Supplementary Material for

On the signature of the cirrus twilight zone

Uri Wollner\textsuperscript{1}, Ilan Koren\textsuperscript{1}, Orit Altaratz\textsuperscript{1} and Lorraine A. Remer\textsuperscript{2}

\textsuperscript{1}Department of Earth and Planetary Sciences, The Weizmann Institute of Science, Rehovot, Israel

\textsuperscript{2}Joint Center for Earth Systems Technology, University of Maryland Baltimore County, Baltimore, MD, USA

Corresponding author: Ilan.Koren@weizmann.ac.il

This file includes:

1) Details of a theoretical sensitivity study on the contribution of low cumulus (Cu) clouds to the cirrus twilight-zone signature

2) Detailed information on all cases examined in this study using MODIS and CALIPSO data

1) Details of a theoretical sensitivity study on the contribution of low Cu clouds to the cirrus twilight-zone signature

A theoretical experiment was conducted to assess how the presence of shallow clouds affects the overall signal. In the paper we describe how we tried to minimize any other effect that might change the observed patterns in reflectance, AOD, Aexp and SST, beside undetected cirrus clouds. The basic purpose of this theoretical model was to answer the following question: What if few small clouds with weak signature did escape our screening and were present in the analyzed area? What is their effect on the trends? The clouds that might escape our screening need to have a weak signature (otherwise we would screen them out) and therefore are likely to be small in size. To answer this we created a theoretical cloud field that contained a clear transition from a cirrus cloud (with a large linear edge) and a cirrus free part (the left part of figure S1 which is a horizontal view of the theoretical cloud field). To keep the model simple, the normalized reflectance of the cirrus was chosen as a unit and the gradient away from the edge of the cirrus was similar to what we saw in real data. Then we randomly added to the field small (one km) clouds and attributed each cloud a unit reflectance and a gradient around it. Note that a unit reflectance is similar to the one...
of the detectable cirrus and therefore simulated clouds with not-so-weak reflectance as an upper limit of the effect.

The left column in Figure S1 illustrates the top of the atmospheric reflectance of the theoretical cloud field. In our simulations, a cirrus deck covered the right third of the domain. At the edge of the deck, our model simulated the contribution from undetectable cirrus clouds with a reflectance that gradually decreased with distance from the nearest cirrus cloud. We set the model such that at the far left side of the domain, there were no cirrus clouds at all and the background ocean surface reflectance was zero. We gradually introduced more and more low convective clouds into this basic model, each with a reflectance of 1. As suggested by a previous study (Koren et al., 2007), we chose to describe the reflectance surrounding a low convective cloud as exponentially decreasing from the value of every cloudy pixel. The right column in Figure S1 presents the average reflectance values among pixels located at similar distances from the nearest cirrus pixel (with standard errors). The same analysis was performed for increasing densities of low-cloud pixels (Figure S1b–d).

As the cirrus clouds decks are relatively large with a more linear structure, their edges are longer, creating a coherent linear structure of distances from the cirrus edge map. As one can see from the reflectance curves, contamination from relatively small size low-level clouds with a circular structure does not destroy the cirrus trend but instead, adds to the background averages. This is true as long as the shallow cloud concentration is not too large, such that the overall signal is not dominated by their contribution.

The model represents a uniform cirrus layer near scattered low-level clouds. It should be noted that it is a simple representation of a cloud scene where the key cloud feature in these regions is the cirrus cloud that has a regular shape. The reflectivity of the cirrus and low-level clouds were chosen to be similar. In fact, this represents an extreme case as the small clouds should be undetectable. Further sensitivity tests showed that even for shallow clouds with reflectance values higher than those of the cirrus clouds, as long as the small ("undetectable") clouds are sparse, the average reflectance values will contain a larger contribution from the main feature in the region (i.e. cirrus cloud), and therefore the decreasing reflectance signature will dominate.
Figure S1: A theoretical experiment of small-size cloud effect on the cirrus reflectance gradients. The left column shows horizontal projection of the theoretical cloud fields. In each case the cirrus is marked on the right hand side of the image with a uniform unity reflectance. Small single-pixel clouds are randomly inserted on the cirrus-free part (on the left side). The modeled scenes change from absence of low clouds (a) through a gradual increase in the low clouds' presence (b–d). The right column presents reflectance values averaged among pixels with similar distance from the nearest cirrus cloud as a function of this distance. Standard error bars are included as well.

