A study of contrail spreading over the Great Lakes

David P. Duda
Hampton University, Hampton, VA USA

Patrick Minnis
Atmospheric Sciences, NASA Langley Research Center, Hampton, VA USA

Rabindra Palikonda
AS&M, Inc., Hampton, VA 23666

Abstract for the
10th Conference on Aviation, Range, and Aerospace Meteorology
13-16 May 2002 Portland, OR

J1.2

A STUDY OF CONTRAIL SPREADING OVER THE GREAT LAKES

David P. Duda*
Hampton University, Hampton, VA 23668

Patrick Minnis
Atmospheric Sciences, NASA Langley Research Center, Hampton, VA 23681

Rabindra Palikonda
AS&M, Inc., Hampton, VA 23681

Abstract. We track contrails from 9 October 2000 over the western Great Lakes region using multi-spectral images from the Geostationary Operational Environmental Satellite (GOES) and the Advanced Very High Resolution Radiometer (AVHRR) onboard the NOAA polar orbiting satellites. Using commercial air traffic data from FlyteTrax and the hourly analyses of height, temperature, relative humidity and horizontal and vertical wind speeds for the Rapid Update Cycle-2 (RUC-2) numerical prediction model, we advect and match the flight tracks with contrails detected from satellite imagery. The combination of datasets will be used to test empirical humidity thresholds required for contrail formation and persistence, as well as relate the rate of contrail spreading and growth to the environmental conditions and air traffic density.

1. INTRODUCTION

Contrails are a source of anthropogenic cloudiness. Similar in physical properties to natural cirrus, contrails affect the atmospheric radiation budget and may influence climate. Because air traffic is expected to grow by 2 to 5% annually for the next 50 years, contrail coverage will also increase and may produce a significant amount of radiative forcing by 2050 (Minnis et al., 1999). To understand and accurately predict contrail climatic effects, accurate estimates and predictions of contrail coverage, optical properties and radiative forcing are needed. Of particular interest are predictions of widespread outbreaks of persistent contrails in otherwise clear skies, as these clouds are likely to have the largest impact on the global radiative energy budget. Toward this goal, we will study cases of widespread persistent contrail outbreaks by using actual flight data, coincident meteorological data and satellite remote sensing to determine under which conditions these outbreaks occur, and to test various empirical humidity thresholds required for contrail formation and persistence. With these data, we also plan to develop a more accurate picture of the diurnal variation of contrails. This paper presents a study of a contrail outbreak over the northern Great Lakes during 9 October 2000.

**Corresponding author address*: David P. Duda, NASA Langley Research Center, MS 420, Hampton, VA 23681-2199. email: d.p.duda@larc.nasa.gov.

2. DATA

2.1 Satellite Data

Many persistent contrails developed over the upper peninsula of Michigan and the surrounding region on 9 October 2000. Many of the contrails were visible in the Geostationary Operational Environmental Satellite (GOES) channel 4 infrared (IR) temperature minus channel 5 split-window (SW) temperature imagery for at least 3 to 4 hours before dissipating (Fig. 1). Data from the *NOAA-14* AVHRR 1-km imager taken at 2050 UTC are also available.

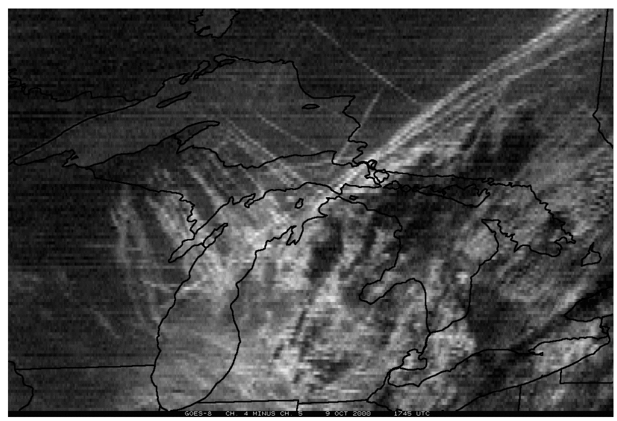

Figure 1. *GOES-8* channel 4 minus channel 5 imagery at 1745 UTC on 9 October 2000 showing many persistent contrails over the western Great Lakes.

Contrails were identified manually in half-hourly *GOES-8* channel 4 minus channel 5 and channel 3 minus channel 4 images from 1015 UTC to 2245 UTC 9 October 2000, and their coordinates were plotted into a database.

2.2 Air Traffic Data

Commercial air traffic data from the FlyteTrax product (FT; FlyteComm, Inc., San Jose, CA) were used to determine flight tracks over the Great Lakes area on 9 October 2000. The database consists of 5-minute readings of aircraft (flight number) position (latitude, longitude, altitude) for every non-military flight over North America. A series of these readings for a particular aircraft flight is referred to here as a flight track, and each reading is called a flight track point. Although the FT database does not include military flights, it contains most of the air traffic over the Great Lakes region.

