Variations in Contrail Morphology and Relationships To Atmospheric Conditions

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Abstract. The typical morphology of jet condensation trails (contrails) is not well understood, primarily due to the lack of in situ observations and the limitations imposed on surface observations and hard copy satellite imagery. This study utilizes digital satellite data to determine the characteristic morphology of contrails and their variation as a function of time of day (or night), amount of natural cloud cover, and atmospheric conditions at contrail altitudes. The analysis is undertaken utilizing the NOAA AVHRR digital satellite data. A total of 1018 contrails, occurring during the mid-season months of 1987 (January, April, July, October), are studied for their length, width, and areal coverage characteristics. Results demonstrate that the widest contrails tend to occur during the nighttime hours. Contrails are longest and tend to have their greatest areal coverage when occurring in cirrus shields. Additional relationships between contrail widths and atmospheric conditions within the 300-100mb layer are presented.

1. INTRODUCTION

Surface-based observations of cloud amount suggest recent marked variations on annual and decadal time scales worldwide. In particular, increases in cloudiness have been noted for Europe, North America, India, and Australia during the 20th century (Karl and Steurer, 1990; Henderson-Sellers, 1992). These general increases in cloud cover are most notable at regional scales (Machta and Carpenter, 1971; Changnon, 1981), suggesting that the changes in cloud cover have been produced by meso to synoptic scale mechanisms rather than larger scale hemispheric or global processes. In addition, the increase in clouds has not been matched by a significant decrease in total sunshine for the same period, which suggests that a majority of the increase is due to high clouds (Angell, 1990). Thus, a need exists to further examine the source and potential climatic influences of the apparent increase in high cloudiness.

Jet condensation trails (contrails) have long been suspected of being an important contributor to the changes in high cloud content in regions experiencing a high density of air traffic (Machta and Carpenter, 1971; Lee and Johnson, 1985; Seaver and Lee, 1987; Angell, 1990). Contrails are linear clouds, composed primarily of ice crystals, that are produced from the mixing of water vapor and particulates from jet aircraft exhaust and ambient air. When sufficient moisture exists, contrails may persist and spread through turbulent diffusion and depositional growth until they become essentially indistinguishable in appearance from natural cirrus. Thus, contrails have the potential to significantly increase the amount of high cloud cover in areas where jet aircraft overflights are frequent (Changnon, 1981). Moreover, studies of contrail frequency, using high resolution satellite imagery, have demonstrated that contrail occurrence is heavily regionalized with distinct "maximum" regions in the United States and Europe (DeGrand, 1991, Bakan *et al.*, 1994).

The objective of this study is to determine the morphological characteristics of contrails, and their variation in relation to atmospheric conditions, using Advanced Very High Resolution Radiometer (AVHRR) digital satellite data. Digital data provide an opportunity to enhance the contrail signal to enable a more complete sample and to reduce the potential biases associated with time of day and amount of natural cloud cover potentially inherent in previous studies limited to hard copy data (e.g. Detwiler and Pratt, 1984; DeGrand, 1991). The results permit one to speculate on the influence of contrails on surface climate and their contribution to anthropogenically-induced climate change.

2. Methods

2.1 Data

To achieve the aforementioned research objectives, contrails occurring over the contiguous

U.S. and adjacent coastal waters during the mid-season months of 1987, were identified for analysis using AVHRR (1.1 km resolution) digital satellite data acquired by two of the National Oceanic and Atmospheric Administration's (NOAA) polar orbiting satellites (NOAA-9 and NOAA-10). This permited consideration of possible seasonal variations in contrail morphology. Contrails are distinguishable from natural clouds in most situations due to their appearance as bright, linear features having no consistent orientation with the atmospheric circulation and often occurring in groups (e.g. Carleton and Lamb, 1986). However, contrail recognition is problematic when contrails occur coincident with natural clouds. Previous studies have indicated that contrails most commonly occur in association with natural clouds, especially cirrus shields and downwind from thunderstorm complexes (e.g. Detwiler and Pratt, 1984; DeGrand, 1991). Hence, it is appropriate to enhance the contrail spectral signature to better distinguish them from natural clouds.

