Remote Sensing of Contrails and Aircraft Altered Cirrus Clouds

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Analyses of satellite imagery are used to show that contrails can develop into fully extended cirrus cloud systems. Contrails can advect great distances, but would appear to observers as natural cirrus clouds. The conversion of simple contrails into cirrus may help explain the apparent increase of cloudiness over populated areas since the beginning of commercial jet air travel. Statistics describing the typical growth, advection, and lifetime of contrail cirrus is needed to evaluate their effects on climate.

1. INTRODUCTION

Contrails may have a significant impact on the regional energy budget by blocking outgoing longwave radiation and reflecting incoming solar radiation. Such effects may also alter weather and climate patterns. The overall impact depends on many factors including the contrail areal coverage, lifetime, time of formation, microphysical properties, altitude, and background. A variety of studies have suggested that cloud cover has risen due to contrails caused by increasing air traffic leading to reduced surface sunshine [1] or to surface warming [2]. Although several papers have been devoted to assessing the frequency of contrail occurrence, knowledge of the areal extent of contrail clouds is minimal. An examination of contrails by Bakan et al. [3] showed a maximum coverage of only 2% over a relatively small part of Europe and the northeast Atlantic. That study and others generally assume that contrail clouds are only those that are the familiar, narrow linear streaks in the sky or in a satellite image. As contrails are usually observed only in the air traffic routes and the routes only cover a small portion of the globe, it is difficult to reconcile the small fraction of cloudiness attributable to contrails and the larger increases in thin cloudiness if only the fresh, linear contrails are considered.

Bakan et al. [3] noted that many of the contrails they observed in a given NOAA Sun-synchronous satellite Advanced Very High Resolution Radiometer (AVHRR) image could be seen in other images 6 to 48 hours later. From the surface, it is possible to observe the transformation of contrails into cirrus clouds having little resemblance to their original linear shape. Given these observations, it is highly probable that some long-lived contrails cannot be recognized as such and will increase the amount of cloudiness caused by jet aircraft exhaust. This paper examines the problem of determining if and how much additional cloud cover can be attributed to contrails. AVHRR and Geostationary Operational Environmental Satellite (GOES) data are used to track contrails for a few select cases and evaluate their areal and optical properties as they develop.

2. DATA AND ANALYSIS

NOAA-12 1-km AVHRR data and GOES-8 at 75°W and GOES-9 at 135°W taken at 15-minute intervals provide a variety of views for studying contrail development. The AVHRR data used here comprise the visible (VIS; 0.65 µm), solar-infrared (SI; 3.75 µm), infrared (IR; 10.8 µm), and

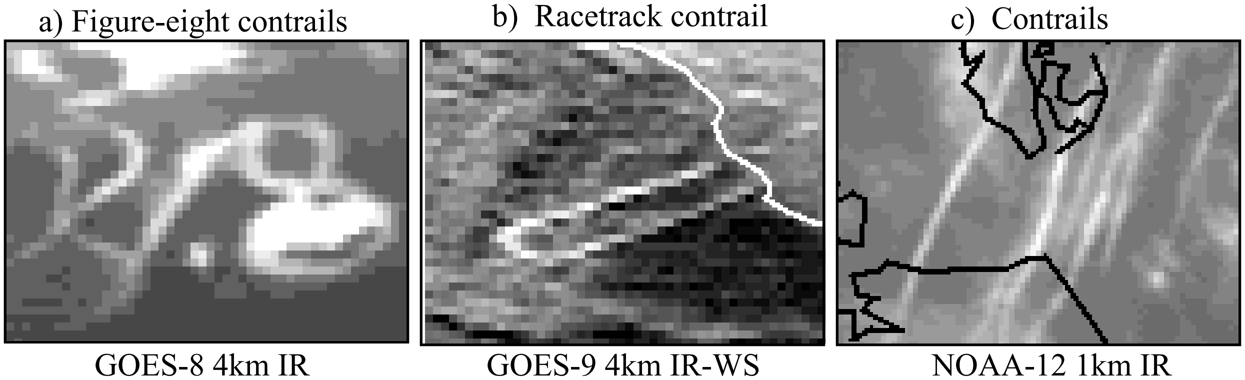

Fig. 1. Satellite thermal imagery (a) 1945 UTC, 11 April 1996 over the Gulf of Mexico. (b) 2330 UTC, 12 May 1996 off the coast of California. (c) 1214 UTC, 26 September 1996 over eastern Virgina.

split window (WS; 12.0 μm). The 4-km GOES imager has similar channels except that the SI central wavelength is 3.9 μm. The GOES VIS data can also be obtained at 1-km resolution. Temperature and humidity soundings from the nearest National Weather Service station were used to relate temperature to altitude.