2.3 Meteorological Data

Atmospheric profiles of height, temperature, humidity and horizontal and vertical wind speeds were derived from the 40-km resolution, 1-hourly Rapid Update Cycle-2 (RUC-2) analyses (Benjamin et al., 1998) in 25 hPa intervals from 375 hPa (approximately 7.8 km) to 175 hPa (approximately 12.9 km). The RUC-2 data were linearly interpolated at each pressure level to a 1°×1° grid at 15-minute intervals from 1000 UTC to 2300 UTC 9 October 2000.

3. METHODOLOGY

3.1 Advection of Flight Tracks

The horizontal winds were used to advect the flight track of a given aircraft for each 15-minute interval. To simplify the advection scheme, the flight tracks were assumed to be located at the pressure level nearest the altitude indicated in the FT database and advected at that level until the end of the simulation (2300 UTC). The north-south (u) and east-west (v) wind speed vectors were combined to compute the wind speed and bearing over the 15-minute time step, and a simple middle-latitude approximation was used to compute the new latitude and longitude at each time step as follows.

$$Lat_2 = Lat_1 + D\cos(\beta) \qquad (1)$$

$$hs = 0.5(\cos(Lat_1) + \cos(Lat_2)) \qquad (2)$$

$$Lon_2 = Lon_1 + \frac{D\sin(\beta)}{hs} \qquad (3)$$

Here, Lat_1 and Lat_2 are the old and new latitudes, Lon_1 and Lon_2 are the old and new longitudes, D is the distance the flight track is advected in each time step, and β is the bearing of the advecting wind, defined as the direction the wind is blowing *toward* in geographic azimuth.

3.2 Matching flight tracks with contrails

The flight tracks were matched using a contrail-centered geographic system assuming a circular earth. The contrails were divided into linear segments and a great circle arc through each segment was found using a series of geometric vector operations. This great circle arc serves as the "equator" of the new geographic system. In addition, a contrail segment-based "longitude" system was used to find the longitudinal distance (D_l) of each flight track point from another great circle arc placed perpendicular to the first great circle and centered on the westernmost end of the contrail segment.

For each time step, the shortest distance (D_s) of all possible flight track points (including current flights and flights advected from an earlier time) from the first great circle was computed. If the flight track does not extend across the longitudinal range of the contrail, the flight track is not considered. For all other flight tracks, D_s is found for all points inside the longitude range of the contrail, and averaged over that range. The flight track with the minimum average D_s is chosen as the flight track matching the contrail.

4. RESULTS

The contrails began forming over the Great Lakes area around 1200 UTC and continued throughout the day. They generally moved to the southwest into Wisconsin, Indiana, and Illinois where they massed into nearly continuous decks of cirrus clouds before dissipating by 0200 UTC 10 October 2000. The typical width for a given contrail was 22 km approximately 3 hours after it was first seen in the GOES imagery. At 1745 UTC, the spreading contrails covered an area of nearly 25,000 km2 over Wisconsin, southern Ontario, the upper peninsula of Michigan, and Lakes Michigan and Superior. By 2050 UTC (Fig. 2), the contrails that could still be identified as such covered an area of more than 24,000 km^2 with an average visible optical depth of 0.14. This coverage does not include the cirrus clouds in Illinois and western Wisconsin that were formed from older contrails.

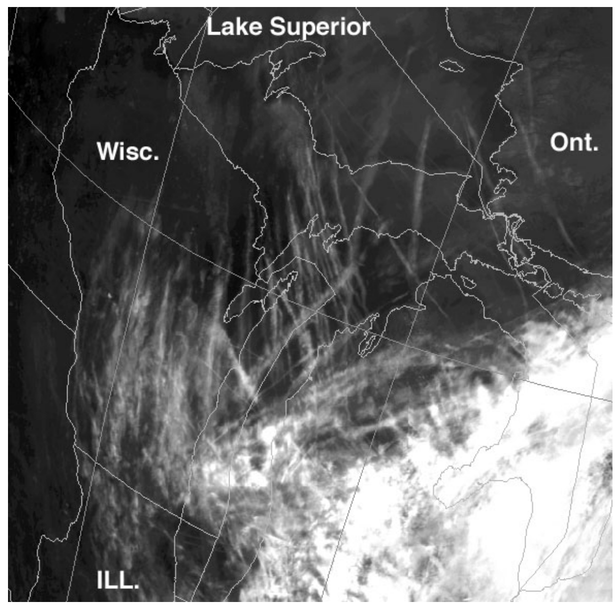

Figure 2. NOAA-14 AVHRR IR image, 2050 UTC, 9 October 2000.

