Regional Variations in U.S. Diurnal Temperature Range for the 11–14 September 2001 Aircraft Groundings: Evidence of Jet Contrail Influence on Climate

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ABSTRACT

The grounding of all commercial aircraft within U.S. airspace for the 3-day period following the 11 September 2001 terrorist attacks provides a unique opportunity to study the potential role of jet aircraft contrails in climate. Contrails are most similar to natural cirrus clouds due to their high altitude and strong ability to efficiently reduce outgoing infrared radiation. However, they typically have a higher albedo than cirrus; thus, they are better at reducing the surface receipt of incoming solar radiation. These contrail characteristics potentially suppress the diurnal temperature range (DTR) when contrail coverage is both widespread and relatively long lasting over a specific region. During the 11–14 September 2001 grounding period natural clouds and contrails were noticeably absent on high-resolution satellite imagery across the regions that typically receive abundant contrail coverage. A previous analysis of temperature data for the grounding period reported an anomalous increase in the U.S.-averaged, 3-day DTR value. Here, the spatial variation of the DTR anomalies as well as the separate contributions from the maximum and minimum temperature departures are analyzed. These analyses are undertaken to better evaluate the role of jet contrail absence and synoptic weather patterns during the grounding period on the DTR anomalies.

It is shown that the largest DTR increases occurred in regions where contrail coverage is typically most prevalent during the fall season (from satellite-based contrail observations for the 1977–79 and 2000–01 periods). These DTR increases occurred even in those areas reporting positive departures of tropospheric humidity, which may reduce DTR, during the grounding period. Also, there was an asymmetric departure from the normal maximum and minimum temperatures suggesting that daytime temperatures responded more to contrail absence than did nighttime temperatures, which responded more to synoptic conditions. The application of a statistical model that ‘‘retro-predicts’’ contrail-favored areas (CFAs) on the basis of upper-tropospheric meteorological conditions existing during the grounding period, supports the role of contrail absence in the surface temperature anomalies; especially for the western United States. Along with previous studies comparing surface climate data at stations beneath major flight paths with those farther away, the regionalization of the DTR anomalies during the September 2001 ‘‘control’’ period implies that contrails have been helping to decrease DTR in areas where they are most abundant, at least during the early fall season.

1. Introduction

An important consideration in identifying the climate impacts of changes in cloud radiative forcing are the role of high clouds, including the ‘‘false cirrus’’ condensation trails (contrails) generated by jet aircraft. Contrails may persist as ‘‘outbreaks’’ on multihour (3–6 h) time scales and over space scales of more than 1000 km^2 (Travis et al. 1997; Penner et al. 1999; Minnis et al. 2002). These contrail outbreaks may obscure a substantial portion of the sky or mix with ‘‘natural’’ cirrus to enhance the total cloud amount (Bakan et al. 1994; Travis et al. 1997; Duda et al. 2001; Fig. 1). Hence, the radiative forcing produced by contrails may be significant for those regions of the United States characterized by many such outbreaks (e.g., the Midwest, parts of the West Coast, the Northeast and Southeast; Minnis et al. 1997; Sassen 1997; DeGrand et al. 2000).

Some researchers have speculated that persisting contrails exacerbate ‘‘global warming’’ in areas where they

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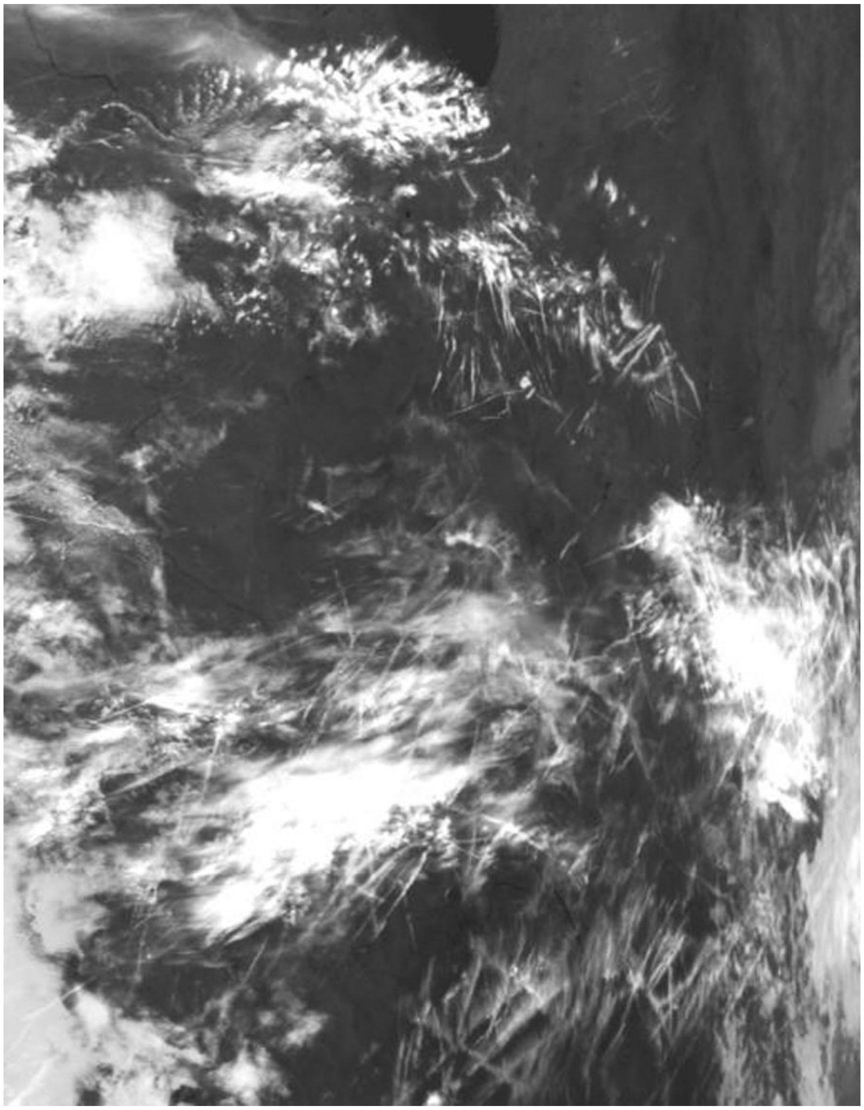