2) Detailed information on all cases examined in this study using MODIS and CALIPSO data

**Method and data:**

The 1-km resolution cloud mask (Platnick et al., 2003) was utilized along with MODIS Cirrus Flag to produce a masked (classified) image (see an example in Figure 1b in the paper) of a selected MODIS granule (Figure 1a in the paper). The classification included cirrus clouds, non-cirrus clouds, land, sun glint and sea surface. We restricted our analysis to areas where the main cloud type at the high levels is cirrus, avoiding 3D effects from proximity to deep convective clouds (Vármai and Alexander, 2002; Marshak et al., 2006), such as towers with high cloud optical thickness (COT > 16) (see example in Figure 1c in the paper). To avoid sun glint and land features, we selected regions (dashed polygon in Figure 1 in the paper) that are at least 30 km away from such features. Euclidean distance from the nearest cirrus cloud was calculated for each cirrus-free pixel within the selected polygons. Nadir reflectance values acquired from the raw MODIS data product were averaged for pixels located at a similar distance from the nearest cirrus. The analyzed reflectance values were in the visible and near infrared range.
A similar analysis was performed for the MODIS Level-2 1-km Sea Surface Temperature (SST, MOD28) (Brown and Minnett, 1999) (Figure 1d), Level-3 8-day-mapped 4-km SST (Brown and Minnett, 1999), and Level-2 10-km aerosol product (MOD04) (Remer et al., 2005). All products were resampled to the reference resolution of 1 km.

Overall, 23 MODIS data granules were examined from the years 2007 to 2011, located over the ocean in the mid-latitudes near South America, North America, the Australian west coast, and Japan (Figure S2). The data were selected manually to include the best regions for examination of cirrus boundaries over oceans.

![Figure S2: Location of 23 granule centers represented by colored dots between the years 2007 and 2011.](image)

**Results:**

For each case, a figure is presented consisting of:

1) A real color image (panel a, similar to Figure 1a in the paper).

2) A feature-classification masking of the granule (panel b, similar to Figure 1b in the paper).

3) An analysis of the average AOD and angstrom exponent (Ang. Exp), (panel c, top), and Level-2 SST and Level-3 SST (panel c, bottom) as a function of distance from the nearest cirrus cloud (with corresponding standard error), (similar to the bottom panel in Figure 2 in the paper).

4) An analysis of MODIS bands 1–7 reflectance as a function of distance from the nearest cirrus cloud (panel d) (similar to the upper panel in Figure 2 in the paper).
Case 1:

The following figure was produced with data acquired by MODIS Aqua satellite on 20 Mar 2007 at 18:05 GMT over the Atlantic Ocean and South America.

Figure S3: (a) Real color image—enhanced to show thin cirrus, (b) masked image of a granule, (c – top) AOD and (c – bottom) SST averaged values as a function of distance from the nearest cirrus cloudy pixel with their corresponding standard errors. (d) Reflectance values per distance per band plotted as a function of distance from the nearest cirrus.
Case 2

The following figure was produced with data acquired by MODIS Aqua satellite on 22 Mar 2007 at 17:55 GMT over the Atlantic Ocean and South America.

Figure-S4: (a) Real color image—enhanced to show thin cirrus, (b) masked image of a granule, (c−top) AOD and (c−bottom) SST averaged values as a function of distance from the nearest cirrus cloudy pixel with their corresponding standard errors. (d) Reflectance values per distance per band plotted as a function of distance from the nearest cirrus.
The following figure was produced with data acquired by MODIS Aqua satellite on 31 Aug 2007 at 17:40 GMT over the Atlantic Ocean and South America.

**Figure-S5**: (a) Real color image—enhanced to show thin cirrus, (b) masked image of a granule, (c – top) AOD and (c – bottom) SST averaged values as a function of distance from the nearest cirrus cloudy pixel with their corresponding standard errors. (d) Reflectance values per distance per band plotted as a function of distance from the nearest cirrus.
Case 4

The following figure was produced with data acquired by MODIS Aqua satellite on 5 Sep 2007 at 18:00 GMT over the Atlantic Ocean and South America.

Figure-S6: (a) Real color image—enhanced to show thin cirrus, (b) masked image of a granule, (c – top) AOD and (c – bottom) SST averaged values as a function of distance from the nearest cirrus cloudy pixel with their corresponding standard errors. (d) Reflectance values per distance per band plotted as a function of distance from the nearest cirrus.
Case 5

The following figure was produced with data acquired by MODIS Aqua satellite on 2 Oct 2007 at 02:55 GMT over the Pacific Ocean and Australia.

