EVIDENCE OF JET CONTRAIL INFLUENCES ON REGIONAL-SCALE DIURNAL TEMPERATURE RANGE

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Abstract. The occurrence of jet contrails at relatively high altitudes in combination with their unique microphysical structure gives them a strong ability to reduce diurnal temperature range (DTR) in regions where they are most frequent. This study attempts to quantify this effect by analyzing trends in diurnal temperature range for a 60 year period (1930-90) for the coterminous U.S. The results, in general, support the hypothesis with the greatest associations between jet contrail coverage and decreases in DTR found for the "Southwest" and "Northwest" regions of the U.S. and for the Summer and Fall seasons. A case study analysis also supports the hypothesis.

1. INTRODUCTION

Jet condensation trails (contrails) have the potential to reduce diurnal temperature range (DTR) due to their unique microphysical characteristics and their location at relatively high altitudes in the troposphere. The high altitude location allows them to act similarly to natural cirrus clouds and efficiently trap outgoing longwave radiation, especially at night, thus producing a nighttime "warming" effect in the atmosphere. However, this influence is somewhat offset during the daytime since contrails efficiently absorb and/or reflect solar radiation. The ability of contrails to efficiently block solar radiation is attributed to their relatively high optical thickness at the solar wavelengths, which is a result of the large number of small ice crystals (< 100 μm) that make up contrails, and resultant greater optical depth, compared to the relatively small number of large ice crystals that comprise natural cirrus (Mulcray, 1970). Though the net influence of these competing effects, when averaged across 24 hours, is probably close to zero (Travis, 1994), their influence on temperature *range* should result in an overall reduction of DTR.

Though jet contrail coverage is not considered sufficient to have a large radiative influence on a global scale, they may play an important regional-scale role where they are most abundant. Recent studies investigating changes in DTR have reported regional-scale decreases in the U.S. and elsewhere during the 20th century (Karl *et. al*, 1993). It is possible that contrails may have contributed to this decrease, especially within those regions favored by a high density of jet traffic where contrails can occur and persist in large groups continuously for extended periods (e.g. the U.S. Midwest). Similarities in the regional-scale nature of the DTR decreases and the peak locations of contrail occurrence would suggest a link between the two. The primary objective of this study is to investigate this hypothesis. This is achieved through two separate analyses: The first uses long-term trends (past 60 years) of DTR in the United States and compares data for two periods, one immediately prior to and the other immediately following the rapid increase of contrail coverage which began in the early 1960's as indicated by the corresponding increase in jet fuel usage (Beckwith, 1972). Though this method does not account for all possible natural or anthropogenic causes of DTR change such as global warming, urban heat islands, and land use changes (Kukla and Karl, 1993), it does provide an opportunity to study the potential longterm influences of contrails on DTR at regional scales and speculate on the future impacts of continued increases in contrail coverage. The second method follows a "case study" approach to determine the influences on DTR caused by an individual "outbreak", or large group, of contrails persisting over a specific region of the United States for an extended period (i.e. greater than 12 hours). This approach allows a detailed determination of the influence that the contrails may have had on DTR within the affected region. The latter analysis was completed by studying a combination of hourly surface data and high-resolution satellite imagery corresponding to the time of the contrail outbreak and the affected region.

2. METHODS OF DATA COLLECTION

2.1 Acquisition of Climate and Satellite Data

A major component of this study was devoted to data acquisition and their preparation for analysis. This was necessary due to the unique nature of the variable being studied (contrails), and differences in the spatial characteristics of the DTR observations and the contrail coverage observations. Hence, it was necessary to obtain an extensive range of climatological datasets that included surface observations from most first-order, second-order, and cooperative weather- observing sites for the U.S (1894-1994). These were obtained on a total of three compact discs and eight magnetic tapes from the National Climate Data Center (NCDC). The data had been archived by NCDC from a total of 3,656 stations, including 318 National Weather Service (NWS) first order stations. Prior to purchase, all of the data had been corrected and standardized to remove potential biases related to (1) differences in observation times, (2) missing observations, and (3) inhomogeneous records primarily related to stations relocating within the period of record. Additional correction factors had been applied to many of the NWS first-order stations to account for variations in urban influences on the station record (e.g. urban heat island, exposure, etc.). Such adjustments ensured maximum consistency between the first order stations and the cooperative stations.