FIG. 1. AVHRR thermal IR (band 4) image (at 1.1-km resolution) of a contrail ‘‘outbreak’’ over the Midwest taken at 1000 UTC 11 Sep 1995. The southern tip of Lake Michigan can be seen at the top of the image.

most frequently occur, due to their ability to reduce outgoing infrared radiation while transmitting some solar radiation to the surface; similar to natural cirrus (e.g., Meerkotter et al. 1999). However, there is probably a diurnal dependence to the role of contrails in radiative forcing that is missing in the case of natural cirrus, and that is enhanced by the strong diurnal variability of aircraft flight frequencies. Because contrails contain a higher density of relatively small ice crystals compared with natural cirrus clouds (Murcray 1970; Gothe and Grassl 1993), the contrail radiative forcing during daylight hours may be dominated by the higher albedo of contrails versus natural cirrus, leading to a potential surface ‘‘cooling’’ (Mims and Travis 1997). At night, the infrared forcing of contrails dominates relative to clear-sky conditions, producing a surface ‘‘warming’’ effect similar to natural clouds. Thus, when considered across a 24-h period it is possible that the net contrail radiative forcing is relatively small. However, the combination of both the daytime cooling and nighttime warming effects should result in a decrease in the diurnal temperature range (DTR), as shown in previous case studies (e.g., Travis and Changnon 1997; Travis et al. 2002). Thus, a need exists to investigate the net effect of contrails on surface temperature across a range of geographic regions and synoptic conditions, especially because significant decreases in DTR have been reported for some areas of the United States during the second half of the twentieth century, including those where contrails are most abundant (e.g., Karl et al. 1993; Travis and Changnon 1997).

Previous attempts to identify a contrail effect in the

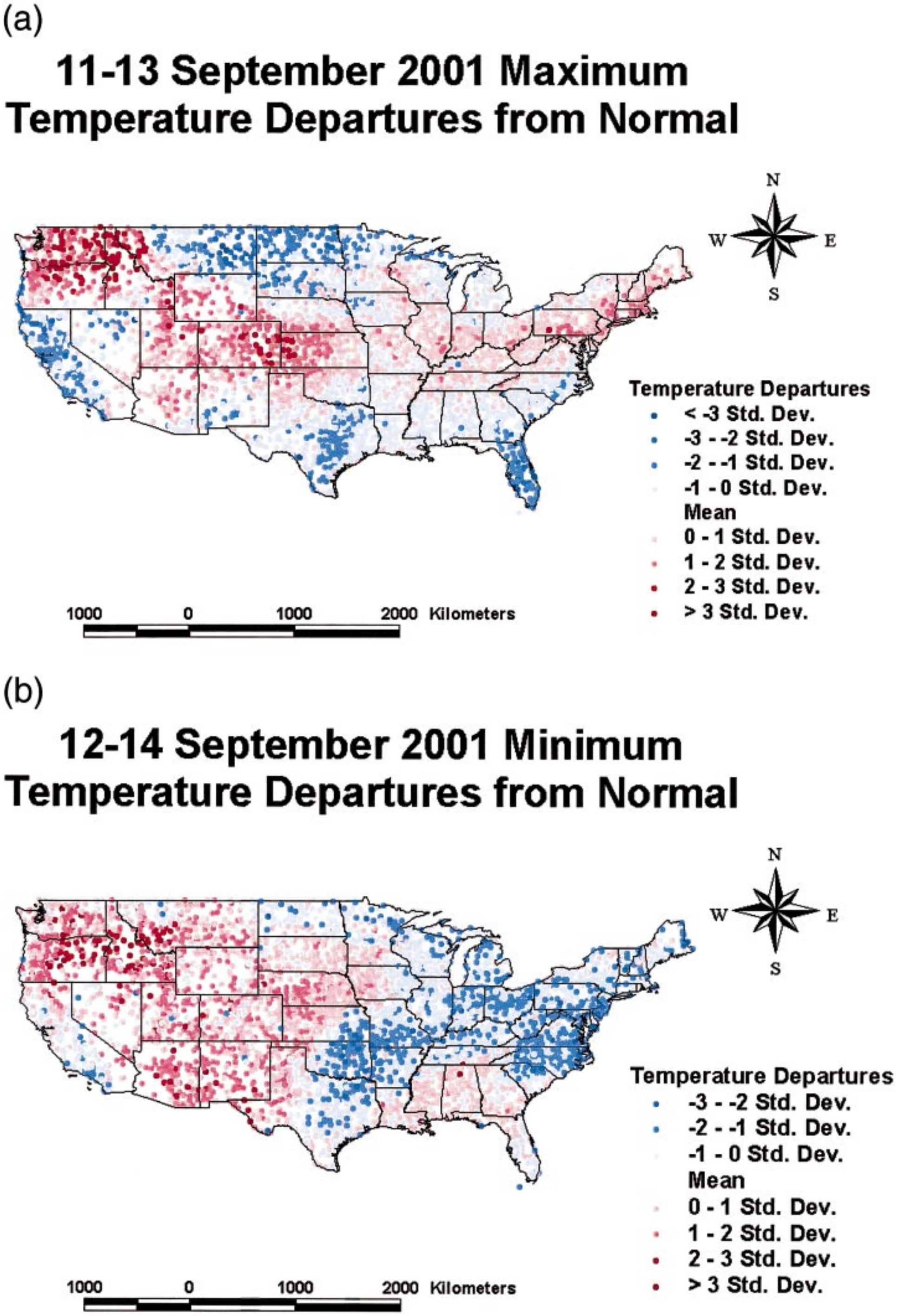

FIG. 2. Map of weather station std dev departures from normal of (a) 11–13 Sep 2001 max temperature ($T_{\max}$), and (b) 12–14 Sep 2001 min temperature ($T_{\min}$).

climate record have been based mostly on circumstantial evidence; from comparisons of locations with high frequencies of jet aircraft flights or contrails to adjacent locations having fewer (Changnon 1981; Travis and Changnon 1997; Allard 1997). Accordingly, it has been difficult to quantify a contrail effect because of the lack of a comparison ‘‘control’’ period during which persisting contrails were absent significantly longer than their typical life span. The grounding of all commercial aviation in U.S. airspace for approximately 72 h between 11 and 14 September 2001 that followed the terrorist hijackings of four jetliners in U.S. airspace pro-

