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# Contrail Tracking and ARM Data Product Development

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**Abstract:** A contrail tracking system was developed to help in the assessment of the effect of commercial jet contrails on the Earth's radiative budget. The tracking system was built by combining meteorological data from the Rapid Update Cycle (RUC) numerical weather prediction model with commercial air traffic flight track data and satellite imagery. A statistical contrail-forecasting model was created a combination of surface-based contrail observations and numerical weather analyses and forecasts. This model allows predictions of widespread contrail occurrences for contrail research on either a real-time basis or for long-term time scales. Satellite-derived cirrus cloud properties in polluted and unpolluted regions were compared to determine the impact of air traffic on cirrus.

# 1. Introduction

This program continues two efforts in the study of radiative processes in the atmosphere. The first involves the combination of aircraft position data, meteorological data, contrail formation conditions and linear contrail retrievals to determine how air traffic density and environmental conditions affect contrail coverage. The second effort is the development of techniques to improve estimates of cloud properties under a larger variety of conditions than current models. Satellite-derived cirrus cloud properties in polluted and unpolluted regions are compared to determine the impact of air traffic on cirrus.

## 1.1 Contrail tracking

Contrails can affect the global atmospheric radiation budget by increasing planetary albedo and reducing infrared emission to space. Our current knowledge of the magnitude of these effects is extremely uncertain. Minnis et al. (1999) estimated the global mean radiative forcing by linear contrails to be on the order of 20 mW $m^{-2}$, while more recent estimates show a trend toward lower values of radiative forcing. Because air traffic is expected to grow by 2%-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).

The relation of contrail properties to meteorological conditions is still unknown. Recent theoretical estimates of global contrail coverage (Sausen et al. 1998; Marquart et al., 2003) are tuned to early measurements of linear contrail coverage determined visually from infrared satellite imagery. The estimates differ based on the parameterization used to diagnose contrails and the meteorological data employed to determine the ambient conditions. Estimates of contrail optical depth and particle size are typically based on aircraft measurements (Strauss et al. 1997; Schröder et al. 2000) or satellite retrievals (Minnis et al. 1998a,b; Duda et al. 1998), and have not been related to the surrounding atmospheric conditions.

To understand and predict contrail climatic effects better, widespread outbreaks of persistent contrails in otherwise clear skies must be predicted accurately from meteorological data. These contrails are likely to have the largest impact on the global radiative energy budget, and determining the frequency of occurrence and the magnitude of such outbreaks would help refine estimates of global contrail radiative forcing.

The main goal of this research was to understand and more accurately predict contrail climate effects. This was accomplished by using actual commercial aircraft flight data, coincident meteorological data and satellite remote sensing to improve the monitoring of contrail-generated cloud cover, optical properties, radiative forcing and by verifying and enhancing predictive models of contrail formation and persistence. The contrail-tracking system was used to determine temperature and humidity thresholds required for contrail formation and persistence. A result of the threshold testing will be a more accurate picture of the diurnal variation of contrails. In addition, a statistical contrail-forecasting model was created by using a combination of contrail observations from the GLOBE (Global Learning and Observations to Benefit the Environment) program (Brooks and Mims, 2001) and numerical weather analyses and forecasts. (The PI for this program also helped to design the contrail reporting protocol for the GLOBE program, a worldwide primary and secondary school-based education and science program that is funded in part by NASA. See http://www.globe.gov for more information about the GLOBE program.) This model allows predictions of widespread contrail occurrences for contrail research on either a real-time basis or for long-term time scales. The real-time forecasts could be used in aviation for the prevention of persistent contrail production. Long-term studies could focus on estimating the radiative impact of contrails on regional or global climate.

## 1.2 ARM data product development

Accurate observations of cloud properties are critical to the goals of the Atmospheric Radiation Measurement (ARM) program. Although satellite remote sensing has advanced considerably, many sources of uncertainty remain. A goal of this grant is to improve the accuracy of the ARM satellite data products and to improve our understanding of the relationships between surface and cloud conditions and the atmospheric fields.

