Assessment of a Global Contrail Modelling Method

K. Klima[*], I. Waitz
MIT, Cambridge, Massachusetts, USA

Keywords: contrail, contrails, aviation, contrail modelling, SAGE, RHi, satellite images, aircraft tracts, radar based trajectory, cloud formations, linear features, CONUS, RUC

ABSTRACT: Estimates of radiative forcing contributions from aircraft have raised concerns about the impacts of contrails and aviation-induced cirrus on climate. Increasing demand for aviation will further increase the incidence of contrails. This paper describes the assessment of a method for estimating the formation of contrails. The method couples radar-based flight trajectory information with hourly meteorological data. Estimates of persistent contrails were compared to results obtained from NASA satellite images. For the one week time period we considered, the contrail model coupled with measured aircraft flights tracks did not accurately estimate the occurrence of persistent contrails. This was due both to a limited ability to identify contrails in the satellite images (as a basis for validating the methods) and to uncertainties in the meteorological data and the contrail modeling methods.

1 INTRODUCTION

Estimates of radiative forcing contributions from aircraft have raised concerns about the impacts of contrails and aviation-induced cirrus on climate (IPCC 1999). Within four to six hours after initial formation, contrails, if they persist, may evolve into aviation-induced cirrus. In a study of one region in Europe, contrails were estimated to produce a local annual mean radiative forcing of 0.23 W/m^2 (Stuber et al., 2006). The global and annual average forcing was recently estimated to be 0.01 W/m^2 (Sausen et al., 2005).

There are currently only limited capabilities for evaluating the extent and effects of global contrail coverage. Examples of other work in this area include Williams et al. (2005) who analyzed fuel burn and carbon dioxide penalties as a function of contrail reduction, and Minnis et al. (2004), who described a method to calculate whether a contrail will form and persist along certain routes. Both of these studies used the Appleman criteria (1953) to determine whether or not a contrail will form and persist, and the method presented by Schumann (2000) to relate the thermodynamic conditions in the aircraft plume to the overall propulsive efficiency. Duda et al. (2005) improved upon Minnis's method by using flight data to compute air traffic density. A recent paper by Mannstein, Spichtinger, & Gierens (2005) studied high resolution vertical radiosonde meteorological data, and calculated the potential reduction of contrails by a small change in flight altitude (0 to 1000ft).

This paper presents the assessment of a method for estimating contrail formation and persistence. The method couples radar-based flight trajectories with assimilated meteorological data. The method is assessed through a direct comparison of contrail estimates to satellite imagery.

2 NUMERICAL MODEL

2.1 *Aviation System Model*

To estimate contrail formation, an aircraft model is needed to estimate aircraft overall propulsive efficiency and the emissions index of water. Note that contrail formation does not change greatly as a function of fuel burn (being more significantly influenced by local atmospheric conditions).

---

[*] *Corresponding author:* Kelly Klima, MIT, 54-1719, 77 Massachusetts Ave, Cambridge, MA, USA. Email: klima@mit.edu

However, an accurate aviation system model is needed to examine the extent of contrail coverage. This study used the fuel burn and emissions module of the FAA's System for assessing Aviation's Global Emissions (Kim et al. 2006a, Kim et al. 2006b).

SAGE accepts flight tracks from Enhanced Traffic Management System (ETMS) radar data and therefore contains detailed temporal and spatial information for most of the flights over the continental United States. These flights are processed through the SAGE model, which consists of individual modules (e.g. aerodynamics, engine thrust, etc.) that interact to create a fuel burn estimate. SAGE can therefore calculate the overall propulsive efficiency of each aircraft along the flight trajectory. For the purposes of this research, we examined 54,000 United States continental flights. Sensitivity to aircraft performance modelling was addressed and is discussed in Klima, (2005).

2.2 *Meteorological Data*

The Rapid Update Cycle (RUC) is an atmospheric prediction system comprised primarily of a numerical forecast model and an analysis system to initialize that model ([http://ruc.noaa.gov]). The RUC has been developed to serve users needing short-range weather forecasts. RUC runs operationally at the National Centers for Environmental Prediction (NCEP). Archived RUC data were obtained from a United States program called the Atmospheric Radiation Measurement Program (ARM, [http://www.arm.gov/]) for dates November 12-18, 2001 (to match available satellite imagery/contrail mask data) and October 2000 (to match available fuel burn data). This study used 40km resolution data so that its output could be compared to that of NASA Langley (Duda 2003, Minnis 2004). See Klima (2005) for implementation details.