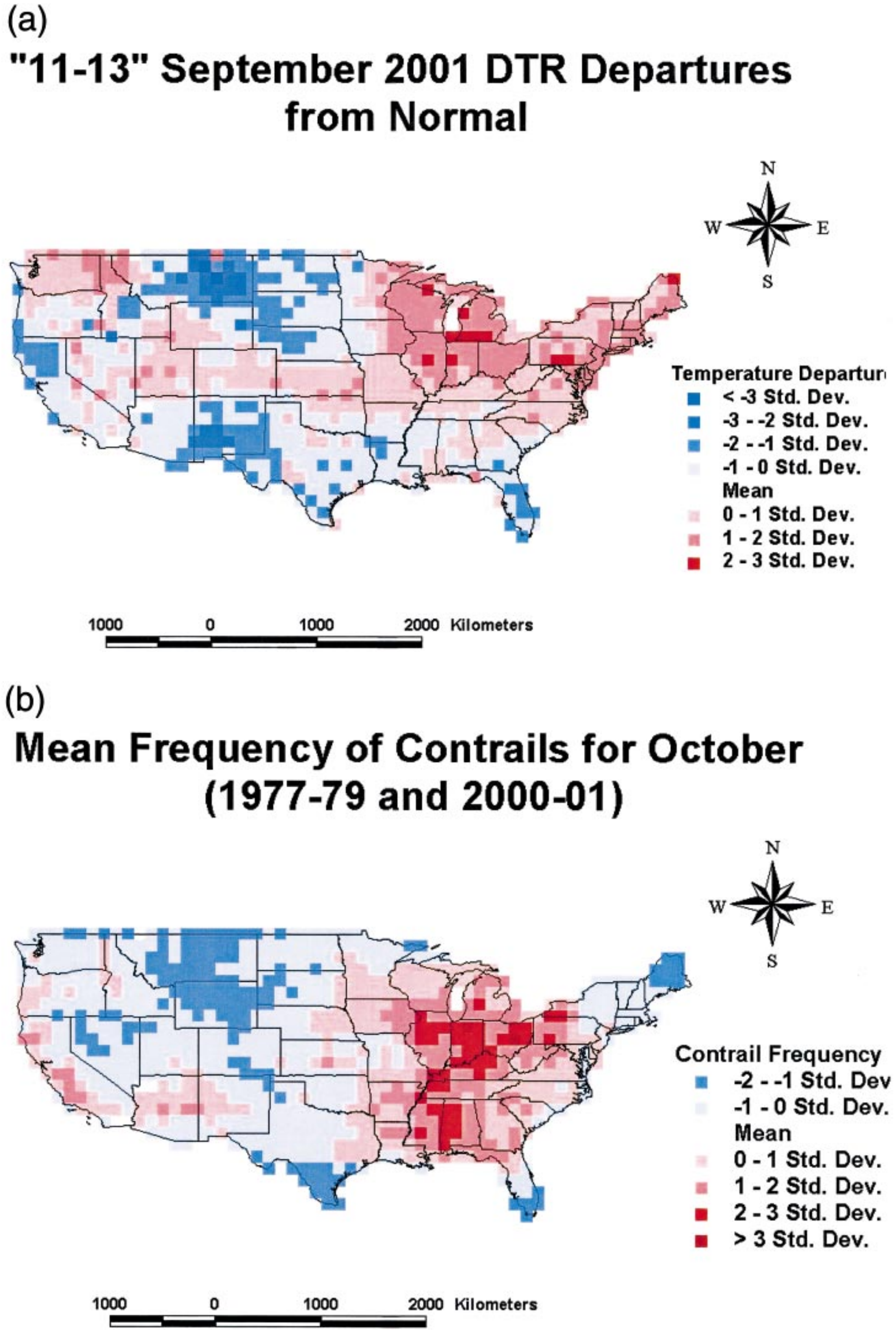

FIG. 3. Map of 1° × 1° resolution (a) grid cell–averaged DTR std dev departure values from long-term (1971–2000) normals for 11–13 Sep 2001, and (b) the combined 1977–79 and 2000–01 mean contrail frequency for Oct.

vides an unexpected opportunity to investigate the regional-scale as well as U.S.-wide effects of contrails on DTR. Our previous study (Travis et al. 2002) has shown that the U.S.-averaged DTR departure for the grounding period increased by approximately 1°C compared to the long-term normals (1971–2000), and 1.8°C compared to the average departure of the adjacent 3-day periods.

To evaluate the presence and magnitude of U.S. re-

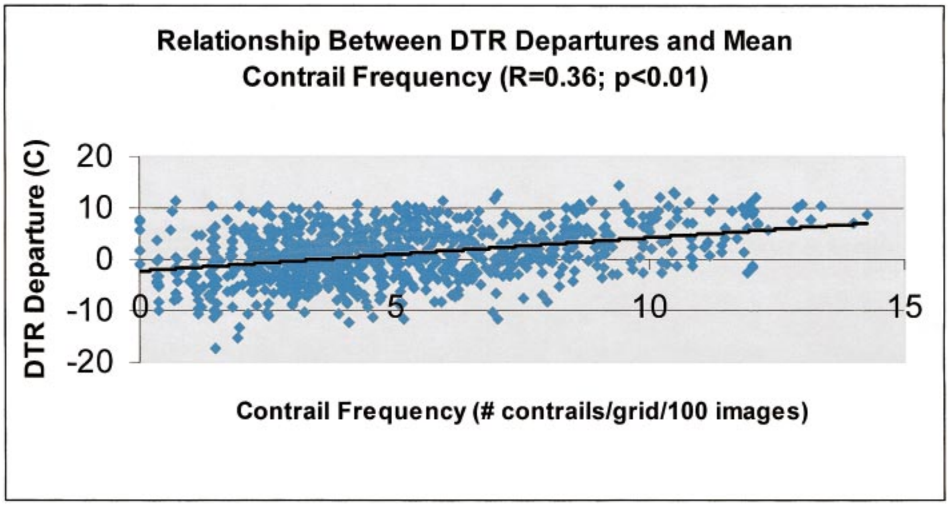

FIG. 4. Scatterplot of the relationship between 11–13 Sep 2001 DTR departures and mean combined 1977–79 and 2000–01 contrail frequency for Oct ($R = 0.36$; $p < 0.01$).

gional-scale DTR anomalies during the grounding period, and determine any associations with the frequency of contrail coverage typically experienced during the fall season, we utilize combinations of surface temperature observations, high-resolution satellite data, and synoptic-scale meteorological reanalyses. Moreover, we provide evidence linking the lack of jet contrails during the grounding period to most observed increases in regional DTR, and also to the asymmetric changes in maximum and minimum temperatures from which DTR is derived.