We compared cirrus cloud properties derived from satellite-based imagers with aircraft-based measurements from two field campaigns. The first was the Interhemispheric Differences in Cirrus Properties from Anthropogenic Emissions (INCA), while the second was the Cirrus Regional Study of Tropical Anvils and Cirrus Layers – Florida Area Cirrus Experiment (CRYSTAL-FACE). To estimate the indirect impact of aircraft-generated aerosols on cirrus cloudiness better, during the INCA experiment we compared ice crystal sizes in the Southern (without strong aircraft pollution) and Northern hemisphere (with strong aircraft pollution) at mid-latitudes by using the CERES (Clouds and the Earth's Radiant Energy System) cloud property retrieval to compile the cirrus properties for one month at comparable latitudes, seasons and backgrounds to determine if there is a significant difference that may be attributable to air traffic. In the CRYSTAL-FACE experiment, satellite retrievals of cirrus cloud properties based on the Eighth Geostationary Operational Environmental Satellite (*GOES-8*) 3.9-μm channel were compared with in situ measurements from aircraft. The purpose of the comparison was to validate the satellite retrievals and to improve the accuracy of the satellite products.

The following section summarizes the details of our accomplishments under the grant. The full details are documented in our publications and extended abstracts. We have 3 peer-reviewed manuscripts published or accepted for publication, and one peer-reviewed manuscript in preparation. A total of 11 presentations were shown at scientific conferences and 8 extended abstracts were published in conference proceedings.

## 2. Summary of research

### 2.1 Contrail tracking

Better understanding and more accurate prediction of contrail climatic effects requires better estimates of global contrail properties and their relation to the atmospheric state. Of particular interest are predictions of widespread outbreaks of persistent contrail in otherwise clear skies; these contrails are likely to have the largest impact on the global radiative energy budget. Determining the frequency of occurrence and the magnitude of such outbreaks would help refine estimates of global contrail radiative forcing. Toward this goal, three research efforts were conducted under the grant. The first was the use of a combination of actual flight data, coincident meteorological data, and satellite remote sensing to build a research framework to study the physical properties of contrails in relation to the meteorological environment. Two case studies of multiple contrail formation were examined with the contrail tracking system (R1, C1, C4, C8). Secondly, contrail coverage over the United States was determined from satellite and by simulating coverage with flight track and meteorological data (R2, R3, C2, C3, C9, C11). The methods were studied and compared in an effort to improve our understanding of the relationship between contrail coverage and the surrounding environmental conditions. The third effort was the development of the first statistical contrail-forecasting model developed from numerical weather prediction models (R4). This model allows for diagnosing and predicting persistent contrail formation from numerical weather output.

In the contrail tracking system, the satellite, flight track, and meteorological data were used together to determine the location and altitude of contrail formation, and the temperature and humidity conditions under which the contrails formed. The flight track data were advected both horizontally and vertically to the times of the satellite observations by using the 3-D wind information from the numerical weather analysis. The advected flight tracks were then compared with the satellite observations of contrails to determine which aircraft produced the observed contrails. From the meteorological data and the contrail position data, the atmospheric conditions in the contrail formation regions could be determined.

The first case study was a multiple contrail outbreak over the western Great Lakes region on 9 Oct 2000 (R1, C4). Several physical properties of the contrails were determined from the available datasets. The areal coverage of the contrails was determined both subjectively by visual inspection of the satellite imagery and objectively by the automated method of Mannstein et al. (1999). The numerical weather prediction model analyses were used to estimate both the rate of contrail spreading seen in the satellite imagery and the fall speeds of the contrails. Multiple satellite remote sensing retrievals of contrail height, optical thickness, particle size, and other properties were made for selected groups of contrails. The numerical weather model analyses were also used to determine the conditions necessary for contrail formation. Finally, the flight track database was used to relate air traffic density to the observed contrail formation density.

