Interactive comment on "Northern Hemisphere Contrail Properties Derived from Terra and Aqua MODIS Data for 2006 and 2012" *by* David P. Duda et al.

Anonymous Referee #1

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We thank reviewer #1 again for their review and comments. They have helped to improve our manuscript.

The paper addresses important objectives: Northern Hemisphere (NH) contrail properties, in terms of coverage, optical depth, particles sizes and radiative forcing, and their changes from 2006 to 2012. It uses valuable data at high level of remote sensing expertise: multispectral MODIS data with high spatial and some temporal resolution from two polar orbiting satellites (AQUA and TERRA), from 2 years. It uses an established algorithm which has been shown to be able to detect linear contrails, at least over quasi-homogeneous surfaces (such as the oceans) and for weak traffic where overlap from various contrails and overlap with other clouds is less important.

The method was known to suffer from spatially variable detection efficiencies and from possibly large false detection rates from misinterpretation of linear structures in natural cirrus.

The claim of "possibly large false detection rates from…natural cirrus" appears to be unsupported speculation by the referee. The manuscript text mentions multiple times that flight tracks are used to screen out false detections. Detection efficiency is discussed later in this reply and dealt with in more detail in a supplement to the paper.

The overpass times of the satellites changed somewhat between the years 2006 and 2012. The changes may have some impact on the results in particular in regions with strong diurnal traffic cycles, such as over the North Atlantic.

This statement is not correct. Terra and Aqua were designed to maintain their overpass times and have been kept in their nominal orbits ever since operations began. The reviewer is welcome to check the overpass times using NASA Langley's orbital overpass predictor at

https://cloudsway2.larc.nasa.gov/cgi-bin/predict/predict.cgi

The following table includes the local overpass times at the Equator computed for 2006 and 2012 Terra and Aqua. All of the overpasses are within a few minutes of each other and of the nominal overpass times (1030 LT for Terra, 1330 LT for Aqua).

Terra				
Date	Overpass Latitude	Overpass Longitude	Overpass Time (UT)	Overpass Time (LT)
1 Jan 2006	0.0 N	-4.33 W	10:45:52	10:28:34
1 Apr 2006	0.0 N	+11.14 E	09:44:36	10:29:11
1 Jul 2006	0.0 N	-8.98 W	11:05:21	10:29:25
1 Oct 2006	0.0 N	+9.66 E	09:50:47	10:29:25
31 Dec 2006	0.0 N	-10.50 W	11:11:35	10:29:35
1 Jan 2012	0.0 N	+6.46 E	10:03:43	10:29:34
1 Apr 2012	0.0 N	+11.18 E	09:44:58	10:29:41
1 Jul 2012	0.0 N	-8.94 W	11:05:28	10:29:43
1 Oct 2012	0.0 N	+9.63 E	09:50:58	10:29:30
31 Dec 2012	0.0 N	-10.45 W	11:11:40	10:29:52
Aqua				
1 Jan 2006	0.0 N	-1.99 W	13:39:57	13:31:58
1 Apr 2006	0.0 N	-11.32 W	14:17:58	13:32:41
1 Jul 2006	0.0 N	-6.65 W	14:00:33	13:33:56
1 Oct 2006	0.0 N	+11.80 E	12:47:39	13:34:50
31 Dec 2006	0.0 N	-8.22 W	14:07:53	13:35:01
1 Jan 2012	0.0 N	+8.80 W	12:59:46	13:34:58
1 Apr 2012	0.0 N	-11.35 W	14:20:58	13:35:34
1 Jul 2012	0.0 N	-6.67 W	14:02:06	13:35:26
1 Oct 2012	0.0 N	+11.93 E	12:47:26	13:35:10
31 Dec 2012	0.0 N	-8.30 W	14:08:30	13:35:18