2. Data and methods

a. Station temperature data

Station data on the daily maximum temperature ($T_{\max}$) and minimum temperature ($T_{\min}$) for all first-order, automated, and cooperative stations in the United States, were obtained from the National Climate Data Center (NCDC 2003) for the most recent 30-yr ''normals'' period (1971–2000), plus 2001 for the grounding period. Although daily normals were available for a total of 5556 stations, data for only 5404 of those stations were available for the 2001 study period. In addition, many of the stations were cooperative observing sites that record maximum and minimum temperatures from only one observation per 24-h period, unlike the remaining first- and second-order stations that compute daily maxima and minima from continuous observations starting after midnight each day. Thus, it was necessary to standardize the cooperative data by observing time. To ensure that the daily maxima and minima for 11–14 September 2001 were assigned to the correct day, we only included those stations that recorded observations between 0700–0900 or after 1600 local time (LT). When observations were recorded between 0700 and 0900 LT the $T_{\max}$ value was assumed to represent the value for the previous day, and when observed after 1600 LT, for the current day. Because only observations from 0700 LT and later were included, each daily $T_{\min}$ was assumed to represent the current day's value. These standardization efforts still allowed 4233 stations to be utilized in the temperature analyses, with a reasonably even distribution across the United States (Fig. 2).

Because the aircraft-grounding period began during midmorning (eastern standard time) on 11 September and ended around noon on 14 September,[1] it was necessary to stagger the calculations of average $T_{\max}$, $T_{\min}$, and DTR across adjacent days. Thus, the afternoon of 11 September and the morning of 14 September represent the beginning and end periods, respectively, of the analysis. The average $T_{\max}$ was calculated as the mean of all such observations for 11–13 September (Fig. 2a) and the mean $T_{\min}$ was calculated as the average of all such observations for 12–14 September (Fig. 2b). The DTR values for ''11 September'' were calculated by subtracting each station's minimum temperature on 12 September from its maximum on 11 September, and similarly for the rest of the grounding period. The DTR values so calculated were then averaged for the ''11–13'' September 2001 period. To evaluate DTR values for the 3-day grounding period in context of the contemporary climatology, we calculated DTR in a similar way for each 11–13 September period for 1971–2000; thus, providing long-term station DTR normals (NCDC 2003). DTR departures for 11–13 September 2001 were then calculated by subtracting station values for 2001 from the corresponding 1971–2000 normals.

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[1] A relatively small number of short flights (approximately 4000) took place during the evening of 13 September to reposition aircraft that were redirected during the shutdown on the morning of 11 September. These should not affect the conclusions of this study.