Lee (1989) provides a method to enhance the contrail signature on the AVHRR through application of the "split-window infrared" method to separate contrails from natural clouds. This procedure utilizes the difference in contrail blackbody temperature between bands 4 (11 μm) and 5 (12 μm) of the AVHRR, which is greater than that for most natural clouds (Englestaad et al., 1992) due to the relatively small size of contrail ice crystals (Murcray, 1970). Hence, a subtraction of the calibrated radiance values for bands 4 and 5 yields an image with the contrail signature enhanced and most other background features masked. Erdas Imagine software (Erdas, 1993) was utilized to calibrate the raw count data and then to complete the band subtraction. The "split-window infrared" method was applied to each NOAA-9 image prior to analysis (48 scenes). The procedure could not be applied to those images from NOAA-10 since the 12 μm band is not available on that satellite. As a result, NOAA-10 images were used primarily to identify and analyze contrails occurring in clear sky situations only (36 scenes).

Hard copy image swaths of the Defense Meteorological Satellite Program (DMSP) (2.7 km resolution) were screened for the mid-season months of 1987 to determine the times and locations of potential contrail outbreaks. AVHRR images corresponding to the approximate time and location of each outbreak were subsequently obtained. Only those image swaths whose nadir points were within 5 degrees longitude of a known outbreak area were obtained. A total of 1018 contrails, occurring within 84 separate "outbreaks" identified on the AVHRR, were then analyzed to determine the characteristic contrail morphology in terms of average length, width, and areal coverage (length multiplied by width). The latter value was calculated separately for each individual contrail and then stratified according to time of day and natural cloud amount, similar to the length and width measurements.

2.2 Contrail Measurement Procedures

Sample measurements (in km) were taken of the width, length, and areal coverage of each contrail by using the Erdas software to "zoom" into each contrail body so that individual pixels could be seen on the computer screen and manually counted. The known pixel size (1.1 km) was then converted into a total distance value for each contrail. Contrail edges were defined by a pixel brightness decrease of at least 50% from the adjacent pixel of the contrail body, and were not counted in the size estimates. Since widths can vary significantly for a single contrail, depending on the distance downstream from the jet, the average width was recorded from a number of transects taken across each contrail at 10 km increments. Thus, the number of transects in each sample increased proportionally to the contrail length. For broken contrails, a width value of "0" was assumed when broken areas were sampled and then averaged with the other width samples for that particular contrail. For those contrails that were 10 km in length or smaller, the width was estimated by sampling once across the midpoint of the contrail. To minimize the influences of viewing angle (and pixel size distortion), only those contrails located near the nadir point of each image were included in the analysis.

2.3 Comparison of Contrail Widths with Atmospheric Conditions

Rawinsonde data is utilized to investigate relationships between contrail width and atmospheric conditions at contrail altitudes. The 300-100mb layer is selected for analysis because most jet aircraft cruise in the upper troposphere or lower stratosphere close to tropopause level (Beckwith, 1972). Only the 58 outbreaks identified on the AVHRR data that were deemed closest in time (within 3 hours) to the available sounding data (00:00Z, 12:00Z), were included in the analysis. The average contrail width for each outbreak was calculated from the individual contrails within, and then tested for correlation with conditions occurring within the 300-100mb layer for the same approximate time and location of the outbreaks. Data was collected at 50mb increments within the 300-100mb layer. Only rawinsonde data from stations located within the contrail outbreak area were included in the analysis. When data from more than one station was available the values were averaged.

3. Results and Discussion

3.1 Contrail Morphological Characteristics

Table 1 presents the results by time of day (i.e. by approximate time of satellite overpass) of the contrail morphological characteristics for all seasons combined (with standard deviation values in parentheses). A t-test applied to the data in Table 1 indicates that areal coverage per contrail is significantly greater ($t=4.05$; $p<0.01$) for the combined 08:00Z (NOAA-9) and 13:00Z (NOAA-10) time periods when compared to the combined 20:00Z (NOAA-9) and 00:00Z (NOAA-10) time periods. This result is particularly interesting because the 08:00Z and 13:00Z time periods correspond, in local time, to the early morning hours (between 12:00AM and 6:00AM) for a majority of the U.S. A greater size of individual contrails during these hours may partially offset the decrease in the number of contrails at night that is due to the reduction in aircraft flights. Hence, overall contrail coverage has likely been underestimated in previous studies, especially since most have based estimates exclusively on the number of flight overpasses (e.g. Manabe, 1975) or on surface-based observations taken only during the daylight hours (e.g. Wendland and Semonin, 1982) and likely assumed nighttime contrail coverage to be negligible.

