INTRODUCTION

The strong growth in commercial aviation during the past 30 years has led to speculation about its potential effects on regional-scale climate via increased jet contrail coverage (Changnon, 1981; Sassen, 1997; Meerkotter et al., 1999; Minnis et al., 1999; Duda et al., 2001; Travis et al., 2002, 2003), as well as changes in the aerosol load and gaseous composition of the upper troposphere and lower stratosphere (e.g. Schulte et al., 1997; Brasseur et al., 1998). Contrails are the visible condensate of aircraft-emitted water vapor and sublimated ambient moisture (Penner et al., 1999; Schumann, 2000). GCM experiments to assess the relative contributions globally of contrails and aircraft water vapor emissions (Ponater et al., 1996; Rind et al., 1996) suggest that radiative forcing from contrails far exceeds that due to the additional water vapor for current air traffic densities, and also as predicted for the near future (e.g., Sausen et al., 1998; Penner et al., 1999; Gierens et al., 1999; Minnis et al., 1999; Marquart et al., 2003). Accordingly, contrails are considered the dominant contributor to radiative forcing from aircraft emissions (Penner et al., 1999; Pielke, 2003).

Recent studies of contrail effects on the US climate indicate that they contribute to a regional-scale reduction in the diurnal temperature range (Travis et al., 2002, 2003), and may cause a net warming of the surface rivaling that of greenhouse gases (Minnis et al., 2004). In certain regions, contrails already may contribute as much as the present anthropogenic CO₂ forcing (Gothe and Grasal, 1993; Sassen, 1997; Minnis et al., 2004). However, large uncertainties in the contrail net forcing are associated with the following factors: the wide range in contrail optical thickness and altitude, the diurnal and seasonal variations in contrail occurrence, contrail interactions with aerosols, and the extent to which contrails co-occur with natural clouds, particularly cirrus (Myhre and Stordal, 2001; Ponater et al., 2001; Minnis...
et al., 2003, 2004; Palikonda et al., 2005). As society’s dependency on aviation continues to grow globally, it is likely that the role of contrails in climate change scenarios will also increase. However, before such an assessment can be reliably undertaken, it is necessary to determine the rate at which contrails are increasing and where they are increasing the most, and better understand the factors controlling these spatio-temporal changes.

For the United States, jet fuel usage more than doubled since the late 1970s (Penner et al., 1999), leading to speculation that jet contrail frequency has increased both in this region and globally (Penner et al., 1999; Gierens et al., 1999). However, contrail frequency is not only dependent on the number of flights but also on the atmospheric conditions occurring at typical flight cruising altitudes (i.e. 10–12 km) (Schmidt, 1941; Appleman, 1953; Pilie and Jiusto, 1958; Schrader, 1997; Travis et al., 1997). Numerous studies have shown that contrail formation and persistence time are controlled by variations in temperature and moisture, especially near the tropopause, with the most ideal set of conditions for extended contrail persistence being an atmosphere that is supersaturated with respect to ice (Pilie and Jiusto, 1958; Hanson and Hanson, 1995; Kastner et al., 1999). The tropopause is a sensitive indicator of climate variation and climate change (Wong and Wang, 2003). Tropopause characteristics, particularly the pressure-altitude and temperature, integrate the tropospheric thickness, which depends positively on the mean temperature of a given layer (Santer et al., 2004). Accordingly, recent large-scale changes in upper tropospheric conditions and mean tropopause height have been observed (Santer et al., 2003a), some of which potentially result from anthropogenically-induced climate change (Santer et al., 2003b, 2004). The latter increases the possibility that the favored regions for contrail formation and persistence have been modified, or will be soon, leading to changes in contrail frequency in the most affected regions (Marquart et al., 2003). Furthermore, some of the upper troposphere changes have been linked to circulation teleconnections, particularly the Arctic Oscillation (AO), which links the troposphere and stratosphere of the polar and middle-latitude zones of the Northern Hemisphere (Thompson and Wallace, 2000; Wong and Wang, 2003).

Several studies have relied upon surface observations to estimate the frequency, sky coverage, and radiative surface-effects of contrails (e.g. Changnon, 1981; Minnis et al., 2003). However, problems with intervening clouds, changing sky-view perspective, and the ability to observe contrails reliably at night have hindered the creation of a comprehensive contrail data set across a wide range of periods and atmospheric situations. For these reasons, thermal infrared (IR) satellite-based observations of jet contrails have become the preferred method for studying contrails on climatic timescales (Carleton and Lamb, 1986; Mannstein et al., 1999; DeGrand et al., 2000). Analysis of these data has resulted in comprehensive inventories of contrail frequency developed for Western Europe, the North Atlantic, and the US (Bakan et al., 1994; DeGrand et al., 2000). When digital, rather than analogue, imagery is available, it is possible to automate contrail detection in certain geographical settings (Lee, 1989; Engelstad et al., 1992; Mannstein et al., 1999). However, this method becomes problematic when surface features mimic the typical linear orientation of young contrails (e.g. rivers, mountain ranges, coastlines), and can result in overestimates of contrail frequency. Comparatively, manual inspection of either digital or hard-copy imagery by a trained technician, who is knowledgeable of the geographic and topographic settings for a given study area, is a method of contrail detection not limited by such issues, although it is clearly more labor-intensive (Carleton and Lamb, 1986; DeGrand et al., 2000).