During the NASA Subsonic Contrails and Clouds Effects Special Study (SUCCESS) conducted over the U.S. during Spring, 1996, two extraordinary contrail systems were observed off the coast. One was a series of figure eights from an unknown source over the Gulf of Mexico during 11 April (Fig. 1a). The eights were originally 30 km wide and extended ~70 km from north to south The other system was a 100-km long oval or race track produced over the Pacific Ocean by the NASA DC-8 as it sampled contrails produced by commercial airliners and its own exhaust (Fig. 1b). These two sets of contrails are ideal for tracking because they are extensive and easily distinguishable from natural clouds. The third case involves linear contrails produced by commercial aircraft over the east coast of the U.S. 26 September 1996 seen over mouth of the Chesapeake Bay in the AVHRR imagery in Fig. 1c.

The data were analyzed with the multispectral techniques of Minnis et al. [4] to derive the phase, effective ice particle diameter D_e, optical depth τ, temperature T_{cld}, and altitude z of the high-altitude clouds within a box defined to include only the clouds arising from the subject contrail systems. The box was also selected to include the portions of the background to compute the clear-sky VIS clear-sky reflectance and IR, SI, and WS clear-sky temperatures T_{CS}. During daytime, the VIS-IR-SI technique (VIST) was used to determine the values for each parameter, while the SI-IR-WS (SIRS method) was applied at all hours [4]. The cloudy pixels were identified over ocean as those having temperatures $T < T_{CS}(IR)$ -1.5K. Over land, the temperature threshold depression varies up to 6K depending on the variability of the backround temperature. The parameters were computed only for the pixels corresponding to the contrail cloudiness. Screening other cloudy pixels can be subjective and difficult, however, some objective criteria were applied to eliminate non-contrail clouds. Clouds having $T_{cld} > 273$K were assumed to be low clouds and clouds with $\tau > 1$ were assumed to be pre-existing cirrus. Cloudy pixels with indeterminate particle size results were assumed to belong to the contrail because those results usually occur for optically thin clouds or those along the edge of a larger cloud. The areal contrail coverage is the number of contrail pixels multiplied by the mean area of a pixel at the given viewing angle. Actual area was computed for the entire cloud ensemble for the racetrack and figure-eight contrails because they remained relatively distinct entitities. Fractional area was computed for the linear contrails using a constant box size of 20 x 30 pixels or ~ 13,600 km^2.