As a test of how consistent the CDA was between the two satellites, we have computed the two-year relative change [(2012 – 2006)/2006×100%] in seasonal [DJF, MAM, JJA, SON] screened and unscreened contrail coverage derived from *Terra* MODIS data versus the corresponding seasonal two-year change in contrail coverage computed from *Aqua* MODIS data for each of the high air traffic regions. The results are plotted below in Figure X, which has been added to the manuscript. Figure X(a) shows a scatter plot of the relative difference in seasonal unscreened contrail coverage between 2012 and 2006 determined from *Terra* MODIS data for each of the high air traffic regions versus the corresponding 2012 minus 2006 relative difference in *Aqua*-derived unscreened coverage. Figure X(b) shows the same scatter plot with the linear regressions for each of the air traffic regions. The unscreened coverages from both satellites are well correlated with each other. The *Terra* and Aqua screened coverages are even better correlated (Figures X(c) and X(d)).

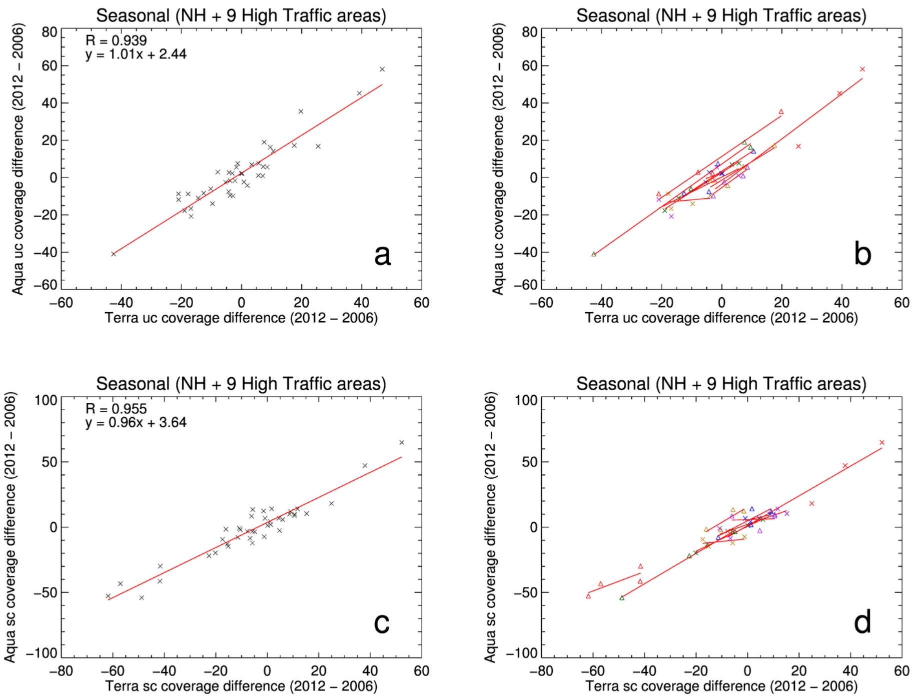


Figure X: Scatter plots of relative difference [(2012 – 2006)/2006×100%] in *Terra* MODIS-derived contrail coverage versus *Aqua* MODIS-derived contrail coverage for each air traffic region.

For correction, meteorological data and traffic data are used, which unfortunately are different in several respect and it is not clear whether the quality of the data over the two observation periods is sufficient to allow for an unbiased comparison of the results from the two one-year periods.

The 2006 meteorological data are from GEOS version 4 (which ended in 2007). We expect only minor differences between GEOS-4 and MERRA, the latter being built on GEOS version 5, which was found to have little impact on cloud detection except in polar regions where surface temperatures are different (see Minnis et al. https://ceres.larc.nasa.gov/documents/STM/2007-04/ce0704241020CloudsMinnis.pdf, https://ceres.larc.nasa.gov/documents/STM/2008-05/pdf/3_Minnis.CERES.5.08.pdf). Thus, we do not expect the winds to be significantly different.