Two periods of climatological data were of greatest interest for this study. These were the periods 1931-60 and 1961-90. These periods were selected for comparison because they represent the two climatological "normal" periods closest to the early 1960s when contrail coverage rapidly increased. By comparing the "normals" for the 1931-60 period with those of the 1961-90 period, and considering where contrail coverage was greatest during the 1961-90 period, it was possible to test the aforementioned hypothesis. Also, by comparing data from two adjacent periods the influences of other anthropogenic (e.g. greenhouse gases, land-use changes, etc.) or natural sources of climate change were minimized.

Satellite data were required for the case study analysis. Digital and hard copy images corresponding to the mid-season months of 1987 (January, April, July, October) were utilized. The data consisted of daily hard copy swaths of Defense Meteorological Satellite Program (DMSP) imagery (2.6 km resolution) and Advanced Very High Resolution Radiometer (AVHRR) digital imagery (1.1 km resolution). The DMSP data were inspected manually for "outbreaks" of extensive contrail coverage of contrails over a specific region for an extended period and then the AVHRR analyzed in more detail (using image processing software, ERDAS, 1994) when a candidate was selected for further analysis. Approximately 3-5 images (of DMSP and AVHRR combined) per day were available.

When a candidate outbreak was selected from the satellite imagery for further analysis, it was also necessary to extract the corresponding surface climate data from the aforementioned data sets. This consisted of hourly observations for all first-order stations and maximum and minimum temperature observations for all second-order and cooperative observing sites. The data were then analyzed in correspondence with the timing of the outbreaks, as viewed on the satellite imagery, to determine possible contrail effects on DTR. A minimum of 24 hours of data (including at least one nighttime and one daytime period) were analyzed for each case.

2.2 Acquisition and Scaling of Contrail Data

A final data acquisition task was to obtain the contrail "climatology" data set from the DeGrand (1991) study. These data represent the only comprehensive analysis of contrail coverage available for the U.S. and were completed for the mid-season months of 1977-79 using DMSP (1.6 km resolution) hard copy imagery. The data then were summarized in 1 x 1 degree (latitude/longitude) grids covering the entire U.S. and adjacent coastal waters in units of the number of contrails per grid per day. Each grid value had also been standardized by considering the number of satellite image swaths available for inspection per grid per day (DeGrand, 1991).

Once the data were obtained it became necessary to scale them up to a 3 x 3 degree grid resolution. This was done to maximize spatial consistency with the climate data which did not have a sufficient density of stations to complete statistical analyses at a 1 x 1 degree resolution. Moreover, the typical size of contrail outbreaks tends to be closer to a 3 x 3 degree grid size (Carleton and Lamb, 1986). Since contrail *outbreaks* are more likely to modify DTR rather than individual contrails, this was deemed a more appropriate scale to complete the analysis. Following the scaling procedure, a total of 99 grid values of contrail coverage were available for the U.S. and adjacent coastal waters for comparison with the climate data.

The value of contrail coverage calculated for each grid was assumed to be representative of the typical amount of coverage for that grid for the entire 1961-90 period. Though it is likely that the actual amounts of coverage per grid had increased with the increase in jet traffic throughout the period, the fact that the DeGrand (1991) study was completed for the period covering 1977-79, which is approximately half way through the 1961-90 period, allowed a reasonable assumption that the values represent a fair estimate of the average contrail coverage for the entire period. Although the number of flights has increased substantially during the study period, the spatial variations in contrail coverage are likely to have remained consistent throughout the period since the flight corridors that most high altitude aircraft follow have changed little during the past 20-30 years. This was confirmed by inspecting current and historical high altitude flight navigation charts (e.g. FAA, 1996, 1986, 1976, 1966). In addition, the results of a similar study for the mid-season months of 1987 (Travis, 1994) demonstrate very close agreement with the spatial distribution of contrails found in the DeGrand (1991) study, even though it analyzed data from nearly 10 years later.

2.3 Scaling and Analysis of Climate Data

To ensure consistency with the contrail data it also was necessary to calculate 3 x 3 degree grid averages of the climate data. To accomplish this task, each of the 3,656 stations included in the analysis were assigned to one of 99 corresponding "contrail" grids based on their latitude and longitude. Once all stations were assigned a grid the values for stations within each grid were averaged to determine an overall grid value for each observation. Each of the 99 grids contained at least one station with the majority having between 3-5 stations.