The only previous satellite-based multiyear spatial inventory of contrail frequency for the coterminous United States was the one developed by DeGrand et al. (2000) for the 1977–1979 mid-season months (January, April, July, and October; other than January 1977). These authors used the IR channel hard-copy Defense Meteorological Satellite Program (DMSP) imagery having 0.6 km pixel resolution. This study demonstrated that contrail frequency during the 1977–1979 period varied on regional-scales, with the greatest (least) concentrations in the Midwest, Great Lakes, and far West (Intermountain West and Deep South). This spatial variation in contrail frequency was not correlated with the density of flight routes, implying a primary association with upper tropospheric conditions. Furthermore, DeGrand et al. (2000) provided a series of case study analyses showing that contrails are favored in atmospheric conditions comprising a higher and colder tropopause. A similar study for western Europe and the eastern North Atlantic by Bakan et al. (1994) used digital data of the advanced very high-resolution radiometer (AVHRR). These authors also reported a regional-scale variation in contrail frequency, further supporting the role of atmospheric conditions in contrail frequency. Although both the DeGrand et al. (2000) and Bakan et al. (1994) studies provided valuable information about contrail frequency during specific periods, no previous attempt has been made to measure the temporal changes in contrail frequency or in their spatial and seasonal characteristics. Such a study would not only permit the estimation of future contrail frequency changes but would also allow an assessment of the relative importance of projected flight frequency increases and anticipated changes in upper tropospheric conditions for contrail increases.

Accordingly, the objectives of this study are as follows:

1. Develop a spatial and temporal ‘climatology’ of contrail frequency for the coterminous United States in the contemporary period (mid-season months of 2000–2002), and compare it with contrail frequencies derived for the earlier 1977–1979 period, in order to determine US-averaged, seasonal, and regional-scale changes in contrail frequency.
(2) Assess the relative importance of variations in jet aircraft flight frequency and tropopause-level temperature to the US-averaged, seasonal, and regional-scale contrail frequency for the 2000–2002 period and differences from 1977–1979.

(3) Relate any large-scale changes in tropopause characteristics occurring between the earlier and contemporary periods to the dominant atmospheric teleconnection patterns, especially the AO.

DATA AND METHODS

Satellite imagery and detection of contrails

To determine the contemporary period contrail coverage, we analyzed 2126 digital images from the AVHRR IR channel (band 4: 10.3–11.3 μm, 1.1 km² nadir pixel resolution) for the mid-season months (January, April, July, and October) of 2000–2002. These images are available online and can be downloaded from the National Climatic Data Center (NCDC) Satellite Active Archive (SAA) (http://www.class.noaa.gov), and were analyzed using a combination of remote sensing and Geographic Information Systems (GIS) software (Leica Geosystems, 2003; ESRI, 2003). The images were selected in pairs from the archive that provided optimal combined coverage of the coterminous United States for local ‘nighttime’ (00–09 UTC), ‘morning’ (09–18 UTC), and ‘afternoon’ (18–00 UTC) periods, while maintaining a reasonable separation time between each image pair to ensure that contrails were not double-counted. An average spacing of 4.5 hours occurred between each image pair: this represents a median of six images per day, approximately corresponding to one image each for night, morning, and afternoon hours for the eastern and western halves of the coterminous United States.