The paper comes to important conclusions: most contrails are 2 h old when detected by the satellites. That conclusion is reasonable and consistent with a few other studies (not only form their own team).

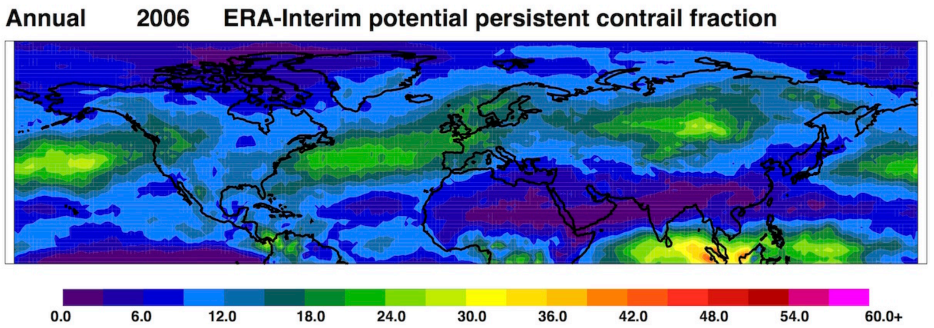
As indicated in the text, this conclusion is also supported by the results of Vázquez-Navarro et al. (2015).

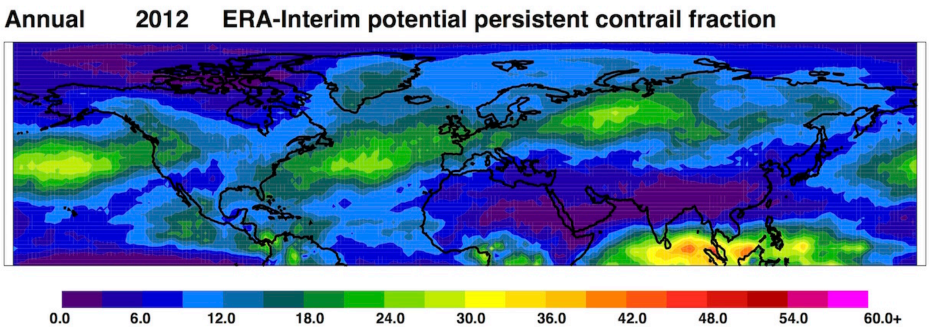
Further the paper suggests that the NH contrail coverage increased from 0.136 % to 0.140 % in coverage or by 3 % in relative terms. Unfortunately, error estimates on these results are missing and difficult. One cannot be sure about the significance of the small *changes because that would require an overall accuracy better than 3 %. So, these data should be presented together with error estimates, which may be large. At present the abstract presents the coverage results as if they were accurate to 3 digits. That needs to be changed.*

We agree that the uncertainty in the screened contrail coverage estimates are probably large enough that the differences between 2006 and 2012 are not likely to be statistically significant, in large part because we have no way of evaluating the air traffic data that are critical to the screening process. We expect the detectability of contrails from year to year to be the same, but the unscreened data, while consistent with the relative changes in screened data over many regions, indicate no change in coverage. Thus, the small positive increase in screened coverage may not be meaningful. Please note that the reported coverage changes are small, thus to compute the relative change, we were required to express the coverage with at least three significant digits. We have removed mention of the 3-digit estimates from the abstract, and modified the text to acknowledge the uncertainty in the screened coverage estimates.

Figure 1 shows the derived annual mean global distribution of detected contrail coverage. The result suggests a strong contrail maximum over the North Atlantic. The result of Figure 1 may be technically correct but the overall result does not look plausible. It contradicts many other studies in terms of the spatial distribution of contrail coverage. See all the global model studies on contrails that have been published so far since 1998 (see reviews in IPCC 1999, 2013, etc.). All of them show contrail maxima over the continents, not over the North Atlantic.