Greater average contrail size at night implies the importance of atmospheric conditions influencing contrail coverage in addition to the bulk density of aircraft flights. Nocturnal cooling likely contributes to an enhancement of contrail persistence at night since areas that were close to saturation with respect to ice during the daylight hours could become saturated or supersaturated with respect to ice as temperatures decrease. The result of this process would be to encourage contrail growth and persistence via entrainment of ambient moisture (as in Knollenberg, 1972). Since contrails are commonly found in or near natural cloud regions, it is appropriate to investigate how their morphology may differ in relation to the amount of natural cloud present when they occur. The statistics on contrail morphology are stratified by sky conditions (clear, partly cloudy, cloudy) (Table 2). For a contrail to be placed into either the "cloudy" or "clear" group the entire body of the contrail had to exist within, or totally outside, a cloud, respectively; otherwise, it was not included in the analysis. Since any natural clouds occurring at contrail levels are likely to be cirriform, band 4 of the AVHRR is an appropriate source to confirm their presence or absence. In addition, natural high clouds tend to become masked when the split-window method is applied. Hence, a comparison of the raw band 4 image to the same image following application of the split-window procedure yielded relatively clear evidence of the presence or absence of natural high clouds.

TABLE 1: Summary of contrail morphology stratified by satellite overpass times.

VARIABLE	08:00Z	13:00Z	20:00Z	00:00Z
Sample Size	202	143	525	148
Length (km)	131.8 (77.4)	125.6 (75.9)	129.7 (94.7)	117.8 (50.7)
Width (km)	3.2 (2.7)	3.1 (1.8)	2.7 (1.9)	3.1 (1.5)
Area (km^2)	418.2 (196.3)	391.4 (141.6)	360.2 (180.1)	365.2 (77.2)

TABLE 2: Summary of contrail morphology stratified by cloud cover situations.

Cloud	Clear	P.Cloudy	Cloudy
Sample Size	618	104	296
Length (km)	119.1 (59.8)	123.1 (81.7)	167.0 (96.6)
Width (km)	3.0 (2.3)	3.2 (1.4)	2.7 (1.5)
Area (km^2)	361.2 (140.0)	388.3 (112.4)	451.2 (144.8)

The results (Table 2) show that contrails tend to be longest and most narrow when located within pre-existing cirrus clouds. This seems reasonable since most contrails co-existing with natural clouds occur within cirrus shields that typically cover hundreds of kilometers in diameter. Cirrus shields occur near the leading edge of cyclonic storms or, in the warm season, typically with the outflow from cumulonimbus anvil tops (Jasperson et al., 1985, DeGrand, 1991). Within, or immediately adjacent to these cirrus areas, conditions are typically saturated, or supersaturated, with respect to ice. Thus, cirrus shields provide a relatively large favorable area for contrails to persist and grow. Clear sky areas, on the other hand, would contain contrails of much smaller lengths due to a limited moisture supply.

The relatively narrow nature of contrails when located within natural cirrus is likely a result of their rapid transformation into naturally-appearing cirrus. This occurs because contrails persisting in natural cloud environments have access to sufficient ambient moisture to allow ice crystal growth to approach the size of those characterized by natural cirrus. Thus, the contrail emissivity, and radiative signature on the AVHRR, quickly becomes indistinguishable from the surrounding natural clouds. On the other hand, contrails persisting in clear skies are likely to retain their identity for longer, due to the contrast in brightness and contrail temperature against otherwise clear sky conditions. Application of the split-window method reduces this problem somewhat by allowing greater recognition of persisting contrails when located among natural clouds. However, other than through in situ measurements, this problem cannot be completely eliminated. Hence, the estimates of contrail widths when occurring within cirrus areas are likely to be slightly underestimated.

The relatively large length of contrails when occurring within cirrus shields offsets the narrower widths, so that contrail areal coverage is significantly greater than for contrails existing in clear sky situations (Table 2). Significantly greater length ($t=3.81$; $p<0.01$) and areal coverage ($t=8.89$; $p<0.01$) characterizes contrails occurring within clouds as compared to those in otherwise clear sky situations. Contrails located within clouds have not been previously given serious consideration for their influence on the Earth-atmosphere radiation balance, primarily because most observers were unaware of their existence. However, the fact that contrails have, on average, their greatest areal coverage when "hidden" within natural clouds suggests that they could potentially have a greater overall effect on the radiation balance then has previously been assumed.