Areal coverage by linear contrails peaked at 30,000 $km^2$, but the maximum contrail-generated cirrus coverage was over twice as large. Contrail spreading rates averaged around 2.7 km $h^{-1}$, and the contrails were visible in the *GOES* imagery approximately one hour after formation. Contrail fall speed estimates were between 0.00 and 0.045 m $s^{-1}$ based on observed contrail advection rates. Optical depth measurements ranged from 0.1 to 0.6. The contrail formation density was roughly correlated with air traffic density after the effects of competing cloud coverage, humidity, and vertical velocity were considered.

The results of the study reinforce the need for adjustment of upper-tropospheric relative humidity fields from rawinsondes and numerical weather prediction models. Grid-averaging effects and the difficulty in measuring upper-tropospheric moisture (Miloshevich et al., 2001) lead to a dry bias in the numerical weather analyses. The results also highlight the difficulties in retrieving microphysical properties of optically thin ice clouds using reflected solar radiation. Contrail fall speed estimates derived from several sources show that to first order the contrail height can be assumed to be constant throughout its lifetime. The vertical velocity analyses from the numerical weather prediction model showed that vertical velocity has an important effect on contrail formation.

The contrail tracking system was also used in a study of potential contrail formation during the air traffic shutdown over the United States on 12 September 2001 (C1, C8). During the shutdown, contrail coverage decreased dramatically. Analyses of weather data during the shutdown period indicate an anomaly in the diurnal range of surface air temperature that was attributed to the lack of contrails (Travis et al., 2003). Such an anomaly would result from the lack of contrail radiative forcing and would indicate that contrails can affect daily weather. To determine if such an anomaly can be realistically attributed to the absence of normal air traffic, the contrail tracking system was used to help estimate the contrail coverage and radiative forcing that would have occurred if normal air traffic had occurred. Using the relative humidity thresholds determined from observations of the few military contrails detected on 12 September 2001, the expected contrail coverage was simulated using the probable air traffic for that day had no shutdown occurred. The contrail spreading and lifecycle was parameterized using a log-normal formula of contrail optical mass (the product of its optical depth and contrail width) based on the results of the Great Lakes study. Calculations of contrail radiative forcing were computed from the simulated coverage. The simulation demonstrates that a large area of contrails would have formed over the northeastern United States if air traffic were normal. This result may help to explain the surface temperature anomaly found over the same area.

Contrail coverage over the contiguous United States (CONUS) was estimated for two months using flight track and meteorological data, and compared to a satellite-based estimate of coverage (R3, C3, C9). Potential contrail frequencies (PCFs) were computed directly from meteorological data from numerical weather prediction analyses using classical contrail formation criteria. The PCFs computed for September and November 2001 show large variations in magnitude depending on the synoptic-scale weather pattern. Several scenarios of simulated contrail coverage were computed for both months using several model options including different cloud masks, air traffic/contrail coverage relationships, vertical resolution of the humidity and air traffic data, and relative humidity thresholds necessary for contrail formation. The simulations show that even in areas suitable for contrail formation, only a small fraction of all flights produce persistent contrails that are detectable by satellite. The satellite-derived contrail coverage, however, was more closely related to the potential contrail frequency (and high cloud coverage) than to air traffic density. This suggests that the coverage of line-shaped contrails is non-linearly related to air traffic, and a smaller fraction of flights produce thick contrails in high traffic areas.

Two numerical weather prediction model analyses [Rapid Cycle Update, RUC (Benjamin et al., 2004a,b) and Advanced Regional Prediction System, ARPS (Xue et al., 2003)] were evaluated by matching several months of contrail properties derived from satellite and surface observations to the models' humidity, vertical velocity, wind shear and atmospheric stability (C10). The relationships between several contrail properties (including optical depth and contrail coverage) and the numerical weather analysis statistics were analyzed to determine under which atmospheric conditions widespread contrail outbreaks are favored.

