Contrail Frequency Over the USA From Surface Observations

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Abstract. The mean hourly, monthly, and annual frequencies of daytime contrail occurrence are estimated using 2 years of observations from surface observers at military installations scattered over the continental United States of America (CONUS). Persistent contrails are most prevalent during the winter and early spring and are seen least often during the summer. Hourly contrail frequencies reflect the pattern of commercial air traffic with a rapid increase from sunrise to midmorning followed by a very gradual decrease during the remaining daylight hours. Although highly correlated with air traffic fuel use, contrail occurrence is governed by meteorological conditions. Accounting for seasonal sampling biases, the mean annual contrail frequencies dropped from 15.2% during 1993-94 to 12.2% in 1998-99 despite a rise in air traffic. The mean relative humidities at 300 hPa decreased from 45.8% to 38.2% in 1998-99, one of the driest periods on record.

Introduction

Contrails are a common sight in the skies over the USA and Europe. They represent a change in atmospheric composition that may impact climate because of their interaction with the Earth radiation budget [e.g., *Minnis et al.* 1999]. In a recent assessment [*IPCC*, 1999], contrails and their effects were recognized as one of the largest outstanding uncertainties in the air traffic impact on the atmosphere. Contrail coverage, distribution, and optical depth are some of the variables that must be accurately quantified. With commercial jet air traffic expected to continue increasing at a rate of 2-5% per annum through 2050 [*IPCC*, 1999], it is important to reduce uncertainties in the parameters that determine the impact of contrails on climate.

The locations of the contrails and the month and time of day when they form affect how they interact with the radiation field [*Meerkötter et al.* 1999]. Satellite estimates of contrail coverage provide the only empirical information for estimating contrail distribution and coverage, while models using numerical weather analyses have been used to provide theoretical estimates of contrail coverage. Satellite estimates are prone to uncertainty because of differences in techniques, satellite sensor differences, and difficulties in discriminating contrails from natural cloud formations. An independent means of quantifying contrails is needed to help validate and assess both the model and satellite estimates of contrail distributions. *Minnis et al.* [1997] documented the frequency of contrail occurrence over the USA based on a year of hourly surface observations taken at US Air Force (USAF) bases (AFB) during 1993-1994. They found a distinctive seasonal cycle and diurnal variations of contrail occurrence that could be related to jet traffic. However, with only 1 year of data, it is difficult to make any climatological conclusions about the observed variations. To ensure that conclusions drawn from the 1993-1994 dataset are reliable, an additional year of contrail observations was taken at USAF bases during 1998-1999. The results from these more recent observations are analyzed here and compared with the data taken during 1993-94 to establish a more reliable contrail occurrence climatology and provide a dataset for comparison with model estimates and satellite observations.

Data

The raw data were taken by weather observers at USAF or Army airfields distributed over the CONUS as shown in Figure 1. Rucker Air Base (not shown) replaced Cairns for the second period. Nominally, an observation was taken once each hour every day at 19 bases during the first period (January 1993 - May 1994) and at 17 bases during the second observing period