Mean values of contrail morphological characteristics across all satellite overpass times and cloud situations are summarized in Table 3. From studying the mean length (136.5 km) and standard deviation (96.4 km) of contrails it can be inferred that favorable areas for persisting contrails, when both clear and cloudy sky areas are considered together, tend to occur in sizes between about 100 and 200 km in diameter. Multiple aircraft passes through these favorable areas often produce groups of contrails, or outbreaks, which are strongly clustered within and immediately adjacent to these favorable areas. As demonstrated in Table 2, cloudy sky areas favorable for contrails (cirrus shields) will tend to be larger, with favorable clear sky areas tending to be smaller.

TABLE 3: Overall summary of contrail morphology.

VARIABLE	MEAN	STD. DEV.	MINIMUM	MAXIMUM
Length (km)	136.5	96.4	11.0	688.6
Width (km)	2.9	1.9	0.6	13.8
Area (km^2)	390.9	169.2	7.2	3270.5

Though no previous studies have been completed to investigate average contrail lengths, two previous studies have estimated contrail widths. Detwiler and Pratt (1984), using hard copy LANDSAT images (100m) of the United States for 1972 and 1975, estimated that the most commonly observed width on each image was between 2-3 km with a rapid decrease in frequency beyond 3 km. These results are in close agreement with the average width value (2.9km) obtained in this study (Table 3). Wendland and Semonin (1982) utilized surface camera observations to calculate the average contrail width over Central Illinois. Their estimates are more than twice that of those found in this study and the Detwiler and Pratt (1984) study. It is possible that contrails over Illinois tend to spread more favorably due to atmospheric conditions. However, another more likely explanation for this discrepancy may be attributed to the differences in methods of estimation, especially considering the strong agreement between the results found in this study and those of Detwiler and Pratt (1984), both of which used high resolution satellite imagery.

3.2. Atmospheric Controls on Contrail Width

Having demonstrated that contrail morphological characteristics can vary significantly due to time of day and cloud cover, it is appropriate to further investigate the importance of upper tropospheric (300-100mb layer) conditions on contrail width. The influences of temperature, stability, and wind on contrail widths are investigated in this section.

A significant negative relationship ($r=-0.38$; $p<0.01$) is identified between contrail width and temperature for the 300-100mb layer (Fig. 1). This seems reasonable since a colder environment is more likely to be closer to saturation or supersaturation with respect to ice than a warm environment. As a result, in colder environments the contrail is more likely to persist and spread by entrainment of moisture from the ambient air, rather than evaporation. Moreover, the contrail is likely to become frozen more quickly in a colder environment thus making the growth process as a solid rather than a liquid. Frozen contrails are more likely to persist, and be recognized, then liquid contrails (as in Pilie and Jiusto, 1958) since moisture is most easily entrained from the vapor to solid phase. DeGrand (1991), using four case studies, also demonstrated that contrail persistence becomes more likely when the temperature at contrail level cools significantly.

Though cooling at contrail altitudes tends to promote greater contrail widths it is worthy to note that this result was obtained only from environments where contrails had already formed and become large enough to be evident on the AVHRR. A minimum temperature threshold has long been suspected to exist that prohibits contrail growth due to the extreme dryness of the air at very low temperatures, and any formed contrails are assumed to quickly evaporate or sublimate (Appleman, 1953; Scorer, 1978). Hence, this result should only be viewed as an indicator of the influence of temperature on contrail widths where conditions are already favorable for their formation and persistence due to an adequate moisture supply. The minimum temperature threshold has not been identified previously, and due to its heavy dependence on the absolute humidity of the upper troposphere which cannot be accurately measured from rawinsonde data at contrail altitudes, it could not be obtained in this study. Futher research using other data sources is needed.