Satellite data were provided by NASA Langley for the hours of 17-24 Universal Time Conversion (UTC) for the week of November 12-18, 2001. One set of data were satellite infrared radiances (IR) from the Sun-synchronous NOAA-16 Advanced Very High Resolution Radiometer (AVHRR) 1-km imager, 10.8 & 12 µm bands (Figure 1, right). Another set of data were contrail masks (Figure 1, left). The satellite data sets for deriving the contrail coverage consist of the NOAA-16 data and multispectral 1-km data from the MODerate Resolution Imaging Spectroradiometer (MODIS) on the Terra satellite (Duda, 2003). NASA Langley researchers applied Mannstein's algorithm (1999) to identify contrails in the satellite imagery. Filtering methods were provided by NASA Langley, and consist of removing points a) outside the satellite image range, and b) near the edges of the image where curvature is high (scan angle magnitude is more than 50°).

Figure 1 - NOAA-16 satellite image (left) and matching contrail mask (right, white pixel indicates contrail formation), November 18, 2001 1888 UTC. Note that the satellite image is reversed from east to west. This occurs due to the direction the satellite passes overhead.

2.3 *Contrail Model*

The aircraft type-specific emissions index of water and the type-specific engine efficiency are reported by SAGE along each chord of the radar trajectory. Then, the temporally and spatially matching relative humidity for ice (RHi) is obtained from the meteorological data sets. The method used to estimate the formation of contrails is based on the methods of Appleman (1953) and Schumann (2000).

We implemented this model using an empirical saturation curve (Sonntag, 1994) and the derived mass-averaged moist air specific heat (Klima, 2005). Given gridded meteorological conditions, aircraft fuel burn, aircraft engine overall efficiency, and fuel characteristics, this model can be used to calculate whether a contrail will form or persist at each location in along the flight path. It reports contrail formation as percentage of distance traveled, and differentiates between contrails forming in clouds and in clear skies (if RHi >75%, the area is assumed to be a cloud). A first-order advection model is applied to the contrails to account for their change in location over time.

Due to the complexity of contrails (see for example, Atlas et al., 2006), several characteristics were not addressed. First, we did not estimate the time evolution of the shapes/sizes of contrails. Second, we did not address sub-grid scale variability in meteorological data. Third, optical depth and radiative forcing were not addressed in this study. Fourth, overlapping contrails were ignored due to the small average width of contrails (satellite images indicate less than 10km) and the small regions of ice-supersaturation. Fifth, we assumed winds are invariant from time of contrail formation. Sixth, the evolution of contrails into aviation-induced cirrus cloudiness was beyond the scope of this study. Finally, the environmental effect of contrails was not addressed.

3 RESULTS

Since contrail identification is integral to comparison of actual and model-predicted contrails, a brief description of the contrail identification method is necessary. Young contrails have a smaller crystal size than natural clouds, and hence have a higher IR transmissivity (brightness) in the 10.8μm image as compared to the 12μm image. Hence a brightness-differencing scheme can be used to identify all image pixels which may be contrails: the 10.8μm minus 12μm brightness temperature difference. However, using only a temperature differencing technique could identify singular pixels, edges of clouds, or ground features. A second property of contrails is their linear structure, especially at a young age. Hence a linear filter is used. Extended information on processing techniques is described by Mannstein et al. (1999).

There is only limited confidence in the ability of these techniques to identify contrails. Wind shear, turbulence and ice particle sizes will affect how the contrail grows and disperses. Young contrails (less than about 50 minutes) and weak contrails are too small to be sensed by the satellites, and therefore are typically not identified. Older contrails (greater than 2.5 hours) have begun to lose their linear features, and so would also not be identified with confidence (Duda, 2003).

NASA Langley estimate the false alarm rate for identification of contrails using these methods is 40% (Minnis, 2004). For example, for the satellite images we examined, many of the features identified as contrails were oriented north-south. Over the continental United States, most of the air traffic is east-west. Since an aircraft is necessary for contrail formation, these were probably false alarms. In particular, striated cirrus cloud formations were often misidentified as contrails.

3.1 *Comparison of Contrail Mask to RHi fields*

Theoretically, clouds and/or contrails should sublime at RHi < 100%. Visual comparison of the contrail masks to satellite data showed that the linear features with high brightness differences were usually either contrails or clouds; they were rarely associated with ground features. Consequently, an accurate RHi data set would be expected to have RHi > 100% in most areas identified as contrails (whether these areas corresponded to contrails or striated cirrus cloud formations).