Following the scaling of the climate data, average grid values of DTR were obtained for both the 1931-60 and 1961-90 periods. The DTR values were calculated by subtracting the average daily maximum and average daily minimum temperature value (listed by year and month on the CD) for each grid and then averaged to obtain a "normal" DTR value for each period. The 1931-60 DTR values were then subtracted from the 1961-90 DTR values at corresponding grid locations to obtain a change in DTR value for each grid location. This provided a new variable labeled ΔDTR, which is the measure of climate change that was used throughout this study.

2.4 Case study analysis of the contrail influences on DTR

To investigate the contrail influence on surface climate from a case-study perspective, it was important to find cases that permit, as clearly as possible, a separation of the influence of contrails from that of natural clouds or other factors that could influence DTR (e.g., soil moisture, mesoscale winds, etc.). A total of 18 "candidate" outbreaks were identified on the DMSP imagery occurring during the mid-season months of 1987. Though a sufficient number of candidates were identified, only one case matched the preset specifications for inclusion into the study (Table 1). The case study that qualified for analysis was an outbreak of contrails that occurred in the Midwest (centered over Illinois and Missouri) on April 17-18, 1987 (Travis, 1995). This outbreak persisted over the 5-state region surrounding Illinois for approximately 20 hours, which increased the potential for the contrails to modify the diurnal

TABLE 1: *Summary of Qualifications for a Contrail Outbreak to be Included in the Analysis*

CHARACTERISTIC OF OUTBREAK	QUALIFICATION LEVEL
Duration	> 12 Hours
Size	> 300 km Diameter
Amount of Natural Cloud	< 25% of Total Cloud/Contrail Combined
Time of Last Precipitation Event	> 48 Hours Prior

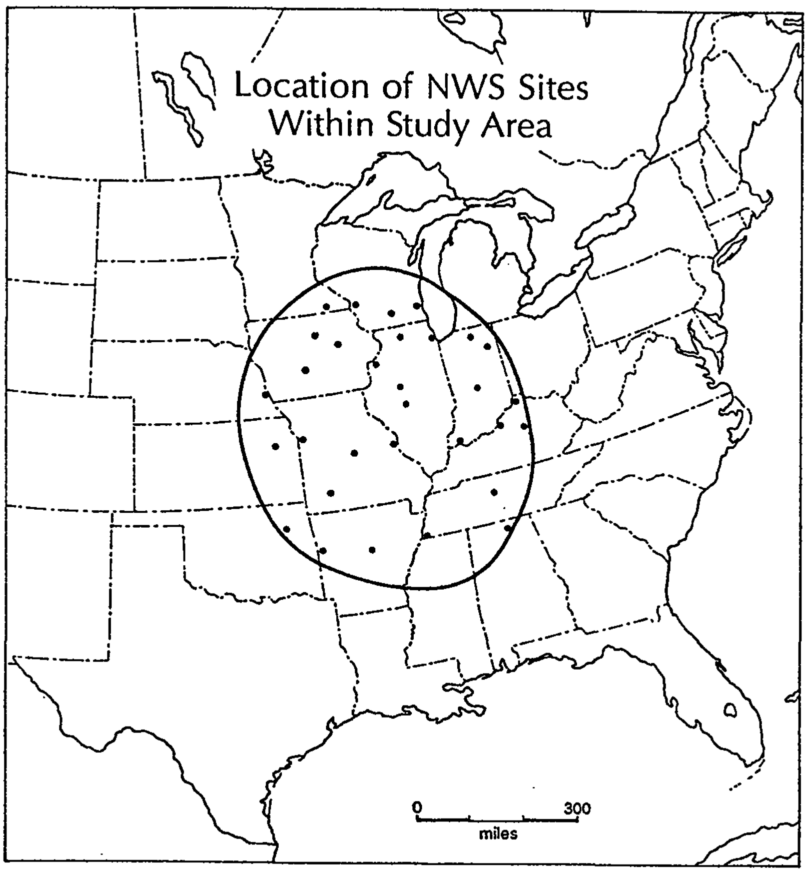

FIGURE 1: *Locations of the contrail "outbreak" region and available NWS stations for April 18, 1987.*

temperature range within the region due to their persistence and widespread coverage. The location of the outbreak of contrails was determined by analyzing a combination of one DMSP "hard copy" image and three AVHRR digital images, all for April 18, 1987. Both the DMSP and the AVHRR imagery provide sufficient pixel resolution to study persisting contrails (Carleton and Lamb, 1986). Images from each satellite overpass (8:50am, 10:00am, 3:15pm, and 8:10pm local time) were utilized to identify the location of contrails and then composited to determine the overall area influenced by jet contrails during this particular day (Fig. 1). It was possible to enhance the contrail signal for two of the AVHRR images by utilizing the "split-window IR" method (Lee,1989).