The large number of usable images and their diurnal coverage represents a substantial improvement in temporal resolution over the comparison period of 1977–1979, for which only about half as many images were available per day, and with only two months available to calculate the winter mid-season averages (January 1978 and 1979) (DeGrand et al., 2000). Moreover, the use of DMSP hard-copy IR imagery in the earlier climatology is an issue. The DMSP has slightly higher spatial resolution (0.6 km) than the AVHRR (1.1 km) and a broader spectral range for July 1977 through January 1978 (8–13 μm), but with approximately the same spectral range as the AVHRR for July and October 1979 (10.4–12.5 μm). The similarity in contrail frequencies identified for the mid-season months of 1977–1979 suggests that the change in spectral range during the earlier period did not significantly affect the ability to identify contrails (DeGrand et al., 2000). To further ensure consistency between the methods of contrail detection used for the 1977–1979 and the contemporary (2000–2002) periods, AVHRR data were manually inspected on computer screen at maximum resolution but with no efforts made to adjust the viewing field (i.e. zoom in or out), enhance the contrail signal on the imagery (e.g. Lee, 1989), or automate their detection (Engelstad et al., 1992; Mannstein et al., 1999). Thus, for both periods, contrails were identified using identical pattern recognition criteria (Carleton and Lamb, 1986; DeGrand et al., 2000), and their frequency of occurrence within 1 × 1 degree grid cells covering the coterminous United States land and coastal areas (n = 900) was cataloged into a series of GIS database files by each mid-season month for statistical analysis. However, adjustments were necessary to compensate for the different media (hard-copy, digital) of the satellite images used in the two contrail climatologies (discussed below).

Although contrails have been reported to often occur in clusters, or ‘outbreaks’ (Travis et al., 1997; Duda et al., 2001), it was only necessary for a minimum of one contrail to be located within a particular grid cell for its inclusion in the GIS database. This duplicates the approach taken to construct the contrail frequency database for the 1977–1979 period (DeGrand et al., 2000).

Adjustments to satellite-retrieved contrail frequencies

Because there are potential differences in the ability to recognize contrails on the hard-copy DMSP images compared to the digital AVHRR, we undertook a contrail detection comparison study between the two satellite data types for the earlier period. Only a limited number of digital images were available for the coterminous United States in this period (n = 47), all for 1979. Thus, the comparison was for that year only. To ensure maximum statistical reliability of the results, and yet maintain a reasonably large number of grids in the comparison, only those 1 × 1 degree grid cells that were included in the field of view of both the DMSP and AVHRR scenes for the same dates and approximate times were included in the comparison procedure. This provided a total of 36 1 × 1 degree grids that could be compared, mainly for the northeastern quadrant of the United States and adjacent coastal areas. The heterogeneous surface that is characteristic of this region (e.g. areas of high and low relief, coastal) provides a reasonable representation of the remainder of the study area for recognizing contrail occurrences. Once we determined contrail frequency on the AVHRR, we compared it to that found for the same grid cells from the DMSP analysis (1979 only), both using the manual interpretation method.

The comparison indicated that the number of grid cells containing contrails was 3.2 times greater on the AVHRR than on the DMSP for the same locations and mid-season months of 1979. This demonstrates the superior ability to recognize contrails on digital imagery despite the slightly reduced pixel resolution of the AVHRR relative to the DMSP. Assuming that this magnitude of improved ability to recognize contrails on the digital AVHRR is representative of the entire 1977–1979 (DMSP) and 2000–2002 (AVHRR) periods and for the entire study area, we divided the 2000–2002 contrail frequency values by 3.2 as a correction factor before calculating...
the contrail frequency changes. In addition, an adjustment was done in terms of the diurnal dependence of contrails, as follows. Because 98% of the DMSP data for the 1977–1979 period were for the evening, nighttime, and morning hours (roughly 0–18 UTC local time) (DeGrand et al., 2000), we used a subset of the 2000–2002 data for the same diurnal period to calculate contrail frequency changes. Although this meant that none of the afternoon (local time) AVHRR data were included in this part of the analysis, a substantial number of images ($n=1398$) remained for use in the contrail frequency change calculations.

**Synoptic meteorological data**

We used NCEP-NCAR reanalysis data to determine the changes in tropopause-level conditions (temperature, pressure-altitude) between the two comparison periods (Kistler et al., 2001; Wong and Wang, 2003). These data are available online at [http://www.cdc.noaa.gov/](http://www.cdc.noaa.gov/) and are readily composited for our two periods (i.e. mid-season monthly averages, annual averages, and overall multiyear averages and differences). As indicated earlier, we focus primarily on changes in temperature and pressure at the tropopause level. These two variables are interrelated such that a cooler (warmer) tropopause is associated with a location at higher (lower) altitudes, or lower (higher) pressure, in the regions where high-altitude jet aircraft cruise. Reliable moisture data are not available for the tropopause level (Kistler et al., 2001).