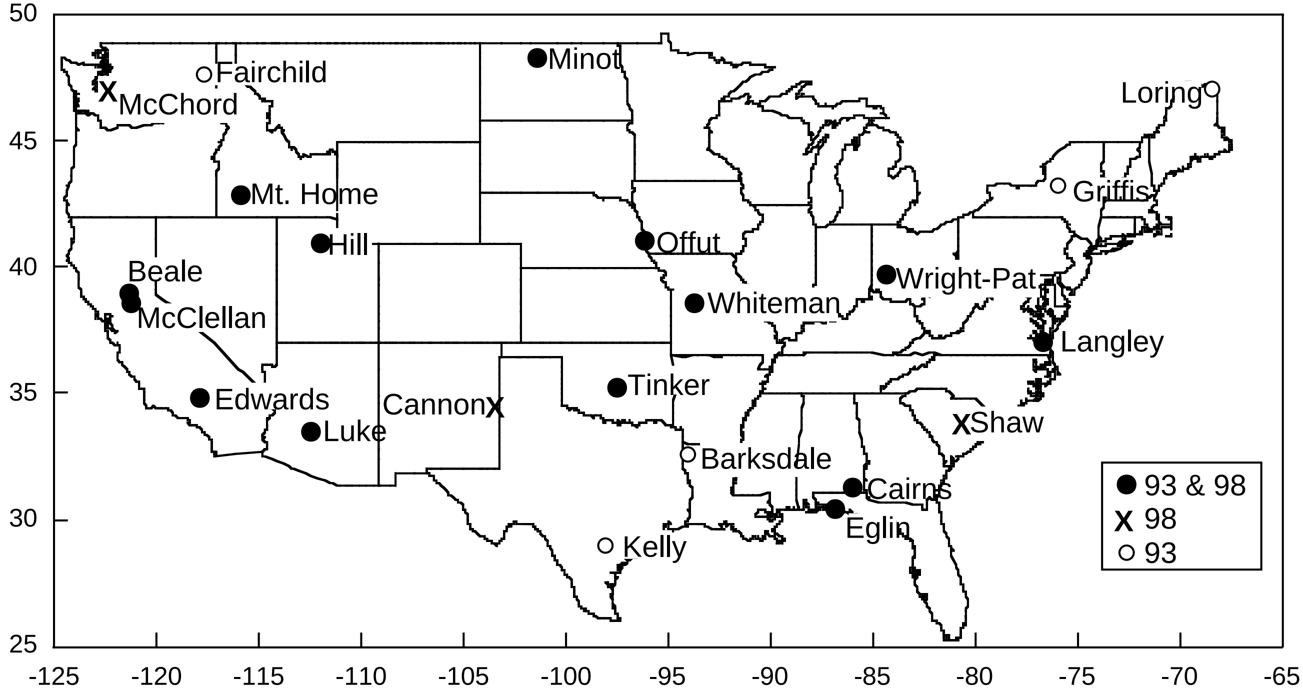

Figure 1. Contrail observing sites for the two periods.

(March 1998 - March 1999), but the actual temporal coverage varied. The geographical distribution changed from the first to the second periods because of base closings, reduction in airfield operating hours, and availability of observers. Monthly sampling for the second period is less complete than for the first period when observations were taken during 94% of the possible time slots. During 1998-99, observations were taken in 75% of the possible time slots with only 31% and 44% during March and February 1999 and up to 94% during April 1998. Observations during the second period ranged from only 1 month at Whiteman AFB to 12 months at Beale, McChord, Shaw, and Tinker AFBs. Since these are daytime data, the number of samples per day varied with season.

Each observation is classified into one of four categories: no contrails, non-persistent contrails, persistent contrails (PC), and indeterminate. Additionally, each classification was qualified as being with or without cirrus. Finally, the contrail observations were not always taken resulting in a no-observation category. The indeterminate category is a result of obscuration of the upper troposphere by haze or clouds. A non-persistent or short-lived contrail is defined as one that tends to evaporate and extends only a short distance from the aircraft. A PC extends at least several miles behind the aircraft and shows no dissipation during the observational time. Older PCs that have spread and cannot be linked to an aircraft might not have been recorded as contrails. Older contrails can develop into cirrus clouds that are unrecognizable as contrails [*Minnis et al*. 1998]. Thus, these estimates represent a minimum for PC occurrence.

Monthly and hourly means were computed to determine the seasonal and diurnal variations of these categories for each site. The same statistics were also computed with indeterminate data excluded. These latter results, which implicitly assume that the contrail probabilities are the same in normal and indeterminate conditions, are assumed to be more representative of the true frequencies of contrail occurrence. *Minnis et al.* [1997] provide a more detailed description of the data, sampling, and averaging. Due to reduced sampling during 1998-99, averages were also computed separately for the 13 sites and the respective months that were common to both periods.

Results

Figure 2 shows the mean PC frequencies computed relative to the total number of observations and to the number of samples excluding indeterminate data. The stations are ordered from north to south in the figure. The mean PC occurrence excluding the indeterminate data is 11.2%, a value 29% greater than the 8.7% frequency relative to the total number of observations. Hereafter, only the PC frequencies computed without the indeterminate data are considered unless otherwise noted. The mean values range from a minimum of 1.5% at Rucker AFB to 29.6% at Wright-Patterson AFB. Data were taken during only 4 months at Rucker and 10 months at Wright-Patterson. The PC frequency based on 10 months of data taken at Eglin AFB, approximately 100 km southwest of Rucker, was 6.6% suggesting that the 4 months of data at Rucker AFB are not a particularly good representation of the annual mean. The greatest change between the 1993-94 and 1998-99 datasets was seen at Luke AFB, where the PC frequency increases from 5.4% to 13.1% in the latter period.