Figure 3 shows the matched flight tracks and contrail segments identified from the *GOES-8* imagery at 1745 UTC. Several of the contrails are well matched to individual flights, although some trails cannot be well matched due to the presence of military flights and limitations in the flight advection/matching scheme. Good matches between the flight tracks and all of the contrails are unlikely due to uncertainties and errors arising from several sources. These include the initial flight track positions, the estimation of contrail location from the GOES imagery, and the advection of the flight tracks using the RUC model winds. The advection of the flight tracks is probably subject to the most uncertainty since the winds from a single pressure level are currently used, while the contrails are continually falling and are influenced by winds at different levels. Setting a maximum threshold of 10 km on D_s eliminated most of the poorer matches. The mean altitude

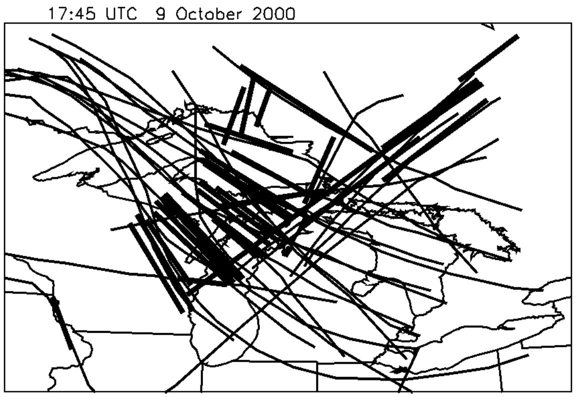

Figure 3. Contrails visually identified in *GOES-8* imagery (thick lines) matched with the nearest flight tracks of commercial aircraft from FlyteTrax (thin lines) at 1745 UTC 9 October 2000. Flight tracks from earlier times were advected to the present time using the RUC horizontal winds at the pressure level closest to the initial flight track altitude.

(pressure level) of the flight tracks that most closely matched the contrails was 36,000 ft (225 hPa).

From the classical Appleman (1953) criteria for persistent contrail formation, persistent contrails form when the relative humidity with respect to ice (RHI) is 100 percent or greater. Widespread cirrus formation is expected to occur above the humidity level required for homogeneous nucleation. Such cirrus would obscure and deplete much of the moisture needed for contrail formation. Sassen and Dodd (1989) developed a theoretical model of the RHI threshold for homogeneous nucleation at temperatures below 238 K. Their results were fit with a polynomial to yield the following RHI threshold for the formation of cirrus,

$$RHI_{cirrus} = 1.09559\times10^{-4}T^3 - 7.77598\times10^{-2}T^2 + 1.77725\times10^{1}T - 1160.77 \quad (4)$$

In equation (4), temperature T is in Kelvins, and the nucleation humidity threshold RHI_{cirrus} is in percent. At the mean flight level of the matched flight tracks, the RHI_{cirrus} would be 154%. Thus, we would expect the contrail outbreak area to occur within the RHI range from 100 to 154%.

The RUC model, like all numerical prediction models, computes a grid-averaged value of relative humidity that is less than the RHI at individual locations within the grid. Thus, persistent contrails can exist even when the true grid RHI is less than 100%. In addition, upper tropospheric humidity measurements (from rawinsondes and other platforms) from which the RUC model analyses are based often underestimate RHI, and a dry bias in the model is likely. [As an aside, at least part of the rawinsonde dry bias appears to be accounted for by the RUC model's moisture scheme. A comparison of upper tropospheric dew point temperatures between rawinsondes and the RUC model during the airline shutdown on 12 September 2001 (when supplemental aircraft measurements were not available) shows that while the mean RUC minus rawinsonde dew point temperature difference was near 0 K at 400 hPa, the difference increased to around 1.8 K at 250 hPa and to 3.7 K at 150 mb. These differences in dew point temperature would increase RHI in the northern Great Lakes region from 10 to up to 35%.]

To determine an empirical humidity threshold where persistent contrails are possible, the locations of the persistent contrails identified from the *GOES-8* imagery were compared to the RUC analyses of RHI. Figure 4 shows the paths of all flight tracks that occur in the area where the RHI was estimated to be 85 percent or greater. Nearly all of the contrails fall within this threshold. The largest RHI found in the area where the contrails appear in Fig. 4 was 105%. Figure 1 shows that cirrus and other clouds covered the remaining portion of the high RHI area south and east of the contrails, where RHI reached as high as 110%.

Minnis et al. (2002) developed an empirical correction for rawinsonde-based RHI measurements based on the observations from Sassen (1997) for temperatures less than 243 K:

$$\Delta RHI(\text{in }\%) = -1.87 * T(\text{in K}) + 443 \quad (5)$$

$$RHI_{corr} = RHI + \Delta RHI \quad (6)$$

Since the temperature at the mean pressure level of the matched flight tracks was 216 K, the corrected RHI for the contrails in this case would be 124 percent or more. The largest corrected RHI in the region containing contrails would be 144%. This corrected RHI range falls well within the limits imposed by classical contrail formation conditions and the Sassen-Dodd criteria for homogeneous nucleation of cirrus.