Contrail mask data from the satellite images and modeled contrail estimates were transferred into specific latitude and longitude points. Next these figures were overlayed on RHi images. Figure 2a shows the contrail mask data on November 12, 2001 at 1996 hours, universal time. Note that this figure is filtered to contain only the region of data present in the satellite image (filter denoted by crosses). Visual examination of Figure 2a shows that contrail pixels appear in areas of RHi < 100%. Similar results were obtained for the other days examined. We then calculated the fraction of contrail mask pixels that would appear in the CONUS region (at 10973m, 36000ft altitude) given a variable RHi threshold. Based on this calculation, we determined that roughly 60-90% of the contrail pixels were misidentified. This result reflects the inability of the meteorological model to predict supersaturation. This exercise demonstrates that the RHi fields, although perhaps representative of the large scale features, did not accurately capture the atmospheric conditions on the days we examined.

Figure 2 – 11/12/2001 hr 1996, RHi hour 19 field A) Filtered contrail mask. Contrails (47N 100W) caused by incorrect RHi field (temporally changing). Contrails (32N 110W) caused by threading B) Flights examined C) Filtered contrail estimation.

3.2 *Comparison of contrail model and satellite image mask results*

Comparisons were made for 53,844 U.S. continental flights performed during the week of November 11/12-18, 2001. Figure 2b shows the set of continental flights that temporally match the contrail mask image. Areas of contrail formation are generally consistent between the satellite images and the model estimates (see Figure 2a and Figure 2c). Where the images are not consistent, the estimated contrails match well with areas of high RHi in the meteorological data. The discrepancies can be attributed to the following reasons:

- Inability to represent RHi gradients with altitude – In the figure we overlay the contrail estimates (from throughout the atmosphere) on meteorological data from one altitude level.
- Incorrect RHi fields – The RHi fields in the meterological data are imperfect reconstructions of the true RHi fields.
- Misidentification of striated clouds and ground features as contrails. There are also regions

where the clouds are so thick that contrails are not identified.

- Incorrect contrail advection – A shearing of contrails will appear due to a combination of aircraft traveling the same route and wind advection; a better contrail advection model may more correctly locate these contrails. Wind shear, turbulence, contrail precipitation, and stratification will all be important in determining how a contrail evolves.
- Insufficient flight data – Recall that this study examined commercial, continental U.S. flights only. Neglecting international flights leads to an underestimate of persistent contrails near the edges of the United States. This discrepancy does not apply to our example figures, but was noted in other results shown in Klima (2005).

3.3 *Contrail Persistence Threshold*

One important parameter in the contrail model is the percent of RHi at which contrails persist. For homogeneous nucleation of cirrus clouds, this threshold percent is thought to be 140-160% (Minnis 2004). However, contrails are formed primarily through heterogeneous nucleation. In the literature, the threshold is variously placed at somewhere between 95-105% (Duda 2003). The nominal value used in our study was 100%.

The effect of changing the contrail persistence threshold over the globe was examined. Assuming the RHi data were flawed and the contrail persistence threshold varied from 90-110% RHi (instead of the assumed 100% RHi), one can calculate the change in ground coverage over which contrails could form. Based on this analysis, if the contrail persistence threshold was allowed to vary from 90-110%, contrail coverage area could vary between 13%166% of the currently estimated coverage area. If the persistence threshold was allowed to vary as literature suggests from 95-105% RHi (instead of 100% RHi), continental coverage area could vary between 51%-135% of the currently estimated coverage area.

3.4 *Contrail Length*

The typical length of the estimated contrails was larger than 100km, (several degrees in length), while the typical length of the observed contrails was about 50km. This length is much larger than the meteorological grid scale resolution, so it is not a reflection of subscale RHi gradients.

This occurs because the SAGE model uses preprocessed ETMS data; in order to shorten the dataset for storage purposes, “chords” are constructed on which the aircraft travels the same direction and magnitude for a long period of time. The discrepancy between the long predicted contrails and the short contrails observed in the satellite images implies that the chord lengths used within SAGE need to be shortened - at least to the extent to where they are consistent with length-scales observed in the RHi data.

4 DISCUSSION

In this paper, we compared estimates of persistent contrails developed using radar-based flight trajectories and assimilated meteorological data to contrails identified from satellite data. This comparison highlighted the following issues.