**US Jet aircraft flight activity data**

To determine the influence of changes in flight activity on contrail frequency variations within and between the two study periods, data on aircraft that have flown at higher altitudes over the coterminous United States for both the 1977–1979 and 2000–2002 periods are required. For this purpose, we obtained flight statistics on jet-powered aircraft separate from those for turboprop and piston-powered planes, through contract with BACK Aviation Solutions (2005). These data have undergone rigorous quality control to ensure high reliability (BACK Aviation Solutions, 2005), and have been used extensively in a wide range of transportation and economics studies (e.g. Grayling and Bishop, 2001; Nalebuff and Majerus, 2003; Eyers et al., 2004). The two parameters readily available for denoting jet traffic activity and their changes between the two periods were: (1) the daily total scheduled number of flights, and (2) the daily total scheduled number of flight kilometers (i.e. total flight distance between all scheduled departure locations and their destinations). Moreover, by dividing values in (2) by (1) one can create a third parameter, (3) the daily average length of flights. Changes in average flight length are potentially important because longer flights typically cruise at higher altitudes. This will increase (decrease) the likelihood of contrail formation if the aircraft is below (above) the tropopause (Sausen et al., 1998; Williams et al., 2003; Fichter et al., 2005). Improvements in engine design and fuel efficiency have resulted in a gradual increase in maximum height cruise capability for newer aircraft (Penner et al., 1999), although it is not possible to determine what impact these have had on changes in mean cruising altitudes. One limitation to the data was that the scheduled flight information for the earlier period was only available for 1979 (BACK Aviation Solutions, 2005); thus, we considered that year to be representative of the entire period 1977–1979.

Limited information on flight route details within the aviation data set precluded us from including international flights, mostly because it was not possible to determine how much of each flight was spent within US airspace. Thus, the flight activity data are based exclusively on US domestic flights (i.e. flights departing and arriving in the coterminous United States). However, we were able to obtain the number of scheduled international flight departures for both periods (BACK Aviation Solutions, 2005), and determined that the percentage of international to total flights in 1979 was approximately half (7%) of that for 2000–2002 (13%), a rate which is similar to that for other flight activity changes.

**RESULTS AND DISCUSSION**

**Contrail frequencies in the contemporary (2000–2002) period**

The climatology for the 2000–2002 period is presented in two parts. First, in map form with contrail frequencies averaged by 1 × 1 degree grid values across each group of mid-season months and years. This permits a spatial assessment of contrail frequency and determination of the regions that are most and least favored for contrail coverage during the contemporary period. Second, we present contrail frequency as US-wide averages for the same groups of mid-season months and years, which permits assessment of the temporal variations within the contemporary period as well as the importance of changes in flight activity relative to changes in upper tropospheric conditions.

Figure 1 shows the 2000–2002 spatial distribution of contrail frequencies averaged across all mid-season months and years for the coterminous United States. It is evident that contrails are much more (less) frequent in the East (West), with greatest (least) concentrations in the Midwest and southern Great Lakes (Intermountain West and Deep South) regions. Such variations can be attributed to a combination of air traffic density and upper tropospheric conditions. In the East, typically there is more frequent warm air advection associated with deeper moisture in the mid-to-upper troposphere along the leading edge of cyclones, where persisting contrails frequently form (Changnon, 1981; DeGrand et al., 2000; Minnis et al., 2003). The lack of contrails in the Intermountain West and Deep South likely result from the upper troposphere being too dry and too warm, respectively, in these regions.

When the contrail frequency data for 2000–2002 are averaged separately by mid-season months, further
insights are yielded into the importance of atmospheric conditions in controlling their distribution (Figure 2). In the winter (summer), contrail frequency maxima are furthest south (north) and centered on the Mid-South (Northeast) US region (Figure 2(a), (b)); areas close to the average jet stream location for that time of year. During the transition seasons (Figure 2(c), (d)), the peak contrail frequency falls in between these extremes, across the southern Great Plains and Midwest, which again are in close proximity to the mean jet stream position for those seasons. Thus, contrail frequency tends to follow the mean jet stream location in each season, as also found for the inter-seasonal variations depicted in the earlier climatology (DeGrand et al., 2000).

Perusal of the coterminous US-averaged contrail frequency by mid-season month (Table I) indicates substantial month-to-month variation between seasons and within season. We completed an analysis of variance (ANOVA) of $1 \times 1$ degree grid mean frequency values ($n = 900$) to determine whether the contrail frequency values within season were significantly different from each other; this was confirmed for all seasons ($p$-value < 0.01). Variations in jet aircraft flight activity, as measured by the mean daily number of flights and kilometers
Table I. Summary of contrail frequency (number of contrail grid cells/100 images) by year and month, with jet airplane flight activity for the same periods. Analysis of Variance (ANOVA) tests indicate that the month-to-month frequencies within each season are significantly different from each other at \( p < 0.01 \) levels.