Short-lived non-persistent contrails were seen in 4% of the no-indeterminate observations yielding a mean total contrail frequency of 15.4% for all of the sites. Non-persistent contrails have negligible impact on climate. Cirrus clouds were observed simultaneously with PCs 93% of the time compared to 79% of the time during 1993-94. Overall, the mean PC frequency during 1998-99 is only 74% of the 15.2% found for the first period.

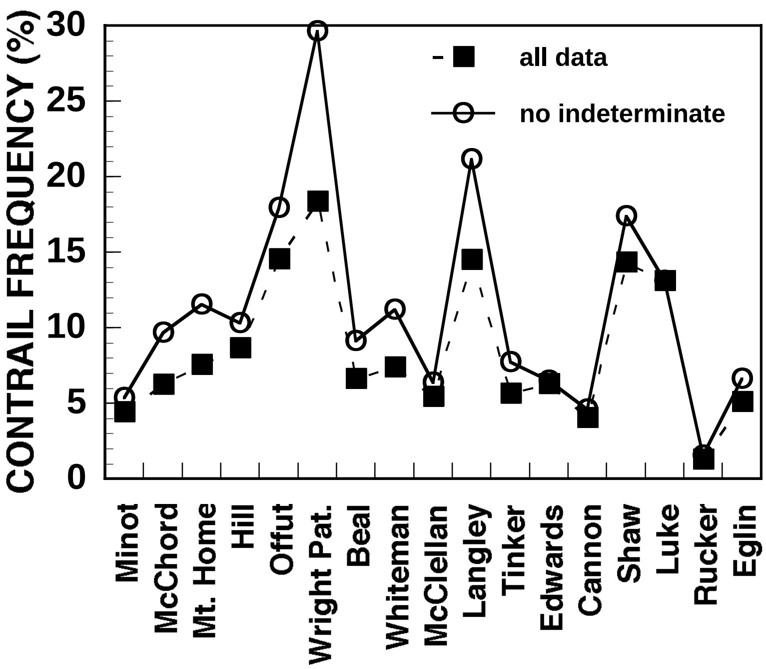

Figure 2. Mean PC frequencies during 1998-99 observing period.

The 1998-99 monthly mean PC frequency in Figure 3 shows a maximum during February and a minimum during September. In general, PCs occur least often during summer and most often during winter. These results are similar to those for the first period when maximum and minimum frequencies were observed during February and July, respectively. To ensure that sampling differences do not cause the interannual change in PC frequencies, monthly means were computed using only the sites and months with observations common to both years. Means computed using those criteria, shown as open symbols in Figure 3, were less in 1998 than during 1993, except for January and August. The seasonal variations are similar to the 1998-99 average. The mean values for the first and second periods with common months are 13.4% and 11.5%, yielding a smaller difference between the two periods than computed using a straight average of all data from both periods. The larger difference is likely due to biased seasonal sampling. To account for the sampling differences for all regions, an adjusted annual mean value of 14.0% was computed for 1993-94 using the monthly mean PC frequencies for the first period weighted by the number of monthly samples for the second period. The ratio of the original 1993-94 mean PC frequency to the adjusted mean provides a seasonal adjustment factor of 1.086 that, when multiplied by the 1998-99 mean, yields a seasonally adjusted annual mean of 12.2% for 1998-99. Thus, the true decrease in PC frequency between 1993 and 1998 is probably closer to 20% ([15.2-12.2]/15.2) than the 25% computed from the actual sampling.

Mean PC frequency is plotted as a function of local time in Figure 4. The frequency increases from 0600 LT until 0900 LT when it peaks at ~12.5% and then slowly decreases down to ~10% by 1700 LT. Persistent contrail occurrence then drops to 8% for the remainder of the daylight period. In relative terms, this diurnal variation is nearly identical to that seen in the 1993-94 data. The increasing frequencies early in the morning are consistent with the daily cycle of flights that begins around sunrise. Without better flight information, however, it is not clear that the decreased numbers of contrails after 1600 LT are the result of reduced air traffic or a sampling bias characterized by observations taken only during the summer months when the mean contrail coverage is reduced. To explore this issue, the mean hourly PC occurrences were computed using only those months and sites with averages at all hours between 0600 and 1900 LT. The results, normalized to the seasonally adjusted annual mean, are shown as open symbols in Figure 4. The peak shifted slightly to 0800 LT and the sudden decrease in the evening disappears indicating that the air traffic remains steady through 1900 LT. The frequency drop seen in the all-data results is apparently due to the seasonal sampling bias that precludes evening observations during autumn and winter.