The comparison shows that (as expected) relative humidity is the most important factor determining whether contrails are short-lived or persistent. Although most surface observations of contrails occur in nearly clear or partly cloudy skies, the upper-tropospheric humidity observed when persistent contrails form is typically much higher than the average humidities observed under partly cloudy conditions, or when only short-lived contrails are reported. The relative humidity values observed when spreading contrails are reported are slightly larger than when non-spreading persistent contrails are reported, suggesting that humidity is one factor influencing the formation of spreading contrails.

Other factors including vertical velocity and the lapse rate appear to determine where spreading contrails may form. The results from the ARPS model show clearer differences between the conditions in which non-spreading and spreading contrails are present than does the RUC model results. The spreading contrails are more likely to appear when the upper-tropospheric vertical velocities are positive, and the contrails appear to spread more when the atmosphere becomes more unstable (i.e., when the magnitude of the lapse rate increases). Although vertical wind shear is the primary mechanism responsible for contrail spreading (Jensen et al., 1998), it appears to be less important in determining whether contrails will spread than other factors. It is likely that sufficient upper-tropospheric humidity and atmospheric instability is necessary to make the contrails deep enough and long-lived so that the wind shear can spread the clouds.

Finally, a probabilistic contrail-forecasting model was created by using contrail observations from the GLOBE program and numerical weather analyses and forecasts (R4). This model allows predictions of widespread contrail occurrences on either a real-time basis or for long-term time scales. The real-time forecasts could be used in aviation for the prevention of persistent contrail production. Reliable probabilistic forecasts inherently have extra value to users compared to categorical (simple yes or no occurrence) forecasts because users can take advantage of cost-loss analyses better with probabilistic forecasts (Keith, 2003). Although other probabilistic forecasts of contrail formation have been published (Travis et al., 1997; Jackson et al., 2001), this model is the first to use numerical weather model predictions instead of real-time observations. The use of a prognostic model would allow for longer lead-times in forecasts for the purpose of contrail mitigation. Initial results show that contrail formation can be forecast with at least 70 percent accuracy.

## 2.2 ARM data product development

Satellite and aircraft data from the INCA experiment were analyzed to assess the effects of regional pollution on cloud properties (C5). Ice cloud properties in the southern (without strong aircraft pollution) and northern (with strong aircraft pollution) hemisphere at mid-latitudes were compared by using multi-spectral cloud property retrievals to compile the cirrus properties for one month each over both INCA observation regions (southern Chile and Scotland). Data from the eighth Geostationary Operational Environmental Satellite (*GOES-8*) imager and the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the *Terra* satellite were used in the remote sensing retrievals. Thirty-five MODIS overpasses form 18 March 2001 through 15 April 2001 over southern Chile and 22 overpasses between 20 September 2000 and 17 October 2000 were analyzed. A total of 31 *GOES-8* images from 19 March 2000 to 16 April 2000 were also used in the analysis.

The VIST (Visible Infrared Solar-Infrared Technique) was used to derive cloud height, optical depth, phase, effective particle size and water path for each pixel from several *GOES* and MODIS channels for daytime scenes. The VIST retrieval algorithm has been compared to passive and active radiometric measurements at surface sites, and shows good agreement with the ground-based measurements.

To validate the satellite retrievals, the VIST particle size results were compared to aircraft measurements from the INCA campaign. The research aircraft was equipped with several microphysics instruments including FSSP-300 and 2D-C probes. To collocate the satellite values, all retrieved satellite pixels within 4 km of the research aircraft were averaged together. The enclosed figure shows the collocated satellite retrievals plotted with the aircraft measurements. For a more equal comparison with the satellite retrievals, the figure also shows 20-second averages of the aircraft particle size measurements (red triangles). For the time period within a half hour of the satellite overpass of the MODIS instrument, the aircraft and satellite results indicate that the satellite-observed variations are representative of the changes occurring within the clouds.