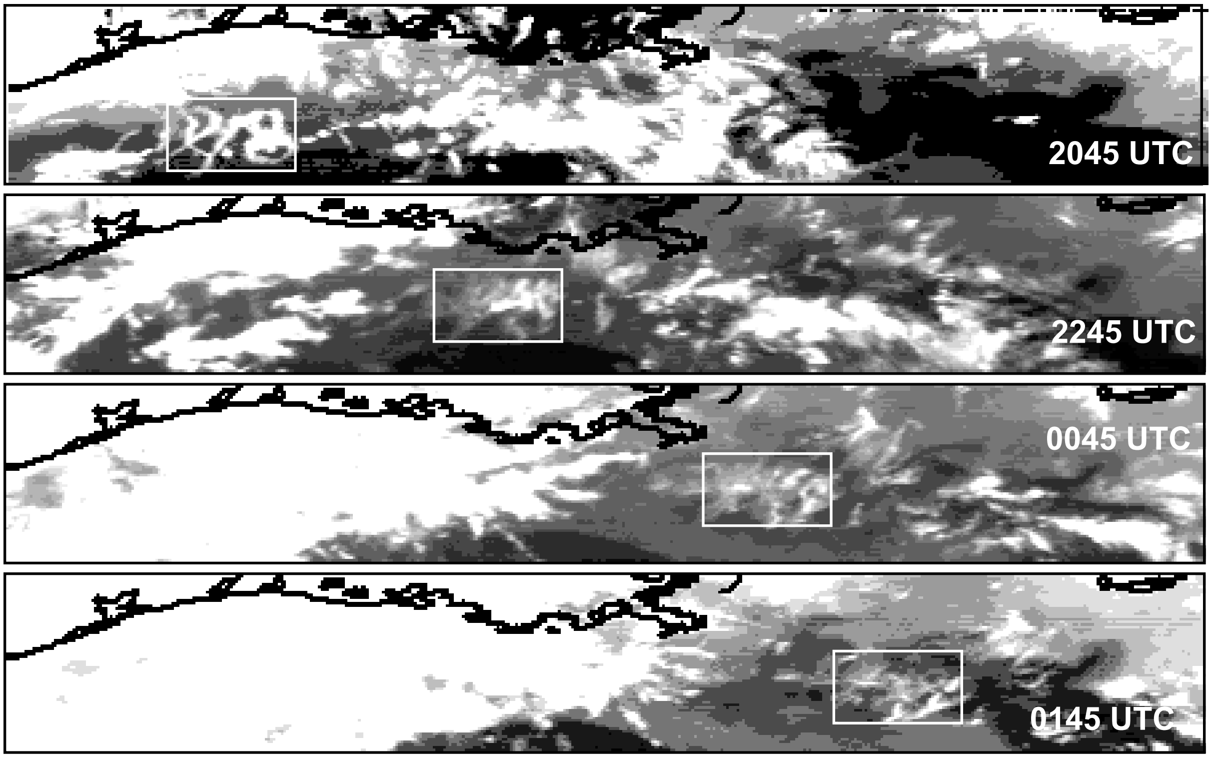

Fig. 2. GOES-8 infrared imagery showing transformation and dissipation of the figure-eight contrails from 2045 UTC, 11 April 1996 to 0145 UTC, 12 April 1996 over the Gulf of Mexico.

3. RESULTS

The transformation and dissipation of the figure-eight contrails can be seen in the GOES IR imagery in Fig. 2. At 2045 UTC, the arms of the eights were 2-4 pixels or ~12 km wide. The eights gradually diffused, filled, and became indistinguishable from other cirrus by 2245 UTC. They advected a total of ~750 km before disminishing to a small area south of the western tip of Florida by 0145 UTC, 12 April. During most of that time, the contrail clouds were too thick or dispersed to be recognizable as contrails from either the satellite or surface perspective. Figure 3 shows the analysis results using the two techniques applied to the GOES data within the analysis boxes. The initial VIST results yield a relatively small average particle size that increases as the contrails advect. At 1915 UTC, shortly after the contrail formed, the VIST-derived cloud temperature is estimated at 247 K. According to a 1200 UTC, 11 April sounding taken at Lake Charles, Louisiana, that temperature corresponds to an altitude of 7.8 km. The sounding also showed that the troposphere above 7 km is extremely moist indicating that an altitude of 7.8 km is reasonable for this contrail. The VIST cloud temperature increased slightly after 3 hours suggesting that the contrail decreased in altitude as it spread. Optical depth remained relatively constant. The SIRS analysis yields a different picture of the cloud parameters with T_{cld} decreasing until 2115 UTC before increasing again. Although the initial values are nearly the same, the optical depths are smaller and D_e is larger, on average, than the VIST results. The SIRS analysis is less reliable during the day than at night so the retrievals after 0000 UTC are more accurate. When lower clouds are absent, the VIST results are more accurate than the SIRS data. Thus, the parameter variations given by the VIST are a better representation prior to 2300 UTC. The results for τ and D_e after 2300 UTC are probably accurate to $\pm$ 50%. The areal coverage increases steadily until it reaches ~24,000 km^2 at 0000 UTC. The mean contrail cloud optical depths decreased after 0000 UTC as the cloud dissipated.

The 12 May, DC-8 contrail forms over a background of low stratocumulus and advects over a clear portion of the ocean along the coast before passing over the land at 0045 UTC, 13 May (Fig. 4).