Minnis et al. [1997] showed that the distribution of contrail frequency was related to the aircraft fuel use above 7 km, f. Between 1994 and 1997, it is estimated that the air traffic increased at a rate of roughly 5%/year over the CONUS [*ICAO* 1998]. Thus, the fuel usage should have increased by 28% from 1993 to 1998. To correlate fuel use with the current dataset, the dataset that was used by *Minnis et al.* [1997] was increased by 28%. The 1998-99 PC frequencies were adjusted for the seasonal sampling bias noted earlier. The resulting scatterplot and linear least squares regression fit (forced through the origin) between the adjusted 1998-99 mean PC frequency of occurrence, PC, and f in Figure 5 show that the two parameters are well-correlated. The linear correlation coefficient is 0.705. Although the slope of the line is 30% less than found for the first period, the level of correlation is nearly the same indicating that the patterns have not changed significantly during the interim. The fuel use data explain about half of the spatial variation in contrail occurrence.

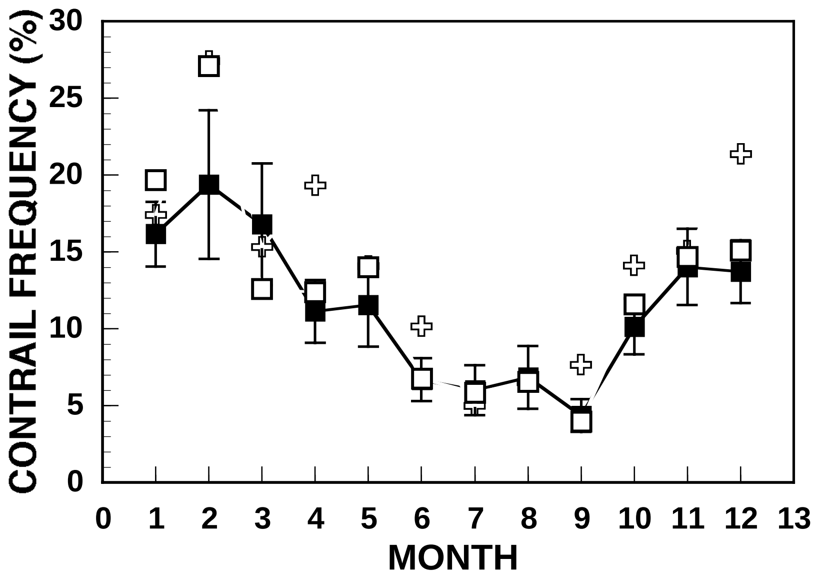

Figure 3. Mean PC frequencies during 1993-94 (cross) 1998-99 (squares) observing period. Solid symbols, all data. Open symbols, matched data only.

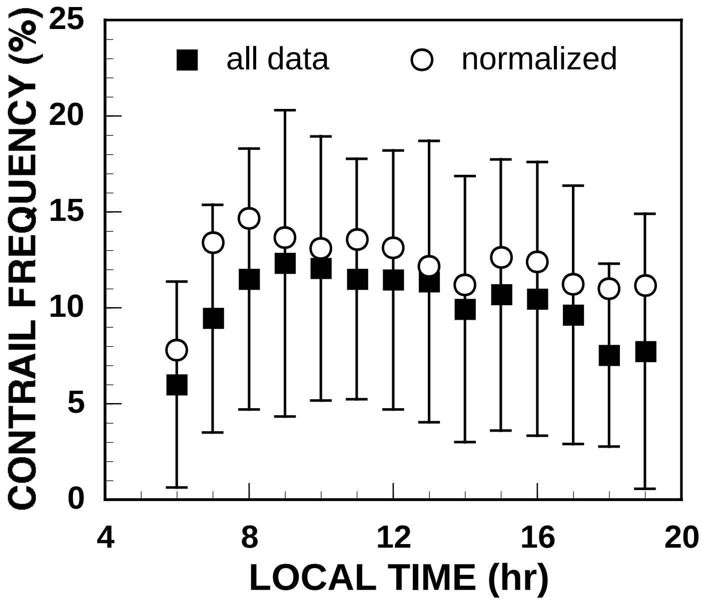

Figure. 4. Mean hourly PC frequency for all regions, 1998-99. Error bars indicate the regional standard deviation.