Since contrails have been most commonly reported as occurring in baroclinic environments (Detwiler and Pratt, 1984; DeGrand, 1991), it is appropriate to examine the roles of vertical stability and horizontal wind shear. The magnitudes of wind shear and instability are both relatively large in baroclinic environments, and their variation can be used as indirect measures of the level of

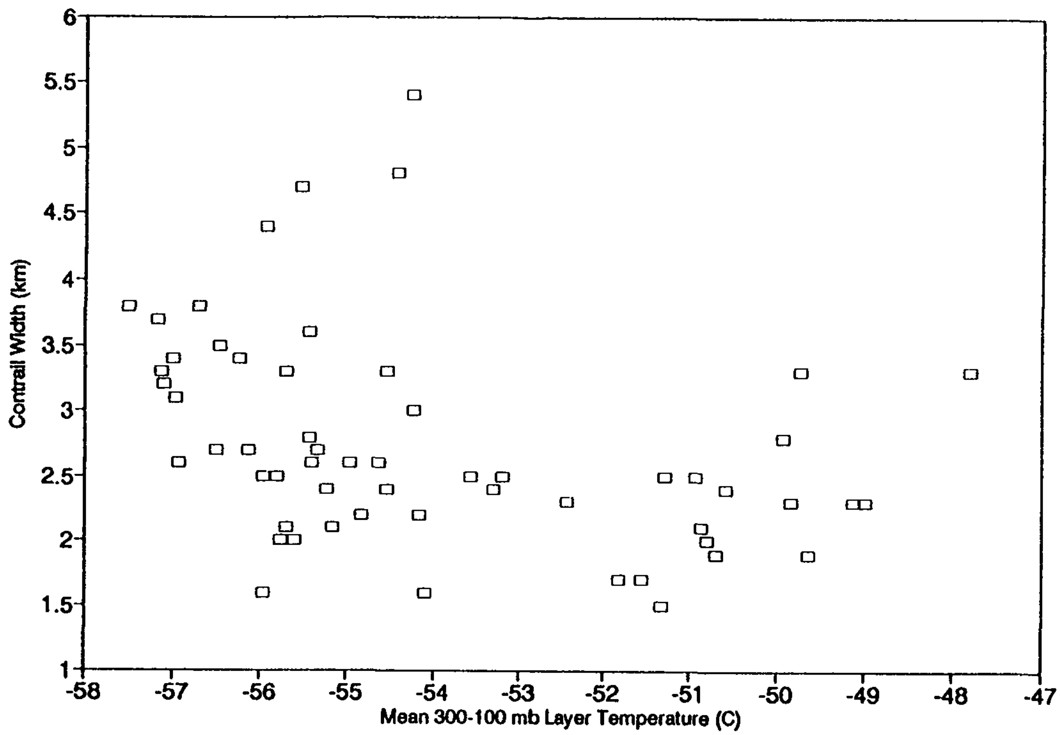

Figure 1. Scatterplot of the relationship between 300-100mb layer temperature and mean contrail width.

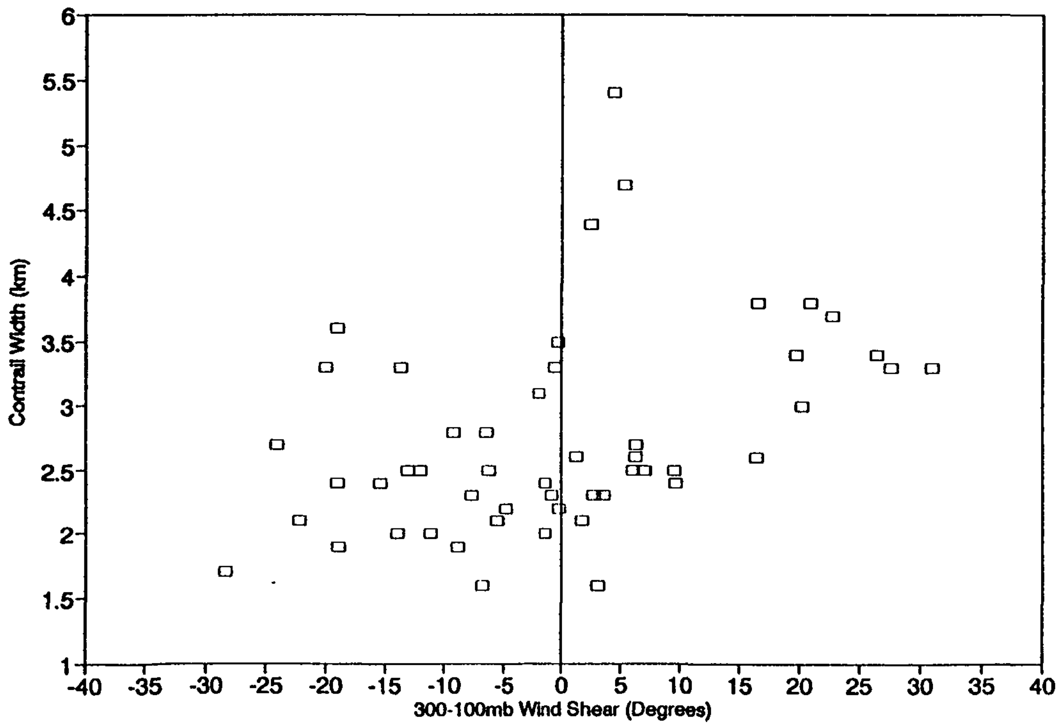

Figure 2. Scatterplot of the relationship between 300-100mb layer wind shear and mean contrail width.