<table>
<thead>
<tr>
<th>Year/Month variable</th>
<th>January</th>
<th>April</th>
<th>July</th>
<th>October</th>
<th>Average</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contrail frequency(^a)</td>
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<td>9.5</td>
<td>4.6</td>
<td>8.9</td>
<td>7.7</td>
</tr>
<tr>
<td>Flight km per day</td>
<td>(2.11 \times 10^4)</td>
<td>(2.19 \times 10^4)</td>
<td>(2.22 \times 10^4)</td>
<td>(2.27 \times 10^4)</td>
<td>(2.21 \times 10^4)</td>
</tr>
<tr>
<td>No. flights per day</td>
<td>1.91 (× 10(^4))</td>
<td>1.96 (× 10(^4))</td>
<td>1.98 (× 10(^4))</td>
<td>2.03 (× 10(^4))</td>
<td>1.97 (× 10(^4))</td>
</tr>
<tr>
<td>Avg. length per flight</td>
<td>1106.9 (km)</td>
<td>1115.1 (km)</td>
<td>1124.7 (km)</td>
<td>1118.5 (km)</td>
<td>1116.2 (km)</td>
</tr>
<tr>
<td>2001</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contrail frequency(^a)</td>
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<td>5.4</td>
<td>7.1</td>
<td>9.1</td>
<td>7.9</td>
</tr>
<tr>
<td>Flight km per day</td>
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<td>2.30</td>
<td>2.41</td>
<td>2.11</td>
<td>2.27</td>
</tr>
<tr>
<td>No. flights per day</td>
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<td>2.06</td>
<td>1.92</td>
<td>1.92</td>
<td>2.04</td>
</tr>
<tr>
<td>Avg. length per flight</td>
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<td>1116.7</td>
<td>1125.6</td>
<td>1096.7</td>
<td>1114.1</td>
</tr>
<tr>
<td>2002</td>
<td></td>
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</tr>
<tr>
<td>Contrail frequency(^a)</td>
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<td>7.3</td>
<td>8.9</td>
<td>4.2</td>
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<td>2.27</td>
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<td>1.87</td>
<td>1.97</td>
<td>2.03</td>
<td>2.01</td>
<td>1.97</td>
</tr>
<tr>
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<td>1121.9</td>
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<tr>
<td>Average</td>
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<td></td>
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</tr>
<tr>
<td>Contrail frequency(^a)</td>
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<td>7.4</td>
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<td>1115.6</td>
<td>1124.1</td>
<td>1116.4</td>
<td>1116.9</td>
</tr>
</tbody>
</table>

\(^a\)Contrail frequency is determined as number of contrail grid cells/100 images.

flown, along with average flight length, are also shown by mid-season month and year in Table I. Visual inspection and statistical analyses of the data (not shown) does not yield a month-to-month positive association between contrail frequency and variations in frequency of jet flights, jet flight kilometers, or mean flight length. All three flight activity parameters gradually increased from January 2000 through July 2001, but then dropped noticeably in October 2001, following the 11 September 2001 terrorist attacks. This downturn in flight activity continued through the mid-season months of 2002, with a strong recovery to above pre-11 September 2001 levels, which was evident for October 2002. We determined that mean daily jet flight departures and kilometers flown, along with average flight length, are also shown by mid-season month and year in Table I. Visual inspection and statistical analyses of the data (not shown) does not yield a month-to-month positive association between contrail frequency and variations in frequency of jet flights, jet flight kilometers, or mean flight length. All three flight activity parameters gradually increased from January 2000 through July 2001, but then dropped noticeably in October 2001, following the 11 September 2001 terrorist attacks. This downturn in flight activity continued through the mid-season months of 2002, with a strong recovery to above pre-11 September 2001 levels, which was evident for October 2002. We determined that mean daily jet flight departures and kilometers flown averaged 3.4% and 4.2% lower, respectively, for the four mid-season months immediately following 11 September 2001 compared to the average of the eight other mid-season months studied in the contemporary period. The average flight length changed negligibly, by less than 1%. Averaging the contrail frequency values by the same groups of mid-season months suggests that the decrease in jet flight activity following 11 September 2001 had no impact on contrail coverage; instead contrail frequency increased by 19.4% during the four mid-season months when jet aircraft frequency and miles temporarily decreased. It is also particularly noteworthy that for October 2002, when jet flight activity had returned to pre-11 September levels, and was the highest of all Octobers in the period 2000–2002, contrail frequency was the lowest of all 12 months studied. These findings confirm that monthly variations in contrail frequency are not fully controlled by variations in flight activity in the coterminous United States, but are heavily influenced by other factors; most likely, the meteorological conditions in the upper troposphere.