First, it was not possible to match particular contrails observed in the satellite images to specific flight trajectories. This occurred largely because the contrail mask algorithm identified both contrails and striated cirrus cloud formations, suggesting limitations in the satellite sensing and extraction methods (Mannstein 1999). We estimate that perhaps 40-50% of the contrail pixels were misidentified.

Second, RUC RHi fields did not accurately portray the true RHi fields for the days examined in 2001. We found that 60-90% of the pixels identified as linear features (demonstrated to be contrails or clouds) were located in areas where the RHi estimated by the RUC meteorological model was theoretically too low to support clouds or contrails. The RUC models do not have the resolution or the microphysics to represent the small scale vertical motions thought to be important for predicting cirrus and thus RHi correctly. Hence at this point in time, it is unknown to what degree a contrail model coupled with measured aircraft flight tracks can be used to accurately estimate contrail formation as given by satellite images/contrail masks. Both the identification of contrails from satellite images and the estimation of upper atmospheric humidity are lacking.

Third, the typical length of the estimated contrails was larger than 100km, (several degrees in length), while the typical length of the observed contrails was about 50km. This length is much larger than the meteorological grid scale resolution, so is not a reflection of subscale RHi gradients. Rather, this occurs because the SAGE aviation model shortens the ETMS dataset for storage purposes. The discrepancy between the long predicted contrails and the short actual contrails implies that the chord lengths used within SAGE need to be shortened until they are consistent with length-scales observed in the RHi data.

These results are not necessarily general. We assessed only one week's worth of flights over the continental United States.

ACKNOWLEDGEMENT

This work was supported by the U.S. Federal Aviation Administration Office of Environment and Energy. Maryalice Locke and Mohan Gupta managed the project. We thank them for their guidance and contributions. We also thank Lourdes Maurice, Curtis Holsclaw and Carl Burleson of the FAA for their guidance and support. The work was the result of a long-standing collaboration with the Volpe National Transportation Systems Center and we thank Gregg Fleming, Brian Kim, Sathya Balasubramanian, Andrew Malwitz and Matt Maki for their contributions with the aviation system model, SAGE. We also thank Patrick Minnis, David Duda and Rabi Palikonda of NASA Langley Research Center for providing the satellite images and for their help interpreting them.

REFERENCES

Appleman, H., 1953: The Formation of Exhaust Condensation Trails by Jet Aircraft. *Bulletin American Meteorological Society 34*, 14-20.

Atlas, D., Z. Wang, D. Duda, 2006: Contrails to Cirrus – Morphology, Microphysics, and Radiative Properties. *Journal of Applied Meteorology and Climatology 45*, 5-19.

Duda, D.P., P. Minnis, P.K. Costulis, R. Palikonda, 2003: *CONUS Contrail Frequency Estimated from RUC and Flight Track Data.* European Conference on Aviation, Atmosphere, and Climate.

Kim, B., G. Fleming, S. Balasubramanian, A. Malwitz, J. Lee, J. Ruggiero, 2006a: *SAGE: Version 1.5 Technical Manual.* FAA-EE-2005-01 [(http://www.faa.gov/about/office_org/headquarters_offices/aep/models/sage/)].

Kim, B., G. Fleming, S. Balasubramanian, A. Malwitz, J. Lee, J. Ruggiero, 2006b: *SAGE: Version 1.5 Technical Manual.* FAA-EE-2005-04 [(http://www.faa.gov/about/office_org/headquarters_offices/aep/models/sage/)].

Intergovernmental Panel on Climate Change. Aviation and the Global Atmosphere. Cambridge University Press: USA, 1999.

Klima, Kelly. Assessment of a Global Contrail Modeling Method and Operationsl Strategies for Contrail Mitigation. MIT: Boston, MA, 2005.

Mannstein, H., R. Meyer, P. Wendling, 1999: Operational detection of contrails from NOAA-AVHRR-data. *International Journal of Remote Sensing 20,* 1641-1660.

Mannstein, H., P. Spichtinger, K. Gierens, 2005: A Note on Avoiding Contrail Cirrus. *Transportation Research Part D 10,* 421-426.

Minnis, P., J.K. Ayers, R. Palikonda, E. Phan, 2004: Contrails, Cirrus Trends, and Climate. *Journal of Climate 17,* 1671-1685.

Sausen, R. I. Isaksen, V. Grewe, D. Hauglustaine, D. Lee, G. Myhre, M. Köhler, G. Pitari, U. Schumann, F. Stordal, C. Zerefos, 2005: Aviation radiative forcing in 2000: An update on IPCC (1999). *Meteorologische Zeitschrift 14-4,* 555-561(7).