To minimize the potential bias introduced by the clustering of observing sites, point values of DTR were transformed into 3° x 3° grid values for the study area. When more than one site was located within a single grid, the average DTR value was calculated from all point values within the grid. A total of 16 grid values were determined, with at least one site located within each. Contouring was then completed, at a 1° C interval, from the midpoint of each grid.

3. RESULTS

3.1 Tests for Correlations between ΔDTR and Contrail Coverage

To test the hypothesis that contrail coverage had reduced DTR, statistical tests were completed between ΔDTR and the scaled contrail data set (DeGrand, 1991). Since the primary purpose of this study was to explore potential relationships between contrails and changes in DTR, statistical tests were completed in two ways. The first utilized Pearson correlation tests to determine if ΔDTR was negatively correlated with the amount of contrail coverage for each grid. This analysis was completed first by considering all of the grids for the U.S., and then second by stratifying the data set according to geographic region (northeast, northwest, southeast, southwest). This provided a means to identify the regions of the U.S. that were most sensitive to contrail influences. The "regions" were defined by subdividing the contiguous U.S. into four approximately equal quarters divided by the 40° N latitude parallel and the 100°W longitude meridian with no specific consideration for physical boundaries. The contrail and DTR data were also stratified by season to study the importance of seasonality on the magnitude of a contrail-DTR relationship. Seasons were defined using the standard 3-month meteorological definition for each (i.e. Winter: December, January, February; Spring: March, April, May; etc.).

Table 2 provides the results of the Pearson correlation analysis and level of significance (p-value) of the relationships between contrail coverage and ΔDTR for all seasons combined and stratified by season. The corresponding scatterplot for all seasons can be seen in Figure 2. The relationship is strongest for the Summer and Fall seasons. The greater abundance of days with clear sky conditions that exists over a large portion of the U.S. during those seasons is likely responsible for the increased importance of contrails during that time of the year. Without the influence of contrails (i.e. prior to 1960) there may have been a higher percentage of cloudfree days (and nights) and a greater likelihood for a larger DTR. Hence, the Summer and Fall seasons should be expected to be more sensitive to the influence of a contrail-induced increase in cloud cover than the Winter and Spring seasons where a greater abundance of natural cloudiness typically exists due to increased jet stream activity. These results concur with those found by Changnon (1981) where the influence of contrails over the Midwest United States was greatest during the Fall season.

Though all relationships between contrail coverage and ΔDTR are negative, which supports the primary hypothesis of this study, the r-values for the Winter and Spring seasons are low and not statistically significant (p-values are greater than 0.05). This may be a result of the influence of the contrails on DTR being overwhelmed by the influences of larger scale sources of climatic variability which provide much greater forcing mechanisms for DTR change (e.g. ENSO, greenhouse gases, natural cloud changes, etc.). Nevertheless, the overall association when all seasons are combined is reasonably good and still statistically significant.

TABLE 2: ***Results of the Pearson correlation analysis of contrails and DTR change by season.***

Season	r-value	p-value	N
All	-0.22	0.03	99
Winter	-0.11	0.30	94*
Spring	-0.01	0.90	99
Summer	-0.27	0.01	99
Fall	-0.29	0.01	99