To compile a dataset of cirrus cloud property statistics comparable in season and location to the INCA flight observations, MODIS data from all available *Terra* overpasses within a one month period during the fall season at both sites of the INCA field campaigns were analyzed. Only ocean pixels were included from the satellite retrievals to reduce satellite retrieval difficulties associated with variable surface properties. These MODIS results indicate a hemispheric difference in cirrus particle sizes that is opposite to the aircraft-based results from INCA, with slightly larger particles in the northern hemisphere (63.3 μm) then in the southern hemisphere (53.2 μm). The southern hemispheric analysis from the *GOES* observations (51.9 μm) also yielded mean cirrus particle sizes smaller than those from the MODIS northern hemisphere observations. The southern hemispheric results were sensitive to satellite viewing angle.

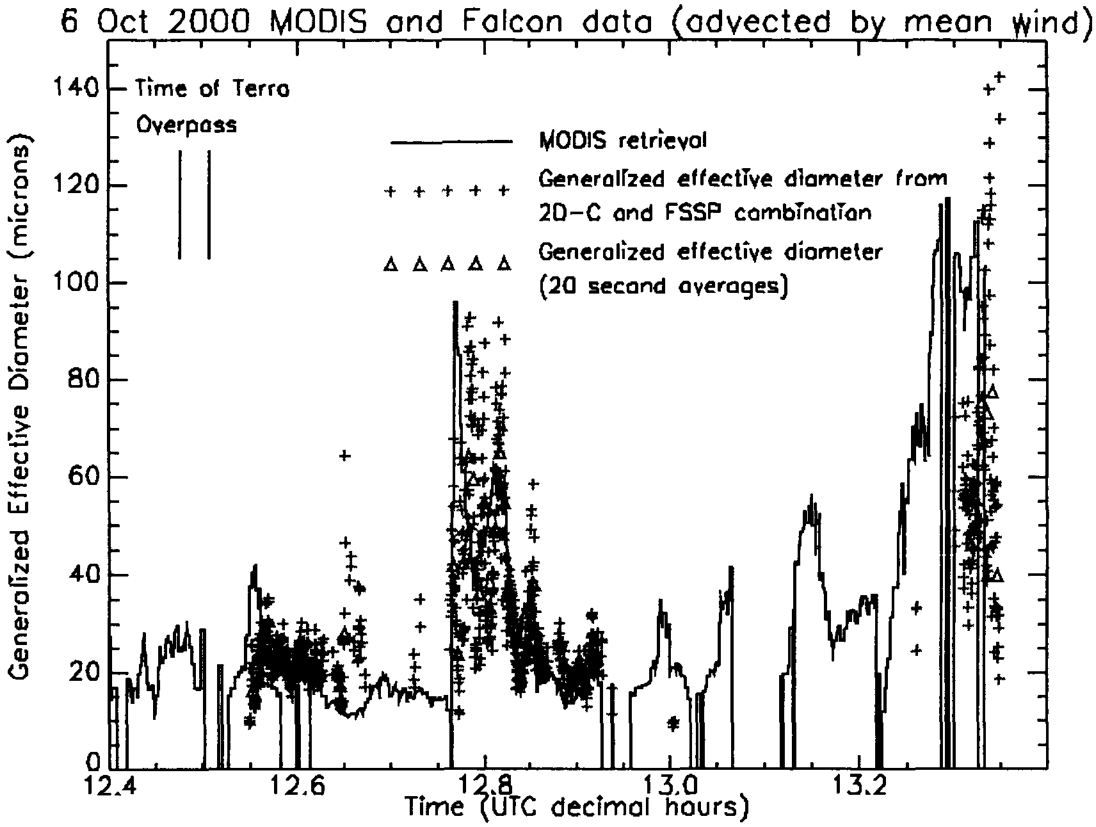


Figure: Ice cloud diameter retrieval from MODIS imagery on 6 October 2000 collocated with the generalized effective diameter ($D_{ge}$) measurements (Fu, 1996) derived from a combination of FSSP-300 and 2-DC measurements. The red triangles indicated the 20-second mean values of $D_{ge}$.

