here constitute the first objective analysis of linear contrails over the western North Pacific. Both contrail coverage and optical depth are twice the annual average derived from theoretical considerations. Contrail longwave radiative forcing is much greater than computed theoretically. However, the results should be considered preliminary because no error analyses have been performed. Furthermore, the data were taken at only one time of day and may not represent the entire daily cycle.

This study has just begun. In the future, detailed error analyses will be performed to optimize the accuracy of the methodology for each satellite separately. A larger dataset including MODIS data and other NOAA satellites will be analyzed to determine the annual cycle and provide results that include all times of day. Shortwave radiative forcing will also be estimated for each retrieval to determine the net radiative forcing for these contrails. The results will be compared with the model-predicted temperature and humidity conditions to help improve the parameterization of contrails in climate models so that a more accurate assessment of contrail effects can be computed for the northwestern Pacific Ocean.

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