When averaged by mid-season months, the greatest (least) contrail frequencies occurred during January (July), with the transition seasons having virtually identical values between the extremes (Table I). A seasonal variation in contrail frequency has been reported through satellite (Bakan et al., 1994; DeGrand et al., 2000) and surface-based observations (Changnon, 1981; Minnis et al., 1997). However, this is the first study to report a comprehensive, satellite-observed finding of a significantly higher (ANOVA; \( p < 0.01 \)) mean contrail frequency for winter season (January) compared to other months for the United States. This result supports the calculations from meteorological theory of the winter season being most favorable for persisting contrail occurrence (Sausen et al., 1998; Fichter et al., 2005). The lack of a significant increase in flight activity in January compared to the other mid-season months (Table I) further supports the contention that the increase in contrail frequency is due to the existence of more favorable meteorological conditions near cruising altitudes during that time. To investigate this hypothesis further, we compare contrail frequency values for the 2000–2002 period to those reported for the earlier (1977–1979) period when January frequencies were much lower than other mid-season months for that same period (DeGrand et al., 2000). Such
a comparison for all mid-season months permits assessment of the different roles of increased flight activity versus changing upper tropospheric conditions on contrail frequency changes.

**Contrail frequency changes between 1977–1979 and 2000–2002**

Similar to the approach used in the previous section for the 2000–2002 contrail climatology, we report contrail frequency changes in both the spatial and temporal contexts. As Figure 3 shows, the greatest contrail frequency increases occurred in the eastern half of the United States, with a small area immediately southeast of the Great Lakes increasing by six or more contrail grids per 100 images. These increases coincide with those regions having the greatest increases in high cloud coverage, upper tropospheric water vapor, and reduction of diurnal temperature range in recent decades; all of which can be at least partly linked to increases in contrail frequency (Karl et al., 1993; Rind et al., 2000; Travis et al., 2002, 2003). Contrail frequency changes are much lower in the West and are even slightly negative (i.e. contrail frequencies decrease) in parts of California and the Intermountain West.

We attribute a substantial portion of the US-wide contrail frequency change between the earlier and contemporary periods to the 114% increase in jet flight miles that followed airline deregulation in the late 1970s (DeGrand et al., 2000). Between the same periods, the US-wide contrail increase of 101.5% is similar to that for flight kilometers, suggesting an association between the two variables when averaged for the entire country. However, the presence of strong regional-scale variations in contrail frequency changes (Figure 3) again suggests that flight frequency may not be the primary controlling mechanism. To investigate the role of changes in atmospheric conditions near the tropopause on the spatial and seasonal contrail frequency change variations, we focus on differences in tropopause temperature between the 1977–1979 and 2000–2002 study periods.

Figure 4 shows that a substantial cooling of the tropopause occurred over much of the coterminous United States between the two periods. This is associated with a decrease in tropopause pressure (i.e. its raising to an increased altitude) of around 2–4 mb (not shown). The tropopause-level changes are consistent with a warming and thickening of the mid and upper troposphere, and cooling of the lower stratosphere, which occurred between the two periods. We calculated a US-averaged tropopause temperature change of $-0.51$°C between 1977–1979 and 2000–2002, similar to the cooling reported previously for Northern Hemisphere middle latitudes over a comparable time interval (Angell, 1999; Santer et al., 2003a, 2004). The large-scale spatial structure of the tropopause cooling (e.g. Figure 4) has been attributed to a combination of coupled troposphere–stratosphere interactions involving the AO teleconnection pattern (Thompson and Wallace, 2000), and a warming (cooling) of the lower troposphere (stratosphere) potentially linked to anthropogenic influences (Santer et al., 2003b, 2004). However, the exact impact of each of these influences remains unclear (Thompson and Wallace, 2000; Santer et al., 2003b).

In terms of contrails, the greatest decreases of tropopause temperature coincide with the greatest contrail frequency increases; in the eastern half of the United States (Figure 4). Little change in temperature, or even a slight warming, is noted in the deep South region and portions of the far West, associated with increases in tropopause-level pressure (i.e. decreasing altitude) of 1–5 mb. These are the same regions having relatively small contrail frequency increases, including some
decreases. We performed a Pearson product moment correlation test for strength of association between contrail frequency change and mean tropopause temperature change on 5 × 5 degree grid-averaged values (n = 43). The 5 × 5 degree grid size approximates the typical size of contrail clusters, or ‘outbreaks’ (Travis and Carleton, 2005), which encompass the vast majority of contrails identified in this study, as well as the spacing of rawinsonde stations that collect tropopause information. Such a larger grid-cell size also reduces the spatial autocorrelation that can occur for smaller grid sizes or closely located grid cells, although this cannot be completely avoided. The correlation test confirms the statistical significance of the regional-scale inverse association between contrail frequency changes and tropopause temperature ($R = -0.68; p < 0.01$) (Figure 5). Thus, the widespread cooling of the tropopause over the central and eastern United States seems to explain a significant portion of the strong increases in contrail frequency there between the two periods, while the lack of cooling in the West has been associated with little increase in contrail frequency.