We remind the reviewer that what we are measuring is not the same as what the models estimate. The satellites detect only some contrails, and at a specific moment in time. The models simulate all contrails (including contrails in preexisting clouds) and average over time. Also, the North Atlantic is a region favorable for the formation of persistent contrails. We have enclosed our annual-mean estimate of the frequency of persistent contrail formation (in percent) between 250 to 200 hPa (typical aircraft cruise altitudes), based on ERA-Interim reanalysis data. The PPCF is higher over the North Atlantic compared to most of Europe and CONUS.





The authors discuss traffic and potential contrail coverage computed for the given traffic using numerical weather prediction data but do not show a NH map of the absolute values of potential contrail coverage and the product of the potential coverage with traffic for comparisons. Figure 2 only shows differences in these parameters between the two annual periods. I strongly suggest to add a plot of the expected coverage and to point out that Figure 1 suffers from the spatially variable detection efficiency.

Relating the potential and observed contrail coverage would be a good project for another paper, but it would require much additional work to determine where natural cirrus and other high clouds may impact the detection of contrails. We also note that we still do not know exactly how detectable contrail coverage relates to potential coverage and air traffic density.

I suggest that the paper presents a table for the nine air traffic regions identified in Figure 5, comparing the observed contrail properties (coverage, RF, etc.) with computed or model-estimated contrail properties.

Such a table would be for another study altogether. To make a **fair** comparison, the model results would have to be screened for natural cirrus and other high ice clouds that would render most contrails invisible to the satellite. In addition, model-based estimates would have to consider the detectability limitations of the satellite imagery and the temporal and spatial sampling of the satellite observations. This would be a far bigger task than due for this paper.

The authors cite Meyer et al. (2002, JGR, doi: 10.1029/2001jd000426) but the list of references misses this paper. Another paper, Meyer et al (2007, Int. J. Rem. Sens., doi: 10.1080/01431160600641707) also discussed contrail coverage,

The missing Meyer references have been added to the text.

and their Table 1 shows what I was looking for: a comparison between observed and computed contrail coverage over various regions of the world. Of course, nowadays such a comparison can be made far better than >10 years ago, and other model results became available in the literature.

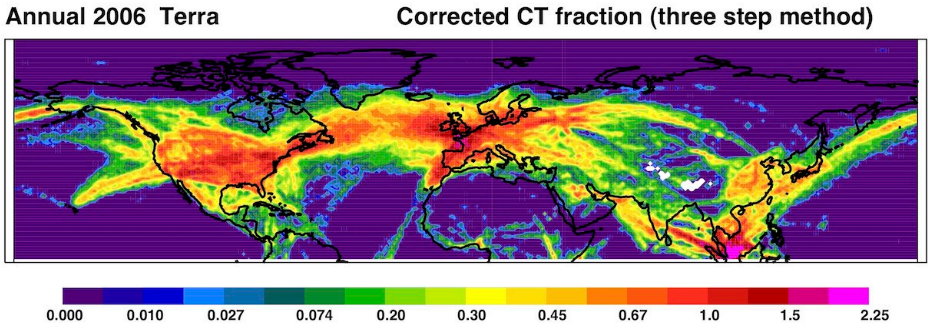
See discussion of model comparisons above.

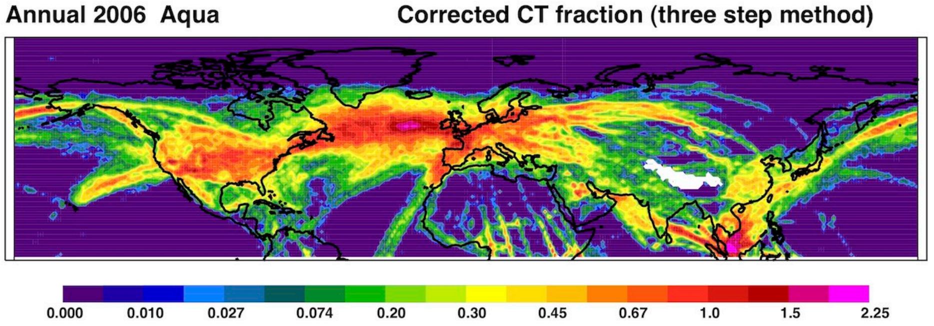
The discussion o altitude changes is not convincing. There is no reasonable and testable argument given for why the mean cruise altitude of air traffic should have been increasing by 0.26 km or 0.79 km over the NH or over the Pacific during the just <6 years since 2006, except that two data sets of different origin indicate this. I suggest skipping this discussion and the related Table 2.