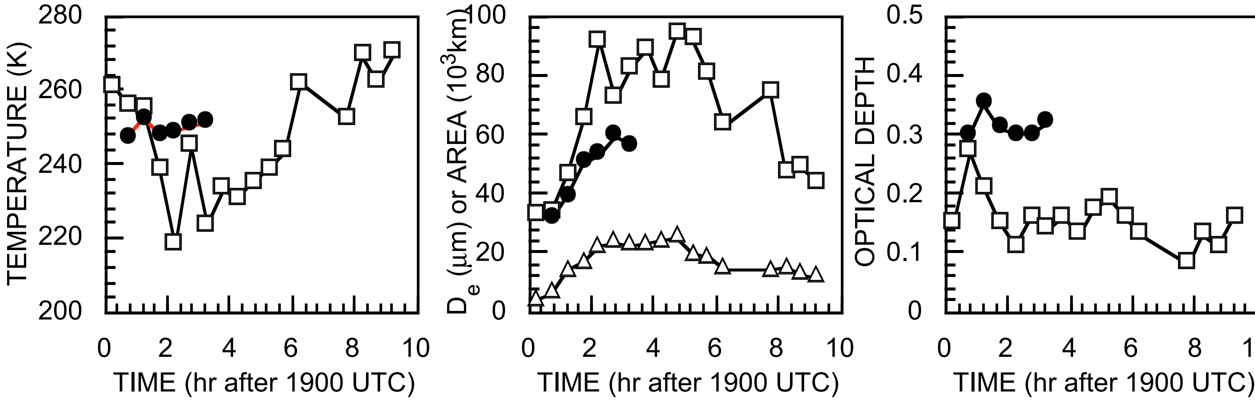

Fig. 3. Cloud parameters from figure-eight contrails over Gulf of Mexico for 11-12 April 1996. Closed symbols from VIST analysis. Open symbols from SIRS. Triangles refer to area.

It also fills and spreads as it moves with the wind. At 0300 UTC, over the foothills of the Sierra Nevada, the oval structure is gone, replaced by a somewhat amorphous shape. When the system reaches the mountains (0445 UTC), the cloud seems to thicken before dissipating over Nevada at 0545 UTC. The analysis results in Fig. 5 show the cloud starting near 230 K and apparently dropping in altitude to warmer temperatures. The particle initially is ~30 μm in diameter and increases