*** The winter season data had 5 missing values.**

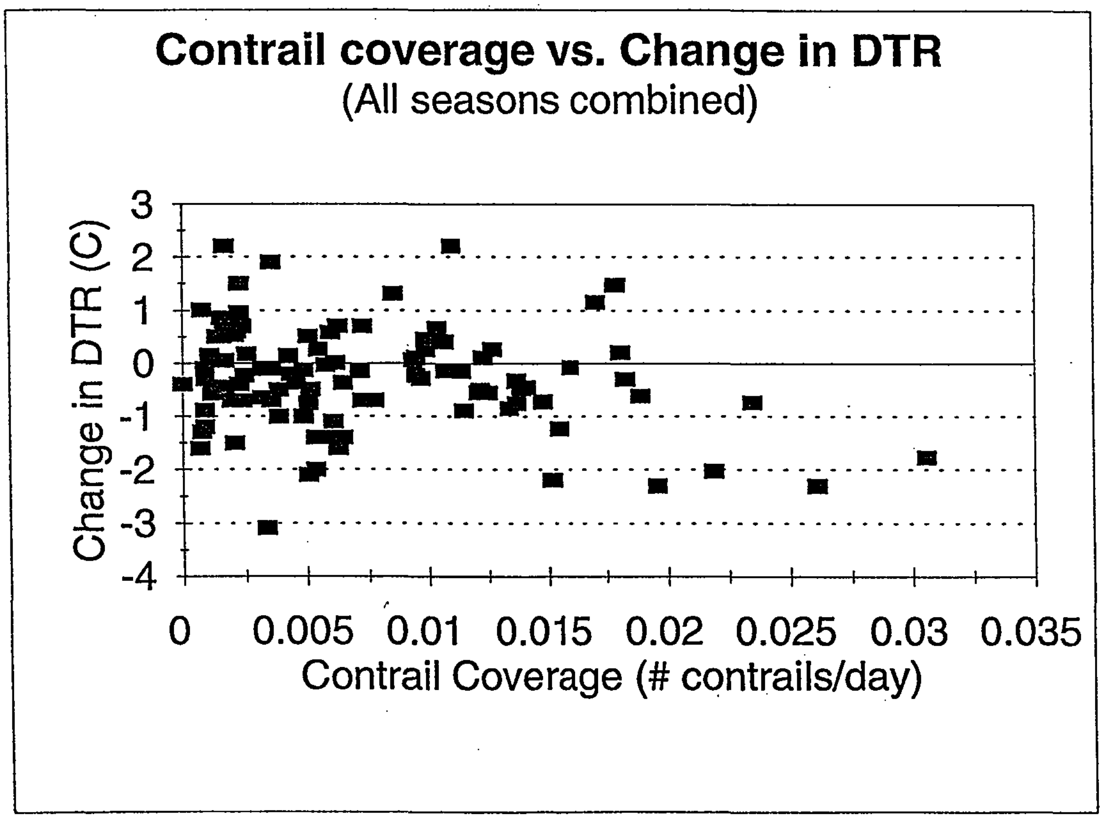

FIGURE 2: ***Scatterplot of the relationship between contrail coverage and DTR change for all seasons.***

Correlation coefficients of contrail coverage versus ΔDTR stratified by region (and repeated for the entire U.S.) are summarized in Table 3. In all cases but the "Southeast" region, there is a negative slope to the relationship, thus, once again supporting the hypothesis that increased contrail coverage has produced a decrease in DTR for much of the U.S. However, not all of the relationships are statistically significant.

The best association between ΔDTR and contrail coverage is for the "Southwest" region of the U.S., with a relatively weak but still statistically significant negative relationship when all regions are combined. The strong association between ΔDTR and contrail coverage for the "Southwest" region can be explained once again by the abundance of clear sky conditions that tend to prevail in that region of the U.S. where typically large values of DTR would be expected to naturally occur. The region would also, therefore, be most sensitive to any increase in clouds provided by jet contrail coverage. A similar effect would also be expected in the "Northwest" portion of the U.S., at least during the warm season, which is usually accompanied by an extended period of dry conditions. This region too would, therefore, be more sensitive than other regions to any increase in clouds provided by jet contrail coverage. This may explain the relatively high R-value between contrail coverage and DTR in that region (-0.35).

This lack of a distinct dry season characterized by a large number of cloudfree days for the remainder of the U.S. provides a possible explanation for the relatively poor fit of the two eastern regions of the U.S. which are dominantly influenced by moisture from the Gulf of Mexico and/or the Atlantic Ocean throughout most of the year.