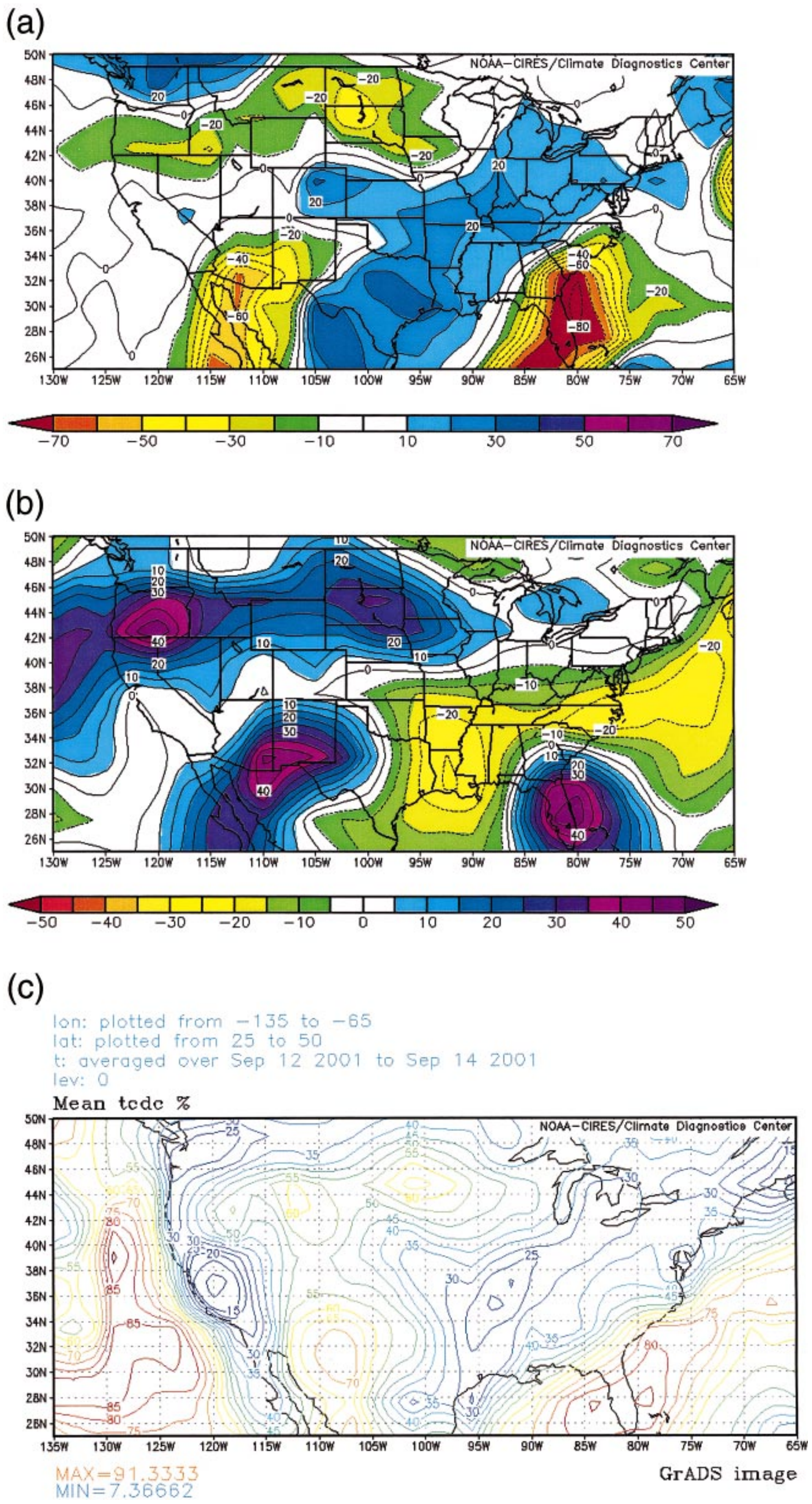

FIG. 5. Mapped 3-day average (12–14 Sep 2001) of (a) anomalies of OLR in W m^{-2}, (b) anomalies of relative humidity at 500 hPa; RH(500) in percent; and (c) mean percentage of total cloud sky coverage, derived using the NCEP–NCAR reanalyses.

b. *Satellite data on contrail outbreaks*

To best represent the variations in frequency and density of ''typical'' contrail coverage across the United States during the fall season for both the recent historical and contemporary periods, we combined two satellite-based data sources of contrail frequency: one previously published and the other original. The first was an analysis of contrail frequency over the conterminous United States for the 1977–79 period based on manual interpretation of high-resolution (0.6 km) Defense Meteorological Satellite Program (DMSP) satellite imagery (DeGrand et al. 2000). This study determined the frequency of contrail occurrence per 1° × 1° grid cells for each of the four midseason months. October was the closest month to our study period and provides an approximation of contrail frequency for the fall season (DeGrand et al. 2000). The procedures used in the recent historical contrail study were duplicated here for the months of October 2000 and 2001, to estimate contrail frequency for the contemporary fall season period. The only exception to this was the satellite data source. For 2000–01, the nonavailability of a dataset having identical temporal and spatial resolutions to the DMSP imagery necessitated that we use data from the Advanced Very High Resolution Radiometer (AVHRR). The AVHRR has a slightly coarser nadir resolution (1.1 km) yet comparable temporal and spatial coverage to that of the DSMP for the 1977–79 period. The slight decrease in resolution of the AVHRR compared with the DMSP should have only a small impact on the ability to recognize *single* contrails (Detwiler and Pratt 1984). More importantly, from the climatic perspective, our use of AVHRR should not substantially impact the relative frequency of regional contrail coverage (i.e., that due to multiple contrails occurring simultaneously). An average of four images per day were analyzed across the two study periods to approximate the regional variations in mean contrail frequency during the climate normals and 2001 periods. The locations of each contrail were stored in a geographic information system (GIS) database [Environmental Systems Research Inc., (ESRI) 1999] for subsequent manipulation and statistical analyses.

Contrails are best distinguished from natural clouds using the infrared band 4 of the AVHRR that is present on all of the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites. We followed the manual pattern recognition method described in Carleton and Lamb (1986) and DeGrand et al. (2000). This method identifies contrails as linear cloud features that are oriented in random directions, unlike natural high clouds, which typically follow the prevailing synoptic flow of the upper troposphere (e.g., Fig. 1). We obtained the contrail dataset for the recent historical period and combined it with our contemporary data to produce mean 1° × 1° resolution contrail frequencies for the conterminous United States.

To permit statistical analyses comparing DTR departures with these satellite-based contrail data it was also necessary to convert all of the point-location weather station observations into grid-averaged (1° × 1°) values. This was accomplished using the same contrail grid GIS database, and spatially associating the location of each grid cell with the underlying weather stations. We then calculated the average temperature values for all weather stations within each cell. The U.S.-averaged number of stations per grid cell was 3.2. When no weather stations existed in a particular grid cell (for 26 of 900 total grids) the grid value was interpolated from the four adjacent grid values. If four adjacent grid values were not available (e.g., along international border and coastal regions) the grid was not included in any further analysis. This procedure resulted in a total of 882 grid cells (98%), containing both fall season contrail frequencies and 11–13 September DTR anomalies, to test the hypothesis that an association existed between the two.

c. *Analysis of synoptic weather conditions*

To more definitively link the regional DTR anomalies with the absence of jet contrails during the grounding period, it is necessary to evaluate the synoptic weather conditions occurring over the conterminous United States. For example, a stagnant weather pattern with anomalously dry air (i.e., low humidity, lack of optically thick clouds) over a large region of the United States for the greater part of the 3-day period, could provide an alternative explanation for the observed anomalous increases in U.S.-averaged DTR (Travis et al. 2002). We used the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis daily-averaged data on top-of-the-atmosphere outgoing longwave radiation (OLR) as a surrogate for cloud cover, and 500-hPa relative humidity to depict tropospheric moisture for the grounding period [NOAA–CIRES (Cooperative Institute for Research in Environmental Sciences) 2002]. We computed the 3-day-averaged departure of each parameter for the grounding period (12–14 September) from its corresponding climatological normal. These were compared to the maps of DTR and T_{max} and T_{min} for the same period for visual associations.