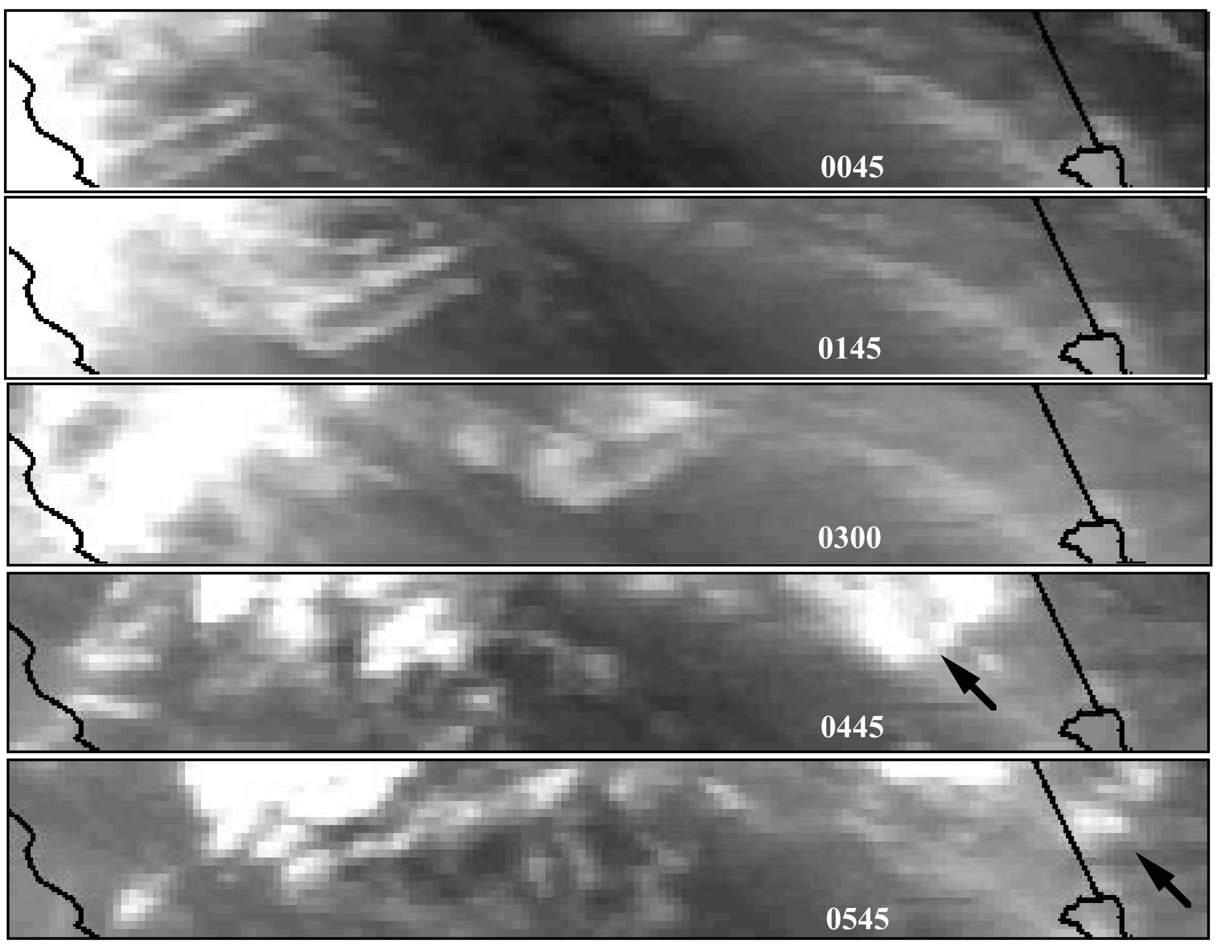

Fig. 4. GOES-9 IR imagery showing transformation and dissipation of the DC-8 racetrack contrail from 0045-0545 UTC, 13 May 1996 over northern California to the Nevada border.

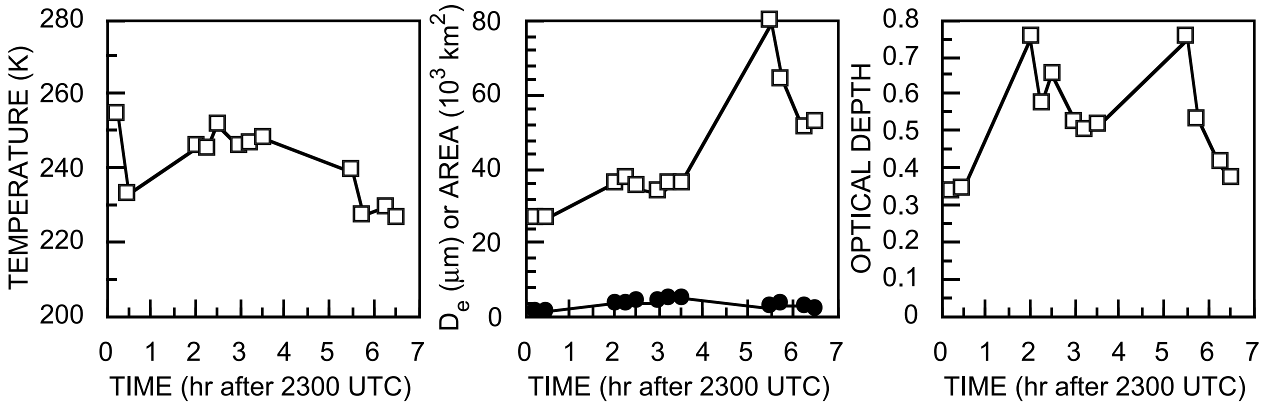

Fig. 5 Cloud parameters computed for racetrack contrail from GOES-9 data 12-13 May 1996. Solid symbols refer to contrail area. Temperature refers to contrail temperature.

to ~ 40 µm for several hours and to larger values over the mountains. The optical depths, which average ~ 0.5, far exceed those seen for the figure-eight contrails. Areal coverage by this contrail-cirrus system reaches a peak of ~ 5000 km^2 at 0230 UTC. The missing hours in Fig. 5 were not analyzed because of the variability in the background temperatures. The DC-8 flew at an altitude near 10 km which corresponds to ~ 229K on the nearest sounding. Thus, it appears that T_{cld} for the contrail was overestimated by more than 10K for much of the cloud's lifetime. The magnitude of this potential error is not surprising given the changing background: low clouds, clear ocean, mountains, and valley. This variability precluded the use of the VIST for all of the contrail.

The linear contrails in Fig. 1c over the Atlantic Ocean and were tracked with a constant-area box using GOES-8 data. Figure 6 shows the cloud parameters derived from GOES-8 for the constant-area box. The cloud temperature remained relatively steady near 245K for the first few hours, then decreased as the cloud optical depth diminished. These temperature changes correspond to height increases from 8 to 10 km. Unlike the previous two cases, the mean particle sizes are more typical of natural cirrus, although they appear to be more like contrails during the most rapid growth of the cloud around 1430 UTC. The contrails in Fig. 1c were observed from the surface around 1230 UTC and occurred with scattered, thin natural-looking cirrus. Therefore, some of the larger particles may be due to pre-existing cirrus. The optical depths are significant, averaging around 0.3 for the study period. The contrails appear to have developed from ~30% coverage in the box at 1245 UTC to 80% 6 hours later. Examination of the surrounding areas in the GOES-8 imagery yielded little cirrus coverage. These same parts of the air mass lacked the original contrails seen at 1230 UTC in the AVHRR imagery suggesting that the contrails were responsible for much of the observed cloudiness in the box which was generally clear before 1200 UTC.