Figure-S7: (a) Real color image—enhanced to show thin cirrus with solid orange line to mark glint areas, (b) masked image of a granule, (c – top) AOD and (c – bottom) SST averaged values as a function of distance from the nearest cirrus cloudy pixel with their corresponding standard errors. (d) Reflectance values per distance per band plotted as a function of distance from the nearest cirrus.
Case 6

The following figure was produced with data acquired by MODIS Aqua satellite on 2 Oct 2007 at 14:25 GMT over the Atlantic Ocean.

Figure-S8: (a) Real color image—enhanced to show thin cirrus with solid orange line to mark glint areas, (b) masked image of a granule, (c – top) AOD and (c – bottom) SST averaged values as a function of distance from the nearest cirrus cloudy pixel with their corresponding standard errors. (d) Reflectance values per distance per band plotted as a function of distance from the nearest cirrus.
Case 7

The following figure was produced with data acquired by MODIS Aqua satellite on 24 Dec 2007 at 11:35 GMT over the Antarctic Ocean.

Figure-S9: (a) Real color image—enhanced to show thin cirrus with solid orange line to mark glint areas, (b) masked image of a granule, (c – top) AOD and (c – bottom) SST averaged values as a function of distance from the nearest cirrus cloudy pixel with their corresponding standard errors. (d) Reflectance values per distance per band plotted as a function of distance from the nearest cirrus.
Case 8

The following figure was produced with data acquired by MODIS Aqua satellite on 3 Jan 2008 at 20:45 GMT over the Pacific Ocean and Central America.

Figure-S10: (a) Real color image—enhanced to show thin cirrus with solid orange line to mark glint areas, (b) masked image of a granule, (c – top) AOD and (c – bottom) SST averaged values as a function of distance from the nearest cirrus cloudy pixel with their corresponding standard errors. (d) Reflectance values per distance per band plotted as a function of distance from the nearest cirrus.
Case 9

The following figure was produced with data acquired by MODIS Aqua satellite on 2 Mar 2008 at 18:30 GMT over the Atlantic Ocean and South America.

Figure-S11: (a) Real color image—enhanced to show thin cirrus, (b) masked image of a granule, (c – top) AOD and (c – bottom) SST averaged values as a function of distance from the nearest cirrus cloudy pixel with their corresponding standard errors. (d) Reflectance values per distance per band plotted as a function of distance from the nearest cirrus.
Case 10

The following figure was produced with data acquired by MODIS Aqua satellite on 1 Sep 2008 at 02:10 GMT over the Pacific Ocean and New Zealand.

Figure-S12: (a) Real color image—enhanced to show thin cirrus, (b) masked image of a granule, (c – top) AOD and (c – bottom) SST averaged values as a function of distance from the nearest cirrus cloudy pixel with their corresponding standard errors. (d) Reflectance values per distance per band plotted as a function of distance from the nearest cirrus.
Case 11

The following figure was produced with data acquired by MODIS Aqua satellite on 4 Jan 2009 at 18:10 GMT over the Atlantic Ocean and South America.

Figure-S13: (a) Real color image—enhanced to show thin cirrus with solid orange line to mark glint areas, (b) masked image of a granule, (c – top) AOD and (c – bottom) SST averaged values as a function of distance from the nearest cirrus cloudy pixel with their corresponding standard errors. (d) Reflectance values per distance per band plotted as a function of distance from the nearest cirrus.
Case 12

The following figure was produced with data acquired by MODIS Aqua satellite on 28 Jan 2009 at 21:00 GMT over the Pacific Ocean and North America.

Figure-S14: (a) Real color image—enhanced to show thin cirrus with solid orange line to mark glint areas, (b) masked image of a granule, (c – top) AOD and (c – bottom) SST averaged values as a function of distance from the nearest cirrus cloudy pixel with their corresponding standard errors. (d) Reflectance values per distance per band plotted as a function of distance from the nearest cirrus.
The following figure was produced with data acquired by MODIS Aqua satellite on 2 Feb 2009 at 21:20 GMT over the Pacific Ocean and North America.

Figure S15: (a) Real color image—enhanced to show thin cirrus, (b) masked image of a granule, (c – top) AOD and (c – bottom) SST averaged values as a function of distance from the nearest cirrus cloudy pixel with their corresponding standard errors. (d) Reflectance values per distance per band plotted as a function of distance from the nearest cirrus.
Case 14

The following figure was produced with data acquired by MODIS Aqua satellite on 24 Feb 2009 at 20:40 GMT over the Pacific Ocean and Central America.