baroclinic environments, and their variation can be used as indirect measures of the level of baroclinicity. The stability is calculated as the temperature lapse rate between 300-100mb. Wind shear is quantified by determining the magnitude of wind direction change (in degrees) between the 300mb and 100mb levels. Thus, a positive wind shear (clockwise turning with height) is a measure of warm air advection, and negative wind shear (counterclockwise turning with height) represents cold air advection.

No significant relationship was found between contrail width and the stability of the 300-100mb layer. This seems reasonable since stability is more likely to influence the vertical growth of the contrail, rather than growth in the horizontal dimension that is viewed by the satellite. Also, the mid and upper troposphere is characteristically very stable. However, a significant positive relationship ($r=0.26$; $p < 0.05$) is identified between contrail width and the magnitude of the wind shear for the 300-100mb layer (Fig. 2).

Visual inspection (Fig. 2) indicates that contrail outbreaks occur about equally in areas of both positive and negative wind shear. This coincides with the results found by DeGrand (1991) where contrail formation was most commonly associated with baroclinic patterns (i.e. waves and jet streams), but not strongly favored towards negative or positive wind shear regions (cold-west side of a trough; warm-east side of a trough, respectively). However, the results also show that an increase in the average contrail width occurs with increased positive wind shear suggesting that contrail growth is favored more when occurring in warm air advection environments. This seems reasonable since warm advection is commonly found on the western side of high pressure systems. Contrails have been noted most commonly in these types of synoptic environments where the leading edges of developing cyclones, and associated cirrus, are often found (Detwiler and Pratt, 1984; Carleton and Lamb, 1986; DeGrand, 1991). Moreover, in these environments warm, moist air is overrunning dryer air at the contrail level, thus providing the additional moisture