3.2 Difference of Means Testing

A second statistical method, difference-of-means testing, was utilized to assess possible influences of contrail coverage on DTR. This was done by simply determining the mean ΔDTR for each 3 x 3 degree "contrail grid", characterized by a relatively large amount of contrail coverage, and then comparing that to the mean ΔDTR for the "non-contrail grids", characterized as having a negligible amount of contrail coverage. In this study, "contrail grids" were defined as those containing 0.01 or greater contrails/grid/100 images. This threshold value was determined by comparing the average amount of contrail coverage in each of the peak regions in the U.S., as identified in the DeGrand (1991) study, to that amount found in less favored regions. Each of the peak areas contained values in excess of 0.01 contrails/grid/100 images, while most other areas that contained contrails had much less than that amount. This follows our contention that a contrail influence on DTR should be most evident within the flight corridor regions. Though contrails can occur anywhere in the U.S., it is unlikely that they will have an important climatic influence unless they occur regularly and in clusters. The cutoff of 0.01 contrails/grid/100 images provided the largest statistical separation between the peak areas and the remainder of the U.S. Using this method, a total of 69 grid points were placed into the non-contrail category with the remaining 30 grid points classified as having sufficient contrail coverage to most likely have an influence on DTR (i.e. greater than 0.01 contrails/grid/100 images).

The average value of ΔDTR for grids containing greater than 0.01 contrails/day, and for those containing a negligible amount, is summarized by season (and for the entire U.S.) in Table 4 along with standard deviation values (in parentheses). Since the overriding hypothesis of this study states that abundant contrail coverage should only produce a *decrease* in DTR, a one-tailed t-test was completed only for those seasons where the ΔDTR was less (more negative or less positive) for the contrail grids than for the non-contrail grids. As a result, no tests were completed for the Winter and Spring seasons. A statistically significant difference of means was found for the Fall season ($p > t = 0.05$) with a moderately strong difference between contrail and non-contrail grids for the Summer season. Though the direction of the annual value of ΔDTR supports the hypothesis at -0.37, the difference is not statistically significant due to the poor relationship found for the Winter and Spring seasons. This follows previous results since those seasons are typically the cloudiest in the U.S. and contrails

TABLE 3: ***Results of the Pearson correlation analysis of contrails and DTR change by region.***

Region	r-value	p-value	N
All	-0.22	0.03	99
NW	-0.35	0.09	24
NE	-0.12	0.58	25
SE	0.07	0.71	24
SW	-0.48	0.01	26

should not be expected to have an important influence on DTR during that time of year.

The strength of the Summer and Fall results reinforces the importance of considering the contrail influence on DTR from a seasonal perspective rather than just on annual time scales. Moreover, these results, when considered in combination with those of the previous section, support the contention that subsequent investigations into contrail-DTR relationships should focus on arid or semi-arid regions during dominantly cloudfree seasons.

3.3. Influences of a Single "Contrail Outbreak" on Surface DTR

A contour map of DTR for April 18, 1987 for the study area is presented in Fig. 3. Results indicate that the smallest DTR values occurred near the center of the study area with a gradual increase in DTR away from the center, especially to the north and south. The difference between the gridded DTR values between the center and those near the outer edges of the area covered by the contrails is approximately 4-6° C. It is worthy to note that some of the cooperative stations near the center of the study area (i.e. Illinois and Missouri) had DTR values of less than 10 °C but these extreme values were lost in the averaging procedure.

Analysis of the satellite imagery indicated that the overall coverage of contrails, during the entire 24-hour period, is most likely to have been greatest near the center of the study area. This result seems to support the hypothesis that persisting contrails can significantly reduce DTR. To ensure that the pattern of DTR was not simply a result of natural cloud cover, a Pearson correlation calculation was computed between total (24 hour) cloud amount (determined from hourly observations) and DTR for each of the 31 NWS stations in the study area (cloud cover data was not available for other observation sites). No significant correlation was found (r=0.04).

Clearly, more case study analyses of this type are required before the decrease in DTR seen in this one example can conclusively be attributed to the influence of contrails. However, these results provide strong circumstantial evidence that contrails may significantly reduce DTR, at least during situations when the influences of other important atmospheric and surface controls on DTR are negligible (e.g., natural cloud cover, surface moisture, etc.).

4. SUMMARY

This study has provided statistical evidence suggesting a link between jet contrail coverage and a decrease in DTR in the U.S. This relationship has been shown both via climatological analyses of DTR trends during the period 1930-1990 and through a case study analysis of an "outbreak" of contrails occurring over the U.S. Midwest on April 18, 1987.