Figure-S16: (a) Real color image—enhanced to show thin cirrus with solid orange line to mark glint areas, (b) masked image of a granule, (c – top) AOD and (c – bottom) SST averaged values as a function of distance from the nearest cirrus cloudy pixel with their corresponding standard errors. (d) Reflectance values per distance per band plotted as a function of distance from the nearest cirrus.
Case 15

The following figure was produced with data acquired by MODIS Aqua satellite on 27 Feb 2009 at 07:55 GMT over the Indian Ocean and Southern India.

Figure-S17: (a) Real color image—enhanced to show thin cirrus with solid orange line to mark glint areas, (b) masked image of a granule, (c – top) AOD and (c – bottom) SST averaged values as a function of distance from the nearest cirrus cloudy pixel with their corresponding standard errors. (d) Reflectance values per distance per band plotted as a function of distance from the nearest cirrus.
Case 16

The following figure was produced with data acquired by MODIS Aqua satellite on 1 Mar 2009 at 21:00 GMT over the Pacific Ocean and North America.

Figure-S18: (a) Real color image—enhanced to show thin cirrus with solid orange line to mark glint areas, (b) masked image of a granule, (c – top) AOD and (c – bottom) SST averaged values as a function of distance from the nearest cirrus cloudy pixel with their corresponding standard errors. (d) Reflectance values per distance per band plotted as a function of distance from the nearest cirrus.
Case 17

The following figure was produced with data acquired by MODIS Aqua satellite on 6 Mar 2009 at 17:40 GMT over the Atlantic Ocean and South America.

Figure-S19: (a) Real color image—enhanced to show thin cirrus with solid orange line to mark glint areas, (b) masked image of a granule, (c – top) AOD and (c – bottom) SST averaged values as a function of distance from the nearest cirrus cloudy pixel with their corresponding standard errors. (d) Reflectance values per distance per band plotted as a function of distance from the nearest cirrus.
Case 18

The following figure was produced with data acquired by MODIS Aqua satellite on 17 Aug 2009 at 17:15 GMT over the Atlantic Ocean and South America.

Figure-S20: (a) Real color image—enhanced to show thin cirrus, (b) masked image of a granule, (c – top) AOD and (c – bottom) SST averaged values as a function of distance from the nearest cirrus cloudy pixel with their corresponding standard errors. (d) Reflectance values per distance per band plotted as a function of distance from the nearest cirrus.
Case 19

The following figure was produced with data acquired by MODIS Aqua satellite on 17 Sep 2009 at 18:10 GMT over the Atlantic Ocean and South America.

Figure-S21: (a) Real color image—enhanced to show thin cirrus, (b) masked image of a granule, (c – top) AOD and (c – bottom) SST averaged values as a function of distance from the nearest cirrus cloudy pixel with their corresponding standard errors. (d) Reflectance values per distance per band plotted as a function of distance from the nearest cirrus.
Case 20

The following figure was produced with data acquired by MODIS Aqua satellite on 30 Oct 2009 at 14:50 GMT over the Atlantic Ocean and Africa.

![Figure S22](image_url)

Figure-S22: (a) Real color image—enhanced to show thin cirrus with solid orange line to mark glint areas, (b) masked image of a granule, (c – top) AOD and (c – bottom) SST averaged values as a function of distance from the nearest cirrus cloudy pixel with their corresponding standard errors. (d) Reflectance values per distance per band plotted as a function of distance from the nearest cirrus.
Case 21

The following figure was produced with data acquired by MODIS Aqua satellite on 19 Mar 2011 at 21:20 GMT over the Pacific Ocean and North America.

Figure-S23: (a) Real color image—enhanced to show thin cirrus with solid orange line to mark glint areas, (b) masked image of a granule, (c – top) AOD and (c – bottom) SST averaged values as a function of distance from the nearest cirrus cloudy pixel with their corresponding standard errors. (d) Reflectance values per distance per band plotted as a function of distance from the nearest cirrus.
Case 22

The following figure was produced with data acquired by MODIS Aqua satellite on 2 Apr 2011 at 06:30 GMT over the Indian Ocean and Australia.

Figure-S24: (a) Real color image—enhanced to show thin cirrus with solid orange line to mark glint areas, (b) masked image of a granule, (c – top) AOD and (c – bottom) SST averaged values as a function of distance from the nearest cirrus cloudy pixel with their corresponding standard errors. (d) Reflectance values per distance per band plotted as a function of distance from the nearest cirrus.
Case 23

The following figure was produced with data acquired by MODIS Aqua satellite on 29 Apr 2011 at 04:45 GMT over the Pacific Ocean and Japan.