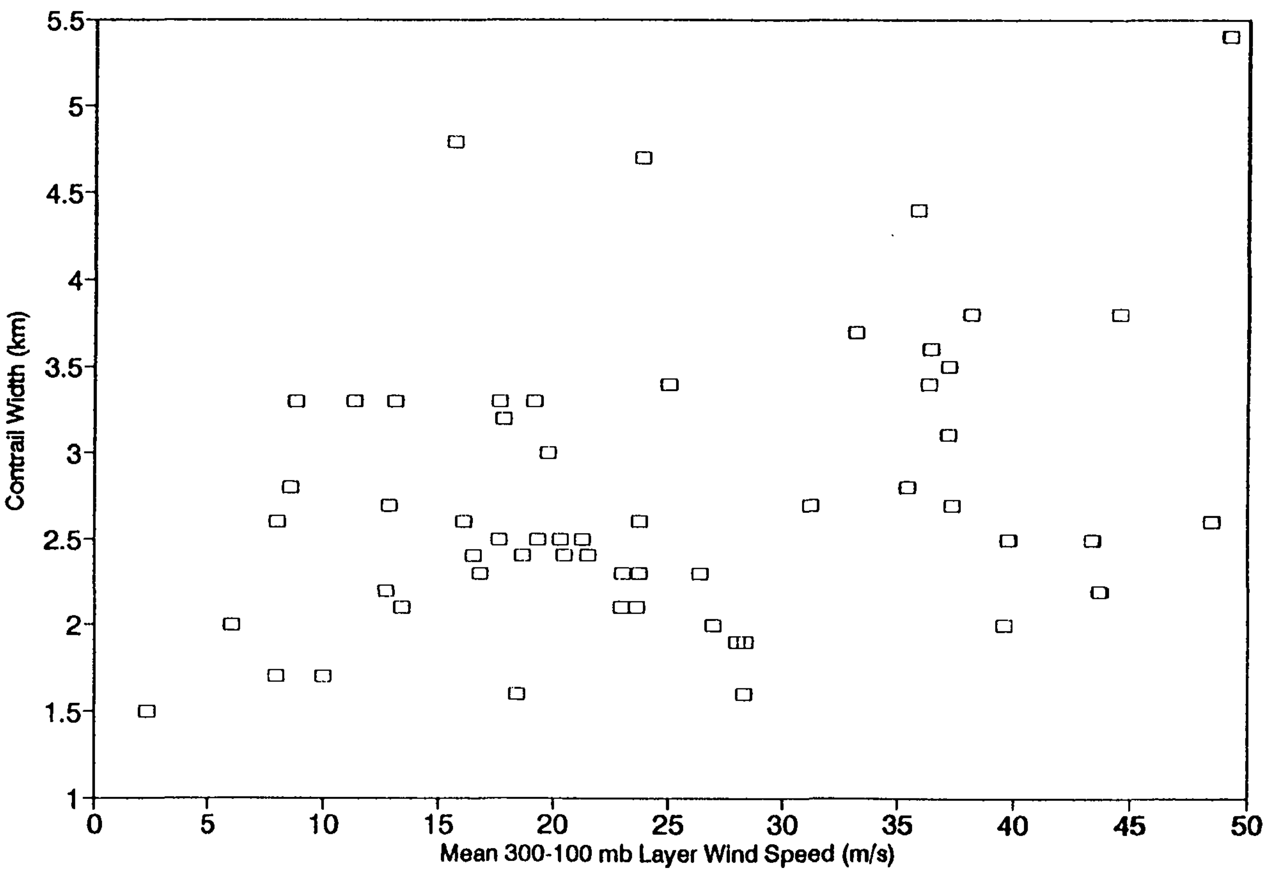

Figure 3. Scatterplot of the relationship between 300-100mb layer mean wind speed and mean contrail width.

necessary to support contrail persistence and growth even where natural cirrus are not present.

A significant positive relationship ($r=0.33$; $p<0.01$) is found between the mean windspeed of the 300-100mb layer and contrail width (Fig. 3), though the scatter is quite large. Contrail spreading is encouraged by a strong horizontal wind, which tends to occur in baroclinic environments. In addition, greater turbulence, which is common in strong wind situations, is likely to enhance the rate of moisture entrainment onto the contrail.

The lack of a more significant direct relationship between contrail width and windspeed is likely a result of the negative (inverse) influence that excessively strong winds potentially have on contrail growth and persistence. Though no specific threshold could be identified in this study, it is likely that contrails are eventually sheared apart if situated in or near very strong windfields (i.e. near jet maximums) for a long enough time period. When in those situations, contrails would rapidly become indistinguishable from "natural" cirrus and also less identifiable on the satellite data.

Further research, via in situ measurements is needed to better understand the role of wind (and temperature) on contrail growth and persistence. In addition, stronger correlations would likely be found between contrail widths and atmospheric conditions if the data were stratified by time of day, amount of natural clouds, and synoptic situation. However, the limited sample size available in this study (58 outbreaks) did not allow such stratifications.

4. Conclusions

The present study is the first to use multispectral satellite data of multiple contrails to determine variation in their morphology according to time of day and amount of cloud cover. More specifically, the primary results of this study are as follows:

1. Contrail areal coverage varies significantly according to time of day. Individual contrails tend to have a greater areal coverage at night and in the early morning compared with those occurring during the mid-afternoon or early evening. This supports the importance of considering upper tropospheric conditions rather than just the absolute density of aircraft flights to estimate diurnal variations in contrail areal coverage.

2. Contrails persisting within natural cirrus clouds are significantly greater in length (167.0 km) and areal coverage (451.2 km^2) than those occurring in "partly cloudy" (123 km; 388.9 km^2) or otherwise "clear" (119.1 km; 361.2 km^2) skies. This suggests that contrail coverage has likely been underestimated since previous studies have based estimates on surface observations or hard copy satellite imagery, where intervening natural cloud cover could not be masked through the spectral enhancement procedures utilized here (i.e. the split-window method).

3. Contrail widths are significantly correlated with atmospheric conditions of the 300-100 mb layer. Specifically, contrail widths are negatively correlated with 300-100mb layer temperature, positively correlated with 300-100mb wind shear, and positively correlated with 300-100mb average windspeed. No significant association between contrail width and 300-100mb layer stability is found.