For the near-zenith viewing angles the southern hemispheric ice crystals were more than 10 microns larger than the northern hemispheric results, while the opposite result occurs for larger satellite viewing angles. Some unresolved factors that may account for the larger particle sizes in the northern hemispheric cirrus are the impacts of low-cloud contamination, cloud horizontal inhomogeneity, and ice particle shape on the satellite retrievals.

A similar comparison between satellite- and aircraft-based retrievals was also done for the CRYSTAL-FACE experiment (C6, C7). Cloud particle sizes were computed from collocated CPI and SPP-100 data using the definitions of generalized effective diameter ($D_{ge}$) of Fu (1996). The satellite retrievals match the $D_{ge}$ based on the CPI-based size distribution (which accounts for the particle's shape) better than the $D_{ge}$ based on the water content/area ratios measured by the probes. The top-of-the-atmosphere (TOA) broadband solar fluxes estimated from the *GOES* narrowband (visible) observations were well correlated with collocated solar flux measurements from the ER-2 aircraft.

## List of Accomplishments

1. This research will lead to a better evaluation of upper tropospheric humidity and contrail/cirrus development in numerical weather prediction models. The results can be used to improve predictions of upper tropospheric clouds in forecast models.
2. This project provides a more accurate assessment of contrail-climate effects and the means for predicting them in future air traffic simulations. These developments will lead to an improvement of contrail mitigation efforts via flight altitude and route adjustments. The program will help to determine only those areas where flight adjustments are needed.
3. The efforts associated with the GLOBE program help primary and secondary school students become more aware of their environment for a scientific viewpoint. The measurement protocols are designed so that the students can provide scientifically valuable measurements to researchers.

4. The program completed the first detailed analysis of contrail formation and motion using actual flight data integrated into numerical weather analyses. A flight track advection and matching scheme was developed that allows for the determination of the atmospheric conditions associated with individual contrails seen in satellite imagery. The analysis procedures will provide the framework for realistic simulation of contrail life cycles and interactions.

5. Contrail coverage over the contiguous United States has been derived from numerical weather prediction analyses and compared to satellite-based retrievals of contrail coverage. The optical properties of contrails were derived by applying a multi-spectral technique to AVHRR and MODIS data over various parts of the United States including land and water backgrounds. Contrail longwave radiative forcing was computed directly from the satellite data.

6. Members of the project participated in the Alliance Icing Research Study II (AIRS-II) in Bangor, ME during November/December 2003.

7. By comparing numerical weather analyses with surface- and satellite-based observations of contrail occurrence, several atmospheric properties were identified that likely determine the occurrence of persistent, spreading contrails.

8. The first probabilistic contrail-forecasting model was developed from numerical weather prediction models.

9. Satellite retrievals were produced that support the findings from the INCA experiment that pollution from aircraft causes differences in the microphysical properties of cirrus clouds between the Northern and Southern hemispheres.

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## Publications and Presentations

All peer-reviewed papers are numbered with "R", while presentations and conference proceedings are number starting with "C".

### Grant Peer-Reviewed Papers:

R1. Duda, D. P., P. Minnis, L. Nguyen, and R. Palikonda, 2004: A case study of the development of contrail clusters over the Great Lakes. *J. Atmos. Sci.*, **61,** 1132-1146.

R2. Palikonda, R., P. Minnis, D. P. Duda, and H. Mannstein, 2005: Contrail coverage derived from 2001 AVHRR data over the continental United States of America and surrounding areas. Accepted, *Meteorol. Z.*

R3. Duda, D. P., P. Minnis, D. P. Garber, and R. Palikonda, 2005: Estimated contrail frequency and coverage over the contiguous United States from numerical weather prediction analyses and flight track data. Accepted, *Meteorol. Z.*

R4. Duda, D. P., P. Minnis, and L. Chambers, 2005: Probabilistic contrail forecasting using high-resolution numerical weather analyses and forecasts. In preparation for *J. Appl. Meteor.*

## Grant Extended Abstracts & Presentations:

C1. Minnis, P., L. Nguyen, D. P. Duda, and R. Palikonda, 2002: Spreading of isolated contrails during the 2001 air traffic shutdown, *Proceedings of 10th Conference on Aviation, Range, and Aerospace Meteorology*, American Meteorological Society, Portland, OR, May 13-16, 33-36.