Figure-S25: (a) Real color image—enhanced to show thin cirrus with solid orange line to mark glint areas, (b) masked image of a granule, (c – top) AOD and (c – bottom) SST averaged values as a function of distance from the nearest cirrus cloudy pixel with their corresponding standard errors. (d) Reflectance values per distance per band plotted as a function of distance from the nearest cirrus.
As a reference to the MODIS cirrus detection limitations, we analyzed the area near the edge of detectable cirrus clouds using the Level-2 vertical feature mask (VFM) product (Powell et al., 2010) from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) aboard CALIPSO. As a part of the “A-Train” satellite constellation (L’Ecuyer and Jiang; 2010) the CALIPSO orbit is designed to provide a detailed vertical cross-section of clouds and aerosols over the middle of the AQUA-MODIS swath with ~1.5 min time delay.

We compared the MODIS cirrus detection with the CALIPSO’s backscatter, depolarization and cloud-masking products. We picked daytime CALIPSO data that were acquired close enough to the analyzed MODIS clouds. The following figures show examples for such a comparison. The backscatter and depolarization data were collected and averaged vertically along the horizontal levels in which the cirrus was detected (lower left) by the CALIPSO algorithm. The averaged backscatter and depolarization lines were plotted (upper right) with the location of the cirrus edge marked according to MODIS (red) (available for day time cases) and CALIPSO (black). For the daytime data the depolarization (upper left) and backscatter data (lower right) are relatively noisy. Nevertheless it can be seen that the edge of the cirrus is characterized by a decay of the backscatter levels to the background levels (where the black line crosses the magenta).
Figure-S26: Day time data retrieved by CALIPSO on Mar 19, 2011 over Eastern Pacific ocean. The upper left graph depicts the depolarization ratio of the selected area. The upper right graph shows averaged attenuated backscatter ($\langle$ABS$\rangle$) at 1064 nm (magenta) and depolarization values (blue) retrieved in the area between the two horizontal dashed black lines shown in the other images. The bottom left graph presents a vertical feature mask (VFM). The bottom right graph shows attenuated backscatter. The vertical dashed black line represents the boundary between a cloud feature and clear air from CALIPSO, while the vertical red dashed line represents cirrus boundaries inferred by MODIS. The difference between the CALIPSO and MODIS cirrus boundaries is 5 km.
Figure-S27: Day time data retrieved by CALIPSO on Apr 29, 2011 over East Asia. The upper left graph depicts the depolarization ratio of the selected area. The upper right graph shows averaged attenuated backscatter (<ABS>) at 1064 nm (magenta) and depolarization values (blue) retrieved in the area between the two horizontal dashed black lines shown in the other images. The bottom left graph presents a vertical feature mask (VFM). The bottom right graph shows attenuated backscatter. The vertical dashed black line represents the boundary between a cloud feature and clear air from CALIPSO, while the vertical red dashed line represents cirrus boundaries inferred by MODIS. The difference between the CALIPSO and MODIS cirrus boundaries is 86 km.
Figure-S28: Night time data retrieved by CALIPSO on Jan 8, 2012 over South America. The upper left graph depicts the depolarization ratio of the selected area. The upper right graph shows averaged attenuated backscatter (ABS) at 1064 nm (magenta) and depolarization values (blue) retrieved in the area between the two horizontal dashed black lines shown in the other images. The bottom left graph presents a vertical feature mask (VFM). The bottom right graph shows attenuated backscatter. The vertical dashed black line represents the boundary between a cloud feature and clear air from CALIPSO.
Figure-S29: Night time data retrieved by CALIPSO on Jan 8, 2012 over Eastern Pacific ocean. The upper left graph depicts the depolarization ratio of the selected area. The upper right graph shows averaged attenuated backscatter (<ABS>) at 1064 nm (magenta) and depolarization values (blue) retrieved in between the two horizontal dashed black lines shown in the other images. The bottom left graph presents a vertical feature mask (VFM). The bottom right graph shows attenuated backscatter. The vertical dashed black line represents the boundary between a cloud feature and clear air from CALIPSO.

0 - Invalid, 1 - Clear Air, 2 - Cloud, 3 - Aerosol, 4 - Strat Feature 5 - Surface, 6 - Subsurface, 7 - No Signal
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