TABLE 4: ***Results of the differences of means tests between "contrail" and "non-contrail" grids by season.***

Season	DTR Change (°C) for "Non-Contrail" Grids	DTR Change (°C) for "Contrail" Grids	t-value Between Grids	p > t Between Grids
Annual	-0.26 (0.95)	-0.37 (1.03)	0.50	0.30
Winter	0.08 (1.10)	0.21 (1.13)	-	-
Spring	-0.02 (1.08)	0.09 (0.67)	-	-
Summer	-0.31 (1.34)	-0.62 (0.98)	1.29	0.10
Fall	-0.71 (0.94)	-1.07 (1.36)	1.54	0.05

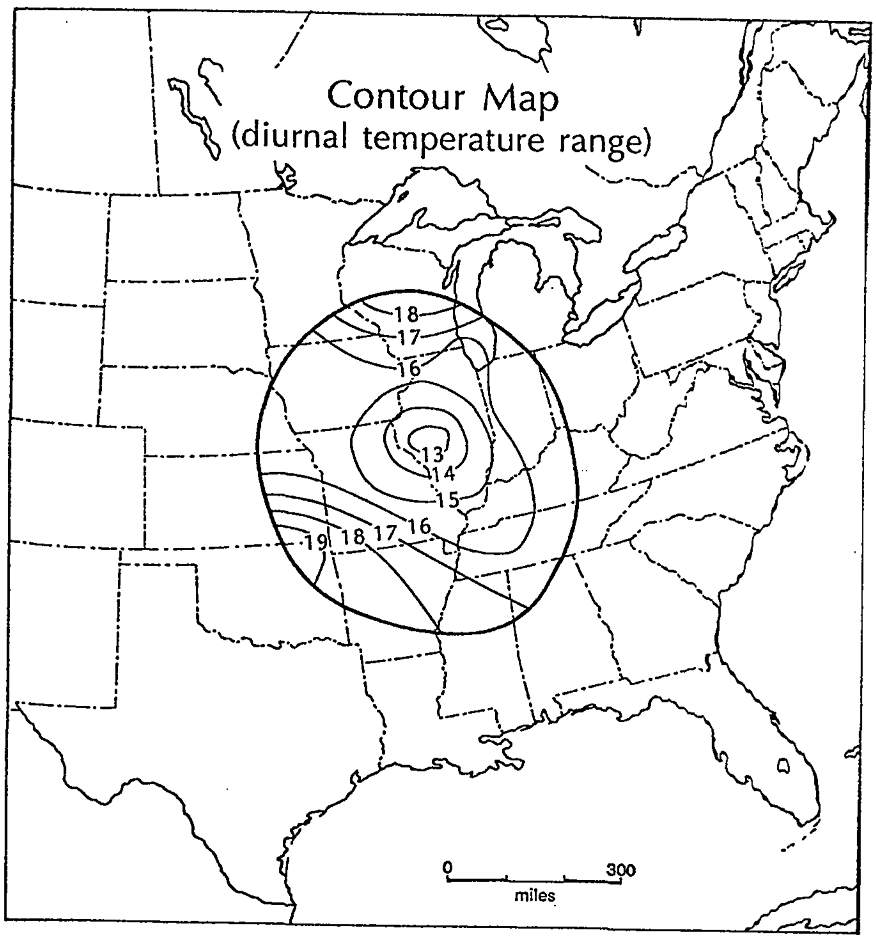

FIGURE 3: ***Contour map of DTR (at 1 degree Celsius intervals).***

The climatological analysis demonstrates the contrail influence is strongest for the "Southwest" and "Northwest" regions of the U.S. and most dominant during the Summer and Fall seasons. Though the influence of contrails on DTR is not statistically significant for the other regions of the U.S., nor during other seasons, the consistency of a negative relationship between contrail coverage and changes in DTR in nearly all cases provides justification for further investigations.

The results of this study suggest that continued increases in jet contrail coverage may result in a continued decrease in DTR across heavily populated regions. Although further analyses are required to confirm the contrail-DTR relationships demonstrated in this study, these results have implications on studies attempting to quantify the magnitude of other anthropogenic sources of regional climate change (e.g. urban warming, land use changes, etc.). It may also be pertinent to reconsider the influence that increasing contrail coverage has on heating and cooling costs as DTR is decreased (as in Detwiler and Pratt, 1984).

The next step to this research for the authors is to further quantify the influence of contrails on DTR by comparing surface observations of temperature from within the flight corridors to those outside the corridors.

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