These results provide an important advancement in our understanding of the variation in contrail morphology, and of the primary atmospheric conditions that influence their width. By gaining a better understanding of the conditions that favor contrail spreading and persistence it is possible to estimate how contrail coverage may change both on a regional and global scale in response to a continued increase in jet air traffic and changes in atmospheric conditions due to future climate variations.

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5. References

Angell, J.K. (1990). Variation in United States cloudiness and sunshine between 1950 and the drought year of 1988. *J. Climate*, 3:296-308.

Appleman, H.S. (1953). The formation of exhaust condensation trails by jet aircraft. *Bull. Amer. Met. Soc.*, 34: 14-20.

Bakan, S., Betancor, M., Gayler, V., and H. Grassle (1994). Contrail frequency over Europe from NOAA-Satellite images. *Annals Geophysical*, 12: 962-968.

Beckwith, W.B. (1972). Future patterns of aircraft operations and fuel burnouts with remarks on contrail formation over the United States. *Preprints of the International Conference on Aerospace and Aeronautical Meteorology*, American Meteorological Society, Boston, MA, 422-426.

Carleton, A.M. and P.J. Lamb (1986). Jet contrails and cirrus cloud: a feasibility study employing high resolution satellite imagery. *Bull. Amer. Met. Soc.*, 67:301-309.

Changnon, S.A. (1981). Midwestern cloud, sunshine, and temperature trends since 1901: possible evidence of jet contrail effects. *J. Appl. Meteor.*, 20:496-508.

DeGrand, J.Q. (1991). A satellite-derived mid-season climatology of jet condensation trails: April 1977-October 1979. *Unpublished M.A. Thesis,* Indiana University, Bloomington, 117 pp. (plus appendices).

Detwiler, A. and R. Pratt (1984). Clear-air seeding: Opportunities and strategies, *J. Wea. Mod.*, 16:46-60.

Englestaad, M. Sengupta, S.K., Lee, T., and R. M. Welch (1992). Automated detection of jet contrails using the AVHRR split window. *Int. Jour. of Rem. Sens.*, 13:(8), 1391-1412.

Erdas, Inc. (1993). *Erdas Imagine*, Erdas Inc., Atlanta, GA.

Henderson-Sellers, A. (1992). Continental cloudiness changes this century. *GeoJournal.*, 27: 255-262.

Jasperson, W.H., G.D. Nastrom, R.E. Davis, and J.D. Holdeman (1985). Variations in cloudiness at airline cruise altitudes from GASP measurements. *J. Clim. Appl. Met.*, 24: 74-82.

Karl, T.R. and P.M. Steurer (1990). Increased cloudiness in the United States during the first half of the twentieth century: fact or fiction? *Geophy. Res. Lett.*, 17: 1925-1928.

Knollenberg, R.G. (1972). Measurements of the growth of the ice budget in a persisting contrail. *J. Atmos. Sci.*, 27:937-942.

Lee, J.E. and S.D. Johnson (1985). Expectancy of cloudless photographic days in the contiguous United States. *Photogram. Eng. Remote Sensing,* L1: 1883-1891.

Lee, T.F. (1989). Jet contrail identification using the AVHRR infrared split window. *J. App. Met.*, 28: 993-995.

Machta, L. and T. Carpenter (1971). Trends in high cloudiness at Denver and Salt Lake City, In: Matthews, W.H., Kellogg, W.W., and Robinson, G.D. (eds.) *Man's Impact on the Climate.* MIT Press, pp. 401-405.

Manabe, S. (1975). Cloudiness and the radiative, convective equilibrium. In: *The Changing Global Environment* (S.F. Singer, ed.), pp. 175-176, Reidel, Boston, MA.

Murcray, W. B. (1970). On the possibility of weather modification by aircraft contrails. *Mon. Wea. Rev.*, 98:(10) 745-748.

Pilie, R. J. and J.E. Jiusto (1958). A laboratory study of contrails. *Jour. Met.*, 15:149-154.

Scorer, R.S. (1978). *Environmental Aerodynamics.* Ellis Horwood Limited Pubs., pp. 395-405.

Seaver, W.T., and J.E. Lee (1987). A statistical examination of sky cover changes in the contiguous United States. *J. Clim. Appl. Meteor.*, 26:88-95.

Wendland, W.M. and R.G. Semonin (1982). Effect of contrail cirrus on surface weather conditions in the Midwest: phase II. *Final Report of NSF Grant ATM 8008812,* Illinois State Water Survey, Champaign, IL, 95 pp.