We deduce that a higher and cooler tropopause in the East provides greater opportunity for high-altitude air traffic cruising over that part of the United States to have been located in the upper troposphere during 2000–2002 rather than in the lower stratosphere in 1977–1979. Combined with the lower temperatures at cruising levels, it would result in a greater likelihood for persisting contrail formation during the latter-listed period; particularly for the winter months when the tropopause tends to be lower and high-altitude aircraft were previously more likely to fly in the lower stratosphere. Supporting evidence for this explanation is the finding reported earlier about contrail frequency being greatest for January 2000–2002 compared to other mid-season months (Table 1). In the West, where the tropopause has not lifted as much between the two periods, we attribute the lack of a substantial contrail frequency increase to the greater likelihood of aircraft there now cruising more often in the lower stratosphere than the upper troposphere, particularly when increases in typical cruising altitudes between the two periods are considered (Penner et al., 1999; Fichter et al., 2005).

To test the above hypothesis, at least in a preliminary way, we examined changes in tropopause-level pressure and geopotential height along the 40°N parallel (from 135° to 65°W), which approximately bisects the coterminous United States and is near the average location where the 200 mb level intersects the tropopause. Assuming a hypothetical jet cruise altitude of 12 000 m, which is close to the mean geopotential height of the tropopause at 40°N, we determined the changes in tropopause pressure level and geopotential height between our two study periods along that same latitude. Figure 6 demonstrates that in the West (i.e. approximately 130°–110°W) the

**Figure 4.** The mean change in tropopause temperature (°C) for 2000–2002 minus 1977–1979.

**Figure 5.** The relationship between contrail frequency change (number of contrail grid cells/100 images) and tropopause temperature change (°C) for the 2000–2002 period minus 1977–1979. Values are based on 5 × 5 degree grid calculations.
positive changes in tropopause pressure (reduced altitude) would result in a greater likelihood of flights cruising above the tropopause, whereas in the East (particularly east of 100°W) the flights cruising at 12,000 m would more often be located below the tropopause, given

the negative changes in tropopause pressure (increased altitude). Spatially (Figure 7), the changes in 200 mb geopotential height are positive throughout the entire study area, including along the 40°N parallel where this standard level approximates the tropopause. However, the increase in tropopause height is substantially greater in the East, again suggesting that 12,000 m flights are more likely to have been located below the tropopause in that region during 2000–2002. This change becomes even more meaningful when one considers the advances in engine design that have permitted an increase in mean cruising altitudes for long haul flights.

To further evaluate a possible seasonality to the inverse relationship between contrail frequency change and tropopause temperature, we investigated the changes in contrail frequency by individual mid-season months (Table II). These are asymmetric, with the extreme season mid-months (January and July) having contrail frequency increases that are 3–5 times larger than those for the transition-season months (April and October). Because the changes in jet flight activity and flight length are relatively constant between mid-season months (Table II) (BACK Aviation Solutions, 2005), we again infer that the variations in mid-season increases in

Table II. Summary of percent contrail frequency change, percent change in flight characteristics and magnitude of coterminous US-averaged tropopause temperature change between 1977–1979 and 2000–2002 periods.

<table>
<thead>
<tr>
<th>Year/Month</th>
<th>January</th>
<th>April</th>
<th>July</th>
<th>October</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Contrail frequency change</td>
<td>168.1</td>
<td>58.5</td>
<td>201.8</td>
<td>34.8</td>
<td>101.5</td>
</tr>
<tr>
<td>% Increase in jet airplane flight (km)</td>
<td>114.7</td>
<td>118.1</td>
<td>108.6</td>
<td>114.1</td>
<td>113.8</td>
</tr>
<tr>
<td>% Increase in number of departures</td>
<td>57.4</td>
<td>62.2</td>
<td>63.3</td>
<td>63.8</td>
<td>61.7</td>
</tr>
<tr>
<td>% Increase in avg. flight length (km)</td>
<td>36.4</td>
<td>34.5</td>
<td>27.7</td>
<td>30.6</td>
<td>32.3</td>
</tr>
<tr>
<td>ΔTropopause temperature (°C)</td>
<td>−0.77</td>
<td>−0.24</td>
<td>−0.74</td>
<td>−0.28</td>
<td>−0.51</td>
</tr>
</tbody>
</table>
contrail frequency respond primarily to changes in flight-level meteorology; specifically, the tropopause-level temperature decreased as this feature rose between the earlier and contemporary periods. The strong inverse association between contrail frequency changes and US-averaged tropopause temperature change for mid-season months again is evident (Figure 8). Tropopause temperature decreased the most in January and July, and least in April and October.