We observe that the technique for reporting heights is the same over CONUS in both datasets, thus the 0.3 km increase in that region is very likely to be real. The differences over other areas may be less certain, but if the CONUS heights are right, the others are probably in the same direction. The height information is used in the retrieved contrail properties (optical depth, effective particle size, and radiative forcing), so we believe it must be included in the paper. To clarify the discussion in the text, we have added that the change in mean cruise altitude was a reported change.

The values given for global radiative forcing do not yet contain error bounds for possibly underestimated contrail coverage over the continents. I suggest that the authors estimate possible underestimates over the continents (e.g., from the mentioned comparison to model data) and use such estimates to derive an upper bound on contrail coverage or RF from their data.

This study focuses on our satellite-based estimates. An estimate of RF over the continents has already been included in the paper based on the contrail cirrus estimate. We also have unpublished work that can provide an annual-mean corrected (for background inhomogeneity) contrail coverage estimate for the 2006 data. This estimate is based on a visual analysis that we performed on the 2006 data, including an inhomogeneity correction based on Meyer et al. (2002). A brief summary of that work has been included as a supplement. The correction increases the Terra NH-mean coverage by 25 percent (from 0.136 to 0.170%), which would thus increase the overall linear contrail RF by an equal proportion. (The corrected 2006 Aqua coverage is 0.169%.) The corrected Terra coverage shows that the maxima in CC is now over CONUS and Europe, although the corrected Aqua coverage still has a maximum over the North Atlantic due to the decrease in detectability of linear contrails over the continents during the afternoon. We are not able to re-do the visual analysis for the 2012 coverage due to the considerable labor requirements. Assuming the same correction as for 2006, the corrected 2012 Terra (Aqua) coverage increases to 0.178% (0.185%).





The discussion of "interannual" changes should be reduced. There is no significance in the detected "interannual variability" if only 2 years are considered. The best one could do is to report differences between the two years. So instead of saying the cover changed from 2006 to 2012, they should say the data from 2012 and 2006 show differences, but should add that the differences can have many reasons, including true contrail changes, humidity changes, traffic changes, changes in the observation method, etc.

As the first sentence of the abstract states, this study compares contrail properties derived from satellite data measured during 2006 and 2012. We believe it is clear to the reader that we are discussing changes in observed contrail properties between the two years, and that several factors may be causing the differences. The use of language such as "contrail coverage changed from 2006 to 2012" is simply a report of a difference between results from two years, not a declaration of absolute accuracy in measurement. As for the use of "interannual", we have removed some unnecessary instances of the word (mostly in the figure captions), and used other phrases when possible to describe "interannual". We note that the phrase "interannual variability" only occurs once in the manuscript, where the future possibility of adding an additional year of contrail properties is discussed.

I encourage the authors to carefully revise the paper and to publish the facts and the data sets, with proper comparisons to model results, more restrictive conclusions, and self-critical discussion.

The referee's comments here are not clear to us. What is meant by "publish the facts and the data sets"? What facts and data sets, the entire two-year, two-satellite set of MODIS imagery? A release of the source code and data sets is not reasonable. It is not feasible to upload the hundreds of gigabytes of satellite data processed in this study. The source code is experimental and not easily implemented by someone unfamiliar with the programs. In addition to contrail detection, we also retrieve contrail optical properties and radiative forcing with additional code and processing systems.