d. *Application of a contrail outbreak ''retro-prediction'' method*

It is instructive to estimate where contrails likely would have occurred if commercial aircraft flights had continued as normal for the 11–13 September period. For this purpose we developed a ''retro-prediction'' (retrodiction) statistical method for contrail outbreaks occurring in otherwise clear air. The retrodiction method uses statistical composites (i.e., ensemble averages and variances) of the upper-tropospheric (300, 250, 200 hPa) meteorological conditions associated with 48 outbreaks that occurred over the conterminous United States during the 8–16 September periods of 1995–97 and 1999–2001 (the calibration period). Data on meteorological parameters (temperature, humidity, vertical wind shear, vertical motion) previously shown (e.g., Appleman 1953; Schrader 1997; Travis 1996; Travis et al. 1997; Chlond 1998; Kästner et al. 1999) to influence the formation likelihood and persistence time of contrails, were acquired for each outbreak using the 6-hourly NCEP–NCAR reanalyses (Kistler et al. 2001). The outbreak data were then expressed as anomalies from the long-term means for each variable, pressure level, and location, and averaged to yield the composites. For the calibration period, the following outbreak meteorological variables/tropospheric levels were statistically different from climatology: increased values of humidity at 300 hPa (RH range $= +7.5\%$–$+58.0\%$), lower temperature and reduced Z_{300}–Z_{200} thickness (-6.5 m), light easterly u-wind anomalies at 250 hPa (range $= -2.2$ to -2.9 m s^{-1}), and slightly negative (i.e., upward) vertical motion (mean $= -0.54 \times 10^{-3}$ Pa s^{-1} at 250 hPa). Using GIS, we applied the outbreak composite statistical ranges to two independent sets of reanalyses ‘‘test’’ periods: 8–16 September 1998, and the day immediately preceding, and also immediately following the grounding period. The AVHRR imagery for these periods was also inspected for contrail outbreaks. Using a test criterion of a minimum of 50% spatial overlap between the retrodicted and observed contrail outbreaks, we found good agreement (25 out of the 30 cases). This allowed us confidently to apply the method to the upper-tropospheric reanalyses for the grounding period. The resulting contrail-favored areas (CFAs) mapped locations, and their associations with DTR departures, are discussed in section 3d.

3. Results and discussion

a. T_{max} and T_{min} spatial trends

Although both the 3-day U.S.-averaged $T_{\max}$ and $T_{\min}$ were warmer than normal for the grounding period, the $T_{\min}$ increase (0.3°C) was about one-fourth that of $T_{\max}$ (1.2°C). This asymmetric variation from the long-term means may indicate that the lack of contrails impacted the daytime temperatures more than those at night. Such a possibility accords with the observed greater frequencies of contrails during daytime versus nighttime hours, in association with diurnal differences in the frequencies of jet aircraft flights (Bakan et al. 1994; Minnis et al. 1997).

The spatial patterns of $T_{\max}$ for 11–13 September 2001 (Fig. 2a) show strongest increases in the Intermountain West and Pacific Northwest, extending through the Midwest and into the northeast United States. Strongest decreases of $T_{\max}$ occurred in California, the northern Great Plains, the Southwest, and Florida. For $T_{\min}$ (Fig. 2b) the largest increases were in the West (except California) and the Gulf Coast states. The largest combined increase of $T_{\max}$ and $T_{\min}$ occurred in portions of the Northwest. This can be partially attributed to a persistent southerly flow that was produced from synoptic-scale circulations associated with a storm system centered off the northern California coast for much of the grounding period. This storm also likely contributed to the large decrease in $T_{\max}$ seen in northern California due to extensive daytime cloud coverage. Strong decreases in $T_{\min}$ occurred through the southern Great Plains, Midwest and Great Lakes, the Mid-Atlantic region, and the northeast United States. Possible associations between these spatial variations of $T_{\max}$ and $T_{\min}$ departures, and the lack of contrails during the grounding period, are discussed in section 3c.

b. DTR spatial trends and associations with contrail frequency

The spatial variation of the grid-averaged DTR anomalies for the grounding period (Fig. 3a) shows that the largest positive departures extended across portions of the central and northeast United States as well as the Pacific Northwest. Because these regions have previously been reported (Minnis et al. 1997; DeGrand et al. 2000) as being climatologically favorable for outbreaks of persisting contrails, we argue that this anomalous increase was associated with the absence of contrails during the aircraft groundings (Travis et al. 2002), in combination with synoptic conditions.

To identify the relationship between the regional DTR increases of the grounding period and spatial variations in the typical fall-season contrail coverage, Fig. 3b summarizes the mean contrail frequency (combined 1977–79, 2000–01) averaged for the same 1° × 1° grids as the DTR data. The frequency pattern of contrails for this period appears broadly similar to that shown in previous studies for other times of the year (Minnis et al. 1997; DeGrand et al. 2000), with the contrail frequency maxima occurring in the Midwest, Southeast, and parts of the West.

Visual comparison of Figs. 3a and 3b suggests some agreement between those regions having the largest increases in DTR during the grounding period and those typically experiencing the greatest contrail coverage during the fall season. To quantify the presence and strength of this relationship a Pearson correlation coefficient was calculated between DTR departure and contrail frequency for the 882 grids available for analysis (Fig. 4). The statistically significant positive relationship ($R = 0.36$; $p < 0.01$) supports our contention that a contrail-induced suppression of DTR was present in the 1971–2000 normals throughout much of the United States, and especially in areas where contrails are typically most prevalent. Moreover, the gradual reduction in statistical scatter about the trend line as contrail frequency increases may indicate that the contrail ‘‘signal'' in DTR departure was more distinguishable from synoptic-scale ''background'' influences for those grids having the highest mean contrail frequency.

c. Synoptic variations in cloud and humidity during the grounding period

The 3-day average (12–14 September 2001) OLR anomaly map (Fig. 5a) shows positive departures (i.e., fewer clouds or lower mean cloud-top altitude) in a swath extending from the south-central United States through the Midwest and into the mid-Atlantic regions. A smaller area of OLR positive departures also occurred in the Pacific Northwest. In contrast, OLR negative departures (i.e., more clouds or higher mean cloud-top altitude) occurred over the Southwest, Florida, and the extreme southeast United States, and parts of the Intermountain West extending through the northern Great Plains. The remainder of the country had close to normal departures of OLR for the grounding period. A comparison of the OLR anomaly field with that of the midtropospheric (500 hPa) relative humidity [RH(500); Fig. 5b], shows general consistency: areas of positive (negative) relative humidity departure accompany increased moisture and ascent of air (decreased moisture and subsidence), and tend to be associated with negative (positive) anomalies of OLR (Fig. 5a). Thus, about one-half of the United States experienced fewer or lower-altitude clouds than normal during the grounding period; the other half had either near-normal or more than normal/deeper clouds. This statement is supported by the analysis of the mean percentage of total cloud coverage (TCDC; departures not available) for the grounding period (Fig. 5c), which shows good agreement with the OLR departures in most areas of the United States. Stratifying the 3-day averaged RH(500) into daytime and nighttime components (Fig. 6) also shows strong spatial consistency and reduces the possibility that the asymmetrical departures of $T_{\max}$ and $T_{\min}$ reported in section 3a are a result of large diurnal variations in relative humidity.