C2. Palikonda, R., P. Minnis, P. K. Costulis, and D. P. Duda, 2002: Contrail climatology over the USA from MODIS and AVHRR data, *Proceedings of 10th Conference on Aviation, Range, and Aerospace Meteorology*, American Meteorological Society, Portland, OR, May 13-16, J9-J12.

C3. Duda, D. P., P. Minnis, P. K. Costulis, and R. Palikonda, 2002: An estimation of CONUS contrail frequency from RUC and flight track data, *Proceedings of 10th Conference on Aviation, Range, and Aerospace Meteorology*, American Meteorological Society, Portland, OR, May 13-16, J70-J73.

C4. Duda, D. P., P. Minnis, and R. Palikonda, 2002: A study of contrail spreading over the Great Lakes, *Proceedings of 10th Conference on Aviation, Range, and Aerospace Meteorology*, American Meteorological Society, Portland, OR, May 13-16, J5-J8.

C5. Duda, D. P., P. Minnis, W. L. Smith, Jr., S. Sun-Mack, J. K. Ayers, J.-F. Gayet, F. Auriol, J. Ström, A. Minikin, A. Petzold, and U. Schumann, 2002: An interhemispheric comparison of cirrus cloud properties using MODIS and GOES, *Proceedings of 11$^{th}$ Conference on Atmospheric Radiation*, American Meteorological Society, Ogden, UT, June 3-7, J17-J20.

C6. Duda, D. P., P. Minnis, D. R. Doelling, M. L. Nordeen, P. Pilewskie, F. P. J. Valero, R. P. Lawson, and K. F. Evans, 2003: Validation of CRYSTAL-FACE satellite-derived cloud properties with aircraft measurements, *CRYSTAL-FACE Science Team Meeting*, Salt Lake City, UT, February 24-28.

C7. Nguyen, L., P. Minnis, D. R. Doelling, W. L. Smith, Jr., D. P. Duda, M. Khaiyer, M. Poellot, G. G. Mace, and T. Uttal, 2003: Comparison of surface, satellite, and aircraft ice cloud properties during CRYSTAL-FACE, 2003 *EGS-AGU-EUG Joint Assembly*, Nice, France, April 7-11.

C8. P. Minnis, L. Nguyen, D. P. Garber, D. P. Duda, R. Palikonda, and D. R. Doelling, 2003: Simulation of contrail coverage over the USA missed during the air traffic shutdown, *European Conference on Aviation, Atmosphere and Climate*, Friedrichshafen at Lake Constance, Germany, June 30 – July 3, Air Pollution Research Report 83, EUR 21051, European Commission, Brussels, 224-231.

C9. Duda, D. P., P. Minnis, P. K. Costulis, and R. Palikonda, 2003: CONUS contrail frequency estimated from RUC and flight track data, *European Conference on Aviation, Atmosphere and Climate*, Friedrichshafen at Lake Constance, Germany, June 30 – July 3, Air Pollution Research Report 83, EUR 21051, European Commission, Brussels, 232-237.

C10. Duda, D. P., R. Palikonda, and P. Minnis, 2004: Relating satellite-based contrail detection to NWA output, *Proceedings of 11$^{th}$ Conference on Aviation, Range,* *and Aerospace Meteorology*, American Meteorological Society, Hyannis, MA, October 4-8, CD-ROM, P8.9.

C11. Palikonda, R., P. Minnis, and D. P. Duda, 2004: Contrail coverage over the USA derived from NOAA and EOS satellite data, *Proceedings of 11$^{th}$ Conference on Aviation, Range, and Aerospace Meteorology*, American Meteorological Society, Hyannis, MA, October 4-8, CD-ROM, P8.1.