Schumann, U., 2000: Influence of Propulsion Efficiency on Contrail Formation. *Aersp. Sci. Technol 4,* .391-401.

Sonntag, 1994: Advancements in the Field of Hygrometry. *Meteorol Zeit 3,* 51-66.

Stuber, N., P. Forster, G. Rädel, K. Shine, 2006: The importance of the diurnal and annual cycle of air traffic for contrail radiative forcing. *Nature 441,* 864-867.

Williams, V., R. Noland, R. Toumi, 2005. "Variability of contrail formation conditions and the implications for polices to reduce the climate impacts of aviation". *Transportation Research Part D* 12, 269-280.

Figure 1

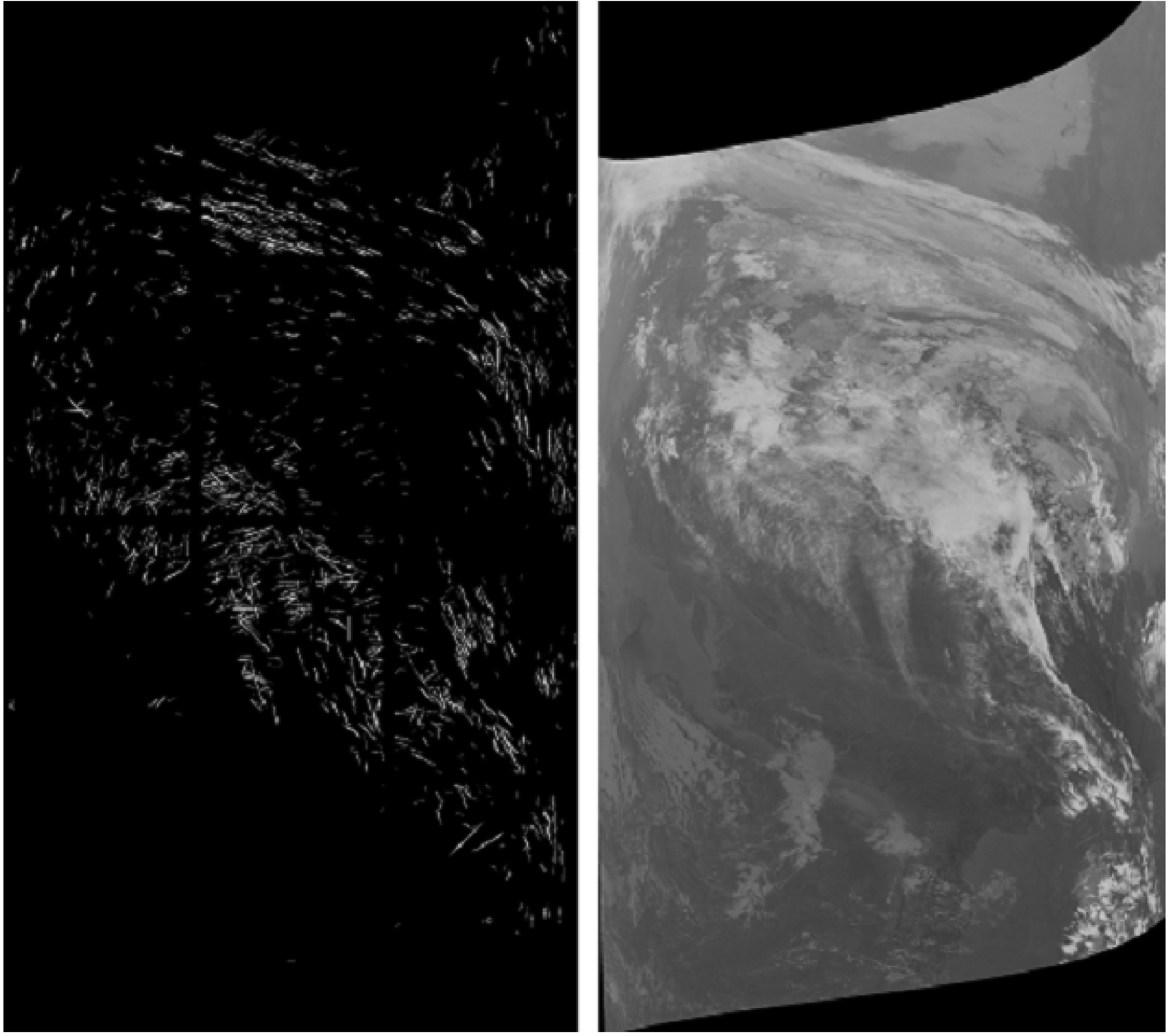
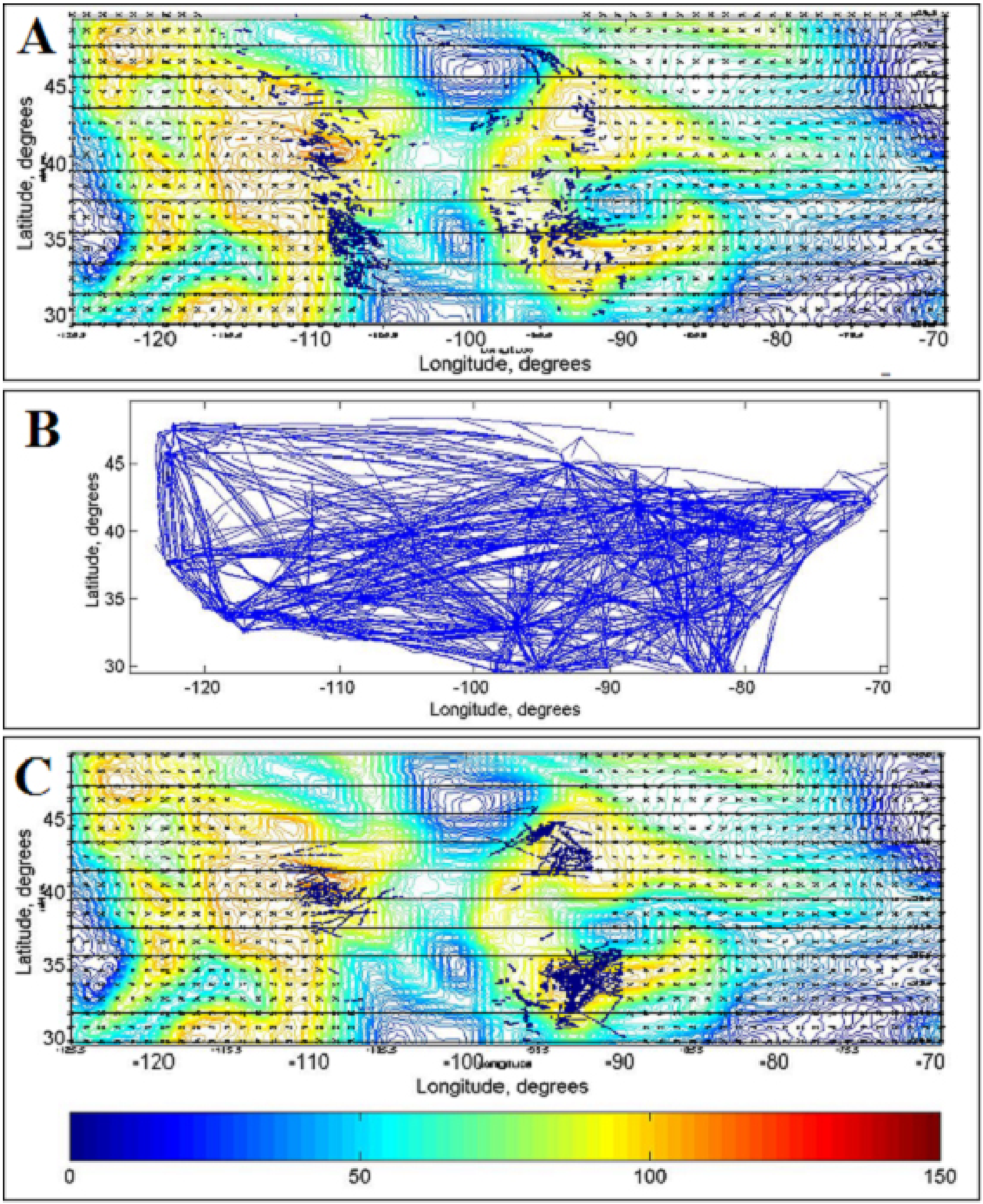


Figure 2


A
Latitude, degrees
45
40
35
30
-120
-110
-100
-90
-80
-70
Longitude, degrees
B
Latitude, degrees
45
40
35
30
-120
-110
-100
-90
-80
-70
Longitude, degrees
C
Latitude, degrees
45
40
35
30
-120
-110
-100
-90
-80
-70
Longitude, degrees
0
50
100
150