To assess the potential role of the AO teleconnection in the spatially asymmetric changes of tropopause temperature between the two study periods, we used composite analysis of tropopause characteristics (temperature, pressure-altitude) for extreme years (i.e. highly positive, highly negative) in the AO Index (AOI) occurring since 1950 (Thompson and Wallace, 2000). The AOI measures the zonal difference in sea-level pressure between middle latitudes and the polar region. Positive (negative) anomaly values indicate higher pressure over middle latitudes and lower pressure over the Arctic (lower pressure in middle latitudes and higher pressure over the Arctic), relative to longer-term normals. The mean AOI value was strongly negative (−1.34) for the 1977–1979 period and weakly positive (0.25) for the 2000–2002 period; a trend consistent with that found by other authors (e.g. Greatbatch et al., 2003; Rind et al., 2005). This trend should be evident in the broadscale circulation patterns, potentially including the tropopause temperature change between these two periods. The mean AOI for the five highest (five lowest) years is 1.73 (−2.10). Accordingly, the mean difference in tropopause temperature for the coterminous United States between these two groups of years (Figure 9) broadly resembles that shown for the tropopause temperature mean change between the two contrail study periods (i.e. 1977–1979 and 2000–2002) (Figure 4), only with more (less) warming (cooling) in the West (East). Moreover, the pattern in Figure 9 is little altered if the AOI criteria are relaxed so that the 10 most positive and 10 most negative years occurring since 1950 are composited (not shown). Thus, Figure 9 suggests that the tropopause temperature change noted between the early and contemporary periods, and its associated spatial variations in contrail frequency change, were related to changes in hemispheric-scale circulation involving the AO.

**Figure 8.** The mid-season month variations of contrail frequency change (CF ∆) (number of contrail grid cells/100 images) and tropopause temperature change (TT ∆ (°C)) for 2000–2002 minus 1977–1979.

**Figure 9.** Differences in mean tropopause-level temperature between 5-year composites of the most positive (1989, 1990, 1992, 1993, 2002) and the most negative (1958, 1960, 1966, 1969, 1970) AO years.
CONCLUSIONS

This study documents a contemporary period, satellite-based climatology of jet contrail incidence for the contiguous United States, as well as the first estimate of contrail frequency changes for this same large area occurring since the earlier (1977–1979) climatology of DeGrand et al. (2000). We show that changes in contrail frequency across a wide range of temporal scales (i.e. seasonally, annually, and inter-decadally between the 1977–1979 and 2000–2002 periods), and also spatially, are not controlled solely by changes in jet aircraft flight activity but are combined with changes in atmospheric conditions near the cruising altitudes of jet aircraft; the tropopause. There is no correlation between the contemporary period mid-season month variations in contrail frequency and variations in aircraft flight activity, as quantified by the number of mean daily scheduled jet departures, mean daily jet flight kilometers, and mean monthly flight length. This is further reinforced by an increase in contrail frequency during the four mid-season months following the 11 September 2001 terrorist attacks when flight activity was temporarily reduced. Even during periods of reduced flight activity it appears that a sufficient number of jets are available to generate contrails, as long as ‘favorable’ atmospheric conditions occur.

The US-wide average contrail frequency change is similar to the increase in mean daily jet flight kilometers. However, the spatial and seasonal distribution of contrail frequency change is not uniformly distributed, again indicating that factors other than changes in flight activity control contrail increases over time. When analyzing contrail frequency changes for specific spatial regions and on shorter periods, a strong association appears with variations in tropopause-level conditions (temperature, pressure-altitude). Changes are greatest for the eastern half of the United States, in particular, the region immediately south of the Great Lakes, with significantly smaller values in the western United States, and even some slight reductions in contrail frequency in parts of the far West. The spatial increases (decreases) in contrail frequency between the two periods correlate significantly with cooling (warming) at the tropopause, associated with this feature’s increased (decreased) altitude. A similar association exists seasonally, with the months having the greatest contrail frequency increases (January and July) also experiencing the greatest decrease in tropopause average temperature.

The importance of variations in tropopause temperature, primarily controlled by variations in its height (i.e. pressure-altitude), has strong implications for future contrail increases and links to possible anthropogenic climate change (Gierens et al., 1999; Marquart et al., 2003). The tropopause variations that are shown here to be important for contrail frequency are influenced, at least in part, by a trend towards more positive values in the AO teleconnection. Thus, to estimate, as accurately as possible, future contrail frequency changes and related changes in contrail-derived cirrus cloudiness, it is appropriate to try to anticipate broad changes in circulation patterns, such as those related to the AO, for their potential influence on the tropopause. Such atmospheric factors are additional to those accompanying anticipated changes in jet flight activity.

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