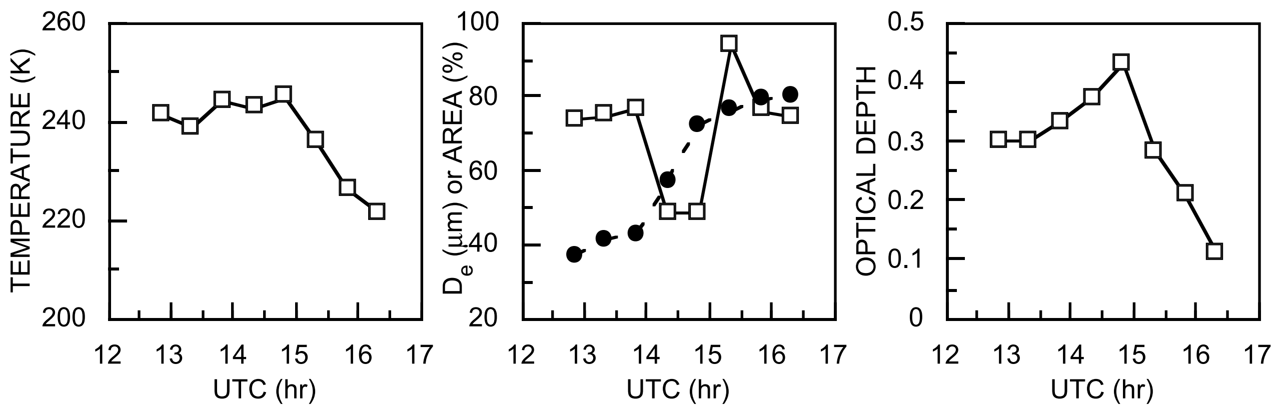

Fig. 6. Cloud parameters computed from GOES-8 data with VIST for a moving 20x30 pixel box containing contrails during 26 September, 1996. Temperature refers to cloud temperature.

4. DISCUSSION

Accurate determination of the cirrus microphysical properties is difficult for clouds with such small optical depths. The sensitivity of the retrievals to variations in background reflectance and temperatures is greatest when the clouds are thin ($\tau < 0.5$). However, the effective particle sizes in Figs. 3 and 5 change as expected for contrails: initially very small particles because of the abundance of nuclei followed by crystal growth as the cloud diffuses into cleaner air. The different behavior seen in Fig. 6 may be due to errors in the analyses for the lower sun angles before 1400 UTC. A closer examination of the data is required to determine if the retrievals are accurate. Similarly, the apparent underestimation of the racetrack cloud height will require further investigation. Because the DC-8 took microphysical measurements during the initial formation of that contrail, it will be possible to estimate the retrieval errors for the first few data points.

The cloud growth rates seen in Figs. 3, 5, and 6 are remarkable. Peak coverage occurs approximately 3 hours after the contrail is detectable from the satellite. The contrail clouds dissipate slowly both in horizontal and vertical extent. The ends of the contrail lifetimes were not totally observed in these results. Significant areal coverage remained in all three cases after 5 to 9 hours. Additional tracking could reveal re-growth or continued dissipation. Assumptions about contrails remaining in the air routes are not supported by these results. Contrail cloudiness can advect considerable distances from their source, substantially increasing the area affected by manmade clouds.

5. CONCLUDING REMARKS

It is clear from these results that contrail areal coverage is much greater than that derived from analyses relying on narrow linear features like those in Fig. 1c. Such analyses provide a minimum estimate of contrail cloud cover. The results found here are not necessarily typical of all contrails. Given the difficulty in analyzing these relatively distinct cases, it may be concluded that objective tracking or automated retrieval of advecting contrail properties will require substantial additional research. Until more automated procedures become available, it will be possible to acquire a more representative statistical base of contrail characteristics by performing analyses similar to the present one using a much larger satellite dataset. Such statistics are crucial elements for understanding the impact of contrails on climate. This study is just an initial glimpse of the potential changes in cloudiness induced by modern air travel.

6. REFERENCES

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