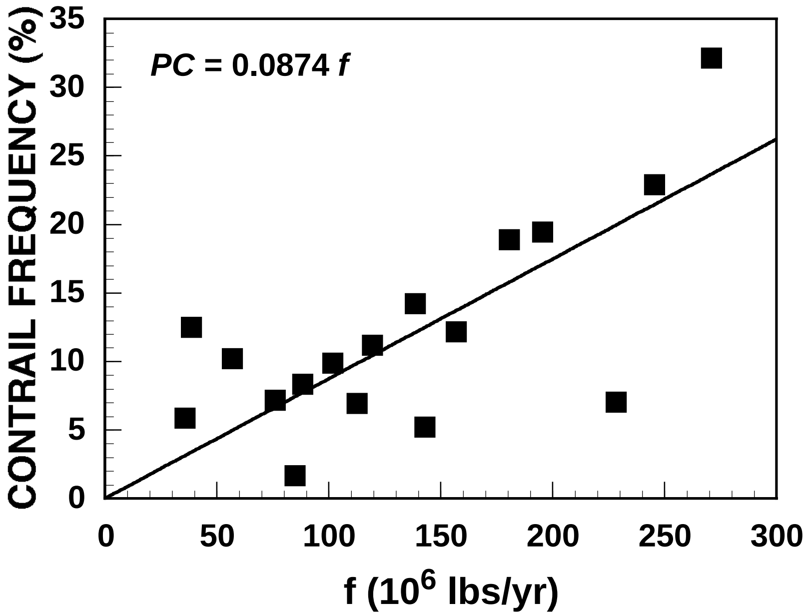

Figure 5. Correlation of seasonally adjusted mean PC frequency at each site and estimated 1998-99 fuel use above 7 km for a 3° region centered on each site.

Discussion

If the original fuel data set were used in the correlation in Figure 5, the resulting slope would still be 12% smaller than that for 1993-94 indicating that the change between the two years is significant. The frequency of PC occurrence should have been larger during the second period than during the first if all other factors were equal. The primary parameters determining persistent contrail occurrence are the air traffic density and the temperatures and relative humidities RH at flight levels. As a proxy for detailed assessment of RH at each location, the mean RHs and temperatures at 300 hPa (the greatest altitude with humidity data) were computed for the CONUS for both periods using the monthly mean 2.5° regional values from National Centers for Environmental Prediction reanalyses [*Kistler et al.* 2001]. During the first period, the mean RH at 300 hPa was 45.8% compared to 38.2% during 1998-99. Furthermore, the monthly mean RH exceeded 50% in 40.5% of the regional data during 1993-94 compared to 17% during the latter period. Mean temperatures at 300 hPa increased by only 0.5°C between the two periods. The driest year between 1971 and 2001 at 300 hPa was 1999, while 1998 was the third driest year. The seventh and second wettest years were 1993 and 1994, respectively, at 300 hPa during that same window. Thus, it is concluded that the conditions favorable for PC formation during the second period were much less likely than for 1993-94 resulting in a decrease in PC frequency, despite an increase in jet air traffic.

Because these two periods represent extremes for RH at 300 hPa, the more likely mean condition for PC frequency would be closer to the average for the two observation periods in Figure 6. The average maximum in late winter is nearly four times greater than the summertime minimum. Both theoretical [*Sausen et al.* 1998] and empirical [*Mannstein et al.* 2000] estimates of contrail coverage and satellite-derived contrail frequencies [*DeGrand et al.* 2000] yield a minimum during July, consistent with the broad summertime minimum seen here. *Sausen et al.* [1998] report a 400% increase in coverage from the July minimum to their April maximum, while *DeGrand et al.* [2000] find a 40% increase in frequency between July and their October maximum. *Mannstein et al.* [2000] obtained a factor-of-two difference in coverage between July and their December maximum (January was not analyzed). *Sausen et al.* [1998] and *DeGrand et al.* [2000] find larger values for both coverage and frequency, respectively, during April than during January over the USA. The *Sausen et al.* [1998] mean coverage during January and October are the same, while Figure 6 suggests that the contrail occurrence steadily increases between October and February. The *Mannstein et al.* [2000] results from 1993 satellite data are qualitatively consistent with the surface observations of *Minnis et al.* [1997]. For April, October, and December, their respective contrail coverage percentages were 2.0, 1.9, and 2.1%, while the contrail frequencies for the 13 sites having measurements during all 3 months during 1993 were 18.8, 16.3, and 19.7%. *Minnis et al.* [1997] discussed several possible reasons for the discrepancies with the *DeGrand et al.* [2000] results. Another possibility is that, during winter, contrails over the USA might spread less and have lower optical depths than during other seasons [*Ponater et al.* 2002] making it more difficult to detect them in infrared imagery. In addition to the shortcomings in the surface observations noted by *Minnis et al.* [1997], the differences between the theoretical results and the surface observations could arise from the highly uncertain humidities in the upper troposphere used in the model [*Sausen et al.* 1998].

