

Evaluations of Thin Cirrus Contamination and Screening in Ground Aerosol Observations Using Collocated Lidar Systems

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Popular Summary

Satellite data play irreplaceable roles in large-scale aerosol observations and relevant global climate change studies. However the accuracy of satellite aerosol retrievals heavily relies on ground measurements because ground-based aerosol observations play an important role in calibrating and validating their spaceborne counterparts. Uncertainties associated with satellite data retrieval algorithms are still at large not well quantified. Cirrus clouds, particularly sub visual high thin cirrus with low optical thickness, are difficult to be screened in operational aerosol retrieval algorithms.

Collocated aerosol and cirrus observations from ground measurements, such as the Aerosol Robotic Network (AERONET) and the Micro-Pulse Lidar Network (MPLNET), provide us with an unprecedented opportunity to examine the susceptibility of operational aerosol products to thin cirrus contamination. Quality assured aerosol optical thickness (AOT) measurements were also tested against the CALIPSO vertical feature mask (VFM) and the MODIS-derived thin cirrus screening parameters for the purpose of evaluating thin cirrus contamination.

Key results of this study include: (1) Quantitative evaluations of data uncertainties in AERONET AOT retrievals are conducted. Although AERONET cirrus screening schemes are successful in removing most cirrus contamination, strong residuals displaying strong spatial and seasonal variability still exist, particularly over thin cirrus prevalent regions during cirrus peak seasons, (2) Challenges in matching up different data for analysis are highlighted and corresponding solutions proposed, and (3) Estimation of the relative contributions from cirrus contamination to aerosol retrievals are discussed.

Such evaluation and examination are valuable for improving operational ground aerosol retrieval algorithms in related to cirrus screening and potential cirrus contamination correction. The results are valuable for better understanding and further improving ground aerosol measurements that are critical for aerosol-related climate research.

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2 **Ground Aerosol Observations Using Collocated Lidar Systems**

3

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16

17 **Abstract:**

18 Cirrus clouds, particularly sub visual high thin cirrus with low optical thickness, are
19 difficult to be screened in operational aerosol retrieval algorithms. Collocated aerosol and
20 cirrus observations from ground measurements, such as the Aerosol Robotic Network
21 (AERONET) and the Micro-Pulse Lidar Network (MPLNET), provide us with an
22 unprecedented opportunity to examine the susceptibility of operational aerosol products
23 to thin cirrus contamination. Quality assured aerosol optical thickness (AOT)
24 measurements were also tested against the CALIPSO vertical feature mask (VFM) and
25 the MODIS-derived thin cirrus screening parameters for the purpose of evaluating thin
26 cirrus contamination. Key results of this study include: (1) Quantitative evaluations of
27 data uncertainties in AERONET AOT retrievals are conducted. Although AERONET
28 cirrus screening schemes are successful in removing most cirrus contamination, strong
29 residuals displaying strong spatial and seasonal variability still exist, particularly over
30 thin cirrus prevalent regions during cirrus peak seasons, (2) Challenges in matching up
31 different data for analysis are highlighted and corresponding solutions proposed, and (3)
32 Estimation of the relative contributions from cirrus contamination to aerosol retrievals are
33 discussed. The results are valuable for better understanding and further improving ground
34 aerosol measurements that are critical for aerosol-related climate research.

35

36 **1. Introduction**

37

38 Satellite data play irreplaceable roles in large-scale aerosol observations and relevant
39 global climate change studies (e.g. Andreae, 1991; Breon et al, 2002; Menon et al, 2002;
40 Huang et al., 2009). However the accuracy of satellite aerosol retrievals heavily relies on
41 ground measurements because ground-based aerosol observations play an important role
42 in calibrating and validating their spaceborne counterparts (Holben et al., 1998).

43 Uncertainties associated with satellite data retrieval algorithms are still at large not well
44 quantified (e.g. Myhre et al. 2005); cloud screening and quality control in ground data
45 retrievals are also challenging (Smirnov et al., 2000; Schaap et al., 2009). For example,
46 the existence of high thin cirrus clouds with low optical thickness, are still sometimes
47 observed in the satellite and ground aerosol products (e.g. Gao et al, 2002a; Kaufman et
48 al., 2005; Huang et al., 2011). Therefore, it is imperative to perform rigorous and
49 systematic global evaluations on the severity of cirrus contamination in ground aerosol
50 products and to investigate better alternatives for cirrus screening schemes.

51

52 With concurrent cirrus observations from ground or spaceborne lidars, quantitative
53 evaluation of thin cirrus contamination in the operational aerosol products becomes
54 possible (e.g. Huang et al., 2011). For ground observations, aerosol retrievals from the
55 Aerosol Robotic Network (AERONET, Holben et al., 1998) and atmosphere profiling
56 from the Micro-Pulse Lidar Network (MPLNET, Welton et al., 2001) provide
57 simultaneous measurements at their collocated sites. For satellite observations, with the
58 advent of the A-Train satellite constellation, global cirrus cloud coverage and its temporal

59 and spatial variability can be comprehensively observed for the first time (Sassen and
60 Liu, 2008; Massie et al, 2010). The collocated MODIS-derived thin cirrus parameters and
61 cloud-aerosol lidar and infrared pathfinder satellite observations (CALIPSO) provide us
62 with an unprecedented opportunity to examine the susceptibility of the ground aerosol
63 products to cirrus contamination and to evaluate the robustness of current cirrus screening
64 techniques. Such evaluation and examination are valuable for improving operational
65 ground aerosol retrieval algorithms in related to cirrus screening and potential cirrus
66 contamination correction.

67

68 For the current AERONET aerosol optical depth (AOT) cloud screening, a series of
69 procedures are adopted by examining the temporal variability of measured AOT
70 (Smirnov et al., 2000). AERONET cloud screening based on temporal variability is
71 effective for eliminating most cloud contamination (e.g., Smirnov et al., 2000; Kaufman
72 et al., 2006); however, residual cirrus contamination in the operational aerosol products
73 are still observed (e.g., Gao et al, 2002a; Kaufman et al., 2005; Schaap et al., 2009;
74 Huang et al., 2011), that warrant in-depth investigations in this study by taking advantage
75 of ground and spaceborne lidar observations for detecting cirrus.

76

77 For those collocated AERONET and MPLNET sites, lidar measurements from MPLNET
78 can provide observational evidence of thin cirrus to help verify the susceptibility of
79 aerosol data to thin cirrus contamination. Similarly, spaceborne lidar observations from
80 CALIPSO can provide an alternative cirrus observation reference, if the CALIPSO tracks
81 are not far from the AERONET sites. Additionally because cirrus clouds usually occur at

82 higher altitude (> 10 km in the tropical region) and are commonly associated with ice
83 clouds, detecting cirrus from satellites, such as MODIS, is based on apparent reflectance
84 at $1.38\ \mu\text{m}$, $0.