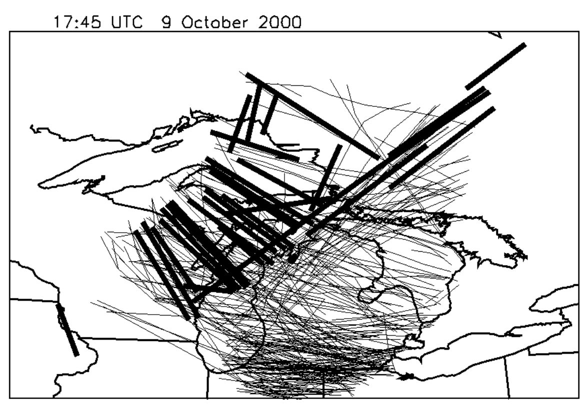

Figure 4. Contrails visually identified in *GOES-8* imagery (thick lines) and *all* flight tracks from FlyteTrax that occur in areas where the interpolated RUC model RHI at 225 hPa is greater than or equal to 85% (thin lines).

5. DISCUSSION

Figure 4 demonstrates that the air traffic density in the region where contrails formed was relatively uniform. The mean air traffic density per 1°×1° grid cell for flights with altitudes greater than or equal to 30,000 ft was usually only 4 per hour, which may account for the overall uniformity and clarity of the identified contrail segments. Higher air traffic densities probably result in a saturation effect characterized by smearing of the contrails in satellite imagery and/or less spreading by individual contrails because of competition for water vapor. The formation of the cirrus deck seen in Fig. 2 is an example of smearing of the individual contrails in areas with dense air traffic.

The preliminary analyses of the contrail outbreak shown here reveal a clear case of relative humidities that exceed ice saturation at flight level over a area where no natural cirrus were forming over the course of the day. These results demonstrate the need for some adjustment to the RHI fields from numerical weather prediction models, even in high-resolution models such as the RUC-2, which also have sophisticated cloud/moisture parameterizations. Grid-averaging effects and the difficulty in measuring upper tropospheric moisture lead to a dry bias in model analyses. More studies are necessary to conclusively determine the magnitude of this adjustment. Applying an RHI adjustment, however, should bring theory and observations into closer agreement.

The datasets compiled here will be analyzed in detail to fully characterize the growth and dissipation of the contrails as well as the environmental parameters controlling them for the course of the outbreak. The variation of the contrail macrophysical properties, optical depth, and radiative forcing will be correlated to the temperature, humidity, and wind fields to develop a crude empirical parameterization of the process leading from a contrail to a cirrus cloud. The expanded results will be presented at the conference.

REFERENCES

Alduchov, O. A., and R. E. Eskridge, 1996: Improved Magnus form approximation of saturation vapor pressure. *J. Appl. Meteor.*, **35**, 601-609.

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

Benjamin, S. G., J. M. Brown, K. J. Brundage, B. E. Schwartz, T. G. Smirnova, and T. L. Smith, 1998: The operational RUC-2. *Proc. AMS 16th Conf. Weather Analysis and Forecasting*, Phoenix, AZ, 249-252.

Busen, R., and U. Schumann, 1995: Visible contrail formation from fuels with different sulfur contents. *Geophys. Res. Lett.*, **22**, 1357-1360.

Meyer, R., H. Mannstein, R. Meerkotter, U. Schumann and P. Wendling, 2001: Regional radiative forcing by line-shaped contrails derived from satellite data. In press *J. Geophys. Res.,* 15 pp.

Minnis, P., L. Nguyen, D. P. Duda, and R. Palikonda, 2002: Spreading of isolated contrails during the 2001 air traffic shutdown. *Proc. AMS 10th Conf. Aviation, Range, and Aerospace Meteor.*, Portland, OR, May 13-16.

Minnis, P., U. Schumann, D. R. Doelling, K. M. Gierens, and D. W. Fahey, 1999: Global distribution of contrail radiative forcing. *Geophys. Res. Lett.*, **26**, 1853-1856.

Sassen, K., 1997: Contrail cirrus and their potential for regional climate change. *Bull. Amer. Meteor. Soc.*, **78**, 1885-1903.

Sassen, K., and G. C. Dodd, 1989: Haze particle nucleation simulations in cirrus clouds, and applications for numerical and lidar studies. *J. Atmos. Sci.*, **46**, 3005-3014.

Schrader, M. L., 1997: Calculations of aircraft contrail formation critical temperatures. *J. Appl. Meteor.*, **36**, 1725-1729.