To determine if the results in Figure 6 are misrepresentative because of sampling deficiencies, mean values of PC were computed for January, April, and October using data from both periods for any site having observations during all 3 months. Overall, the mean values were 17.3, 14.8, and 12.1% for the respective months. The data were also averaged zonally for the 3 months to

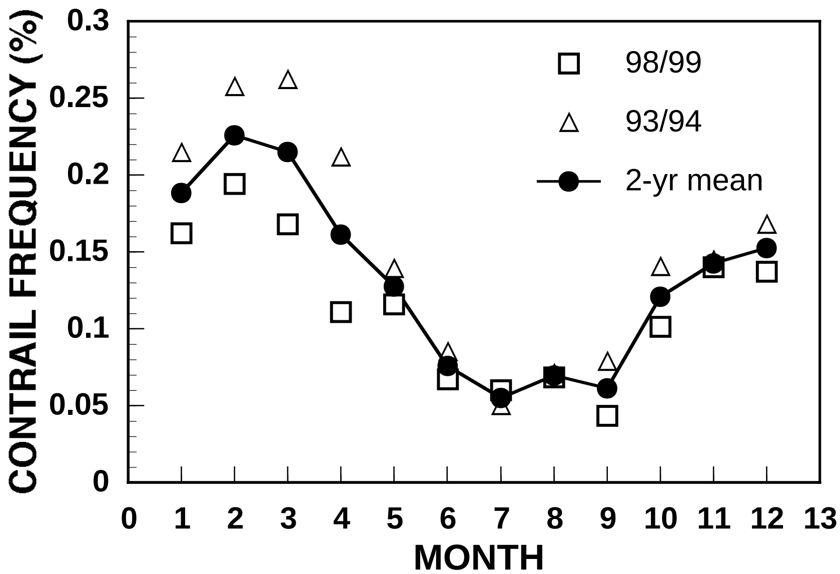

Figure 6. Same as Figure 3, except for combined 1993-94 and 1998-99 datasets.

correspond to the contrail frequency averages given by *DeGrand et al.* [2000]. The maximum value of mean PC frequency occurred during January in the two zones defined by 28.5°N-37.5°N and 37.5°N and 46.5°N. An April maximum was found for the regions north of 46.5°N. The PC frequency was least during October for all 3 zones, a finding consistent with the climatological minimum in cirrus coverage during October [*Minnis et al.* 1997]. Finally, using 10 years of fisheye camera data, *Sassen* [1997] found a maximum in contrail frequency during February over Salt Lake City, Utah, a result consistent with the February maximum over Hill AFB just north of Salt Lake City. From these results and the comparisons with *Mannstein et al.* [2000], it is concluded that the annual cycle of PC frequency in Figure 6 is representative of the USA as a whole. However, it should be noted that the mean seasonal variation of PCs changes with latitude and the frequency of PCs in any given month can differ significantly from the mean variation in Figure 6.

Concluding Remarks

As defined here, contrail frequency provides no information about the number of contrails observed each hour or their thickness and areal coverage. An increase in the number of flights may result in more contrails each hour rather than more hours with contrails. The number of hours when persistent contrails can form is limited by the amount of time that the formation conditions exist over a given site. Thus, the decreased frequency of persistent contrails during 1998-99 might be accompanied by a greater number of contrails within each observation period. It is clear, however, that at least a portion of the frequency decrease is the result of fewer formation opportunities because of reduced humidity at flight levels.

When combined with the results from 1993-94, the data reported here provide valuable independent information on the hourly, seasonal, and interannual variability of persistent contrails. Model estimates of contrail effects on climate should be capable of reproducing, at some level, the variations over a wide range of temporal scales. Because the individual observations are available, it should also be possible to use the data to verify observed and modeled upper tropospheric humidity. Predictions of potential contrail formation conditions can also be validated with the observations from both periods, especially when combined with information about flight times and altitudes.

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