It is particularly interesting that some of the largest DTR and $T_{\max}$ anomalies in the Intermountain West occurred near the outer edges of the areas having the most positive anomalies of humidity and deepest cloud cover (i.e., Colorado, Utah; Fig. 5). The lack of clouds in the adjacent areas suggests that although moisture levels were above normal (Fig. 5b), they were not sufficient for substantial cloud coverage to form through natural processes. However, because such environments are often conducive to contrail formation [i.e., high humidity but few clouds; Travis et al. (1997); section 3d], it is reasonable to assume that contrails likely would have formed in these areas had airplanes been flying. This implies that the lack of contrails in those areas helped offset the tendency for DTR to decrease when averaged over the 3-day grounding period. Such a possibility is now evaluated using the CFA retrodictions for the same period.

d. Retrodicted contrail outbreaks and associations with DTR anomalies

Figure 7 depicts the grounding-period CFAs derived from the contrail-outbreak retrodiction method (section 2d). To facilitate visual comparisons with the DTR departure map (Fig. 3a), the CFAs were converted to $1° \times 1°$ grids for locations where contrail occurrence was favorable for a minimum of at least 12 h during the grounding period (''moderate susceptibility''). Grid cells over which CFAs existed for more than 50% of the grounding period (i.e., 36 h) were deemed to have ''high susceptibility.'' All remaining grid cells were designated as having ''low susceptibility'' (Fig. 7). The Pacific Northwest, Intermountain West, and Southwest U.S. regions were highly susceptible to contrails during the grounding period (Fig. 7). Smaller regions of contrail high susceptibility included the Midwest, Great Lakes, and Florida. These high susceptibility CFAs coincide with the edges of the positive moisture anomaly areas (Fig. 5b). Such a result concurs well with previous research on contrail–synoptic weather associations, which has reported that contrails occur most commonly along the leading edge of cirrus shields associated with frontal cyclones and convective storms (Detwiler and Pratt 1984; Travis et al. 1997; DeGrand et al. 2000).

A visual comparison of the departure maps for $T_{\max}$ and $T_{\min}$ (Figs. 2a,b) with Figs. 5 and 7 suggests that $T_{\max}$ shows a closer association with the CFA high susceptibility retrodiction (except for Florida), whereas $T_{\min}$ shows a closer association with the synoptics; specifically, OLR and total cloud cover. This may imply that the lack of contrails affected $T_{\max}$ more than $T_{\min}$ during the grounding period, especially in the West. There, the combination of a warm, moist southerly flow and the lack of airplanes led to increasing humidity and temperature but less cloud coverage than otherwise would have occurred from contrail formation; especially during the daytime when air traffic would normally have been greatest (with less impact on $T_{\max}$). In the eastern half of the United States, the increased DTR seems to have resulted from a combination of dry air and lack of clouds (lowers $T_{\min}$, raises $T_{\max}$ and DTR) and the lack of contrails. This is consistent with the observation (section 3a) that the U.S.-averaged $T_{\max}$ increased more than $T_{\min}$ during the grounding period.

Comparing Fig. 7 with the DTR departure map (Fig. 3a) shows strong agreement for much of the west, especially in the Intermountain and Northwest regions. For the entire conterminous United States the average DTR departure for the high susceptibility grid cells (+1.3°C) is statistically greater ($p < 0.01$) than that for the moderate susceptibility (+0.9°C) and the low susceptibility grid cells (+0.8°C). The slightly higher av-

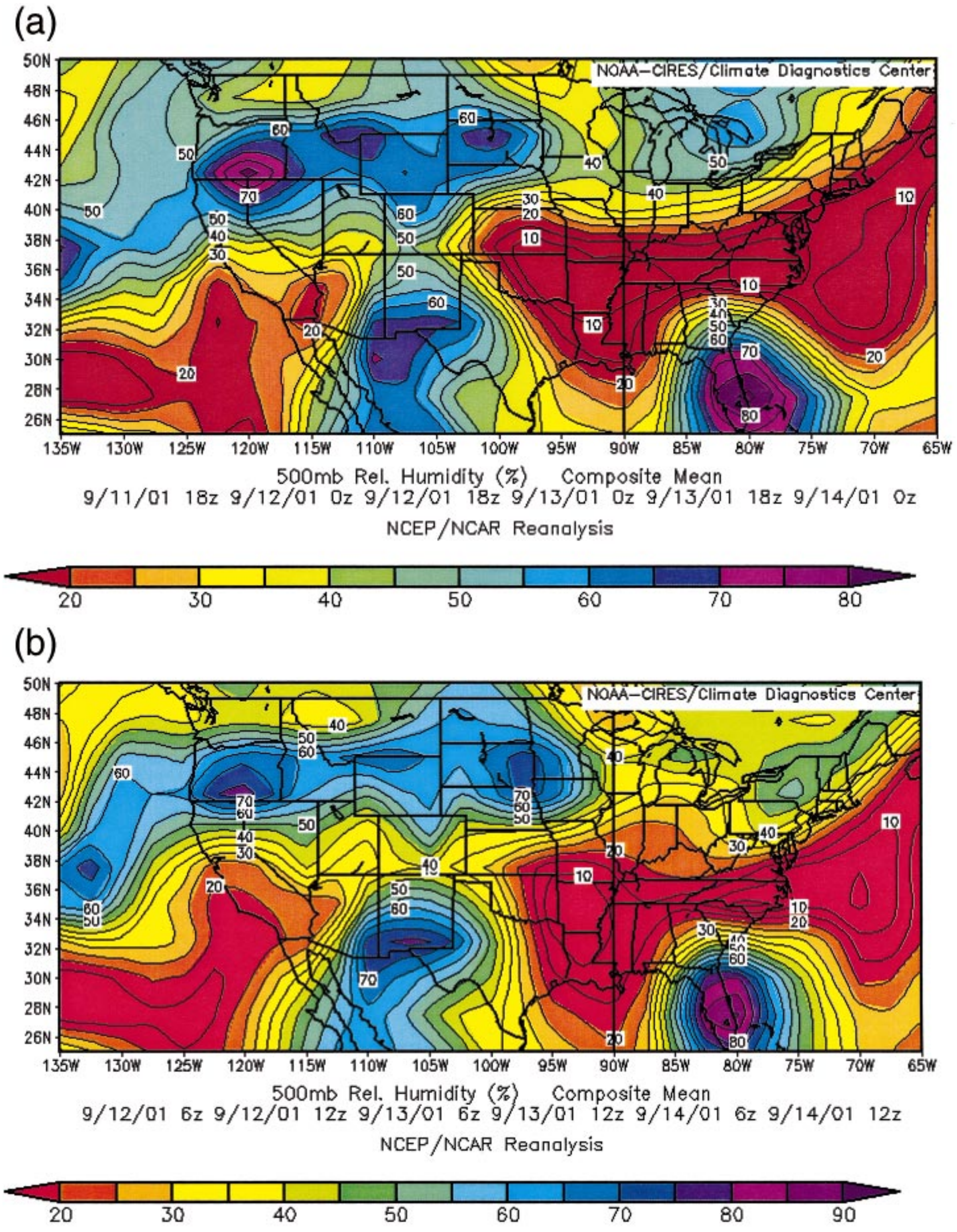

FIG. 6. Mapped 3-day average (1800 UTC 11 Sep 2001–1800 UTC 14 Sep 2001) anomalies of relative humidity at 500 hPa: RH(500) in percent for (a) daytime periods (0000 and 1800 UTC) and (b) nighttime periods (0600 and 1200 UTC), derived using the NCEP–NCAR reanalysis.

erage DTR departures in the moderate susceptibility grid cells compared with the low susceptibility cells are not statistically different. These results further support our contention that the lack of commercial aircraft flying, especially in the areas of contrail high susceptibility, contributed to the 11–13 September DTR anomaly. In combination with the statistical relationship shown earlier between DTR departure and the fall-season contrail frequency (section 3b), this finding implies that the 11–13 September DTR anomaly was caused by a combination of regional-scale, contrail-induced suppression of DTR in the long-term climatological normals and the presence of extensive areas of contrail high susceptibility, which remained unexploited owing to the lack of commercial aircraft flights.

4. Summary and conclusions

These results support the hypothesis that the grounding of all commercial aircraft in U.S. airspace, and the consequent elimination of substantial jet contrail coverage during the 11–14 September 2001 grounding pe-

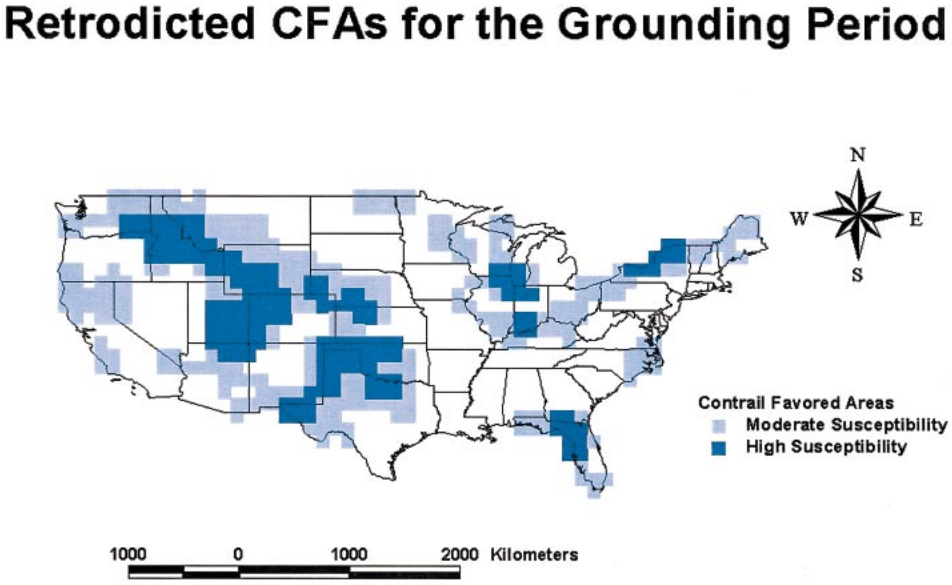

FIG. 7. Grid cell-averaged (1° × 1° resolution) map of CFAs determined for the grounding period (1800 UTC 11 Sep 2001–1800 UTC 14 Sep 2001) using the contrail-outbreak retrodiction method applied to the six-hourly NCEP–NCAR reanalyses of the upper troposphere (refer to text). The lighter (darker) shading refers to moderate (highest) susceptibility of contrail outbreaks. Those regions that were not susceptible to outbreaks are not shaded.

riod, helped produce an enhanced surface DTR in those areas that typically experience the greatest numbers of jet contrails during the fall season (e.g. the Midwest). The DTR anomaly occurred primarily due to large increases in $T_{\max}$ that were not matched by similar magnitude increases in $T_{\min}$. In the West, synoptic weather patterns (mostly cyclonic) during the grounding period appear to have played an important role in enhancing (e.g., the Intermountain region) or negating (e.g., coastal California) the effect of contrail absence on surface temperature. For the country as a whole, the synoptic weather conditions during the grounding period suggest a better association of these with $T_{\min}$ than $T_{\max}$ thus providing a possible partial explanation for the asymmetric response of these two components of DTR.

Our analyses of the AVHRR imagery available for the grounding period indicated several occurrences of single contrails (no outbreaks) produced by military aircraft, including some in the Northeast that demonstrated extensive persistence and spreading characteristics (Minnis et al. 2002). Moreover, the analysis of other imagery showed many contrails occurring just over the border in Canada. When combined with the statistical model retrodictions, these observations suggest that if commercial airplanes had not been grounded, substantial contrail coverage would have been present over large parts of the United States, especially the Pacific Northwest, Intermountain West, upper Midwest, and Great Lakes and the Northeast.

Predicted future increases in aircraft flight frequencies, and subsequent increased occurrences of contrails in the climatologically susceptible extratropics (e.g., Gierens et al. 1999; Minnis et al. 1999), could lead to an even greater influence on DTR. However, potential changes in upper-tropospheric conditions related to global-scale climate change, which can influence both the formation likelihood and persistence time of contrails, need to be considered when projecting future impacts of contrails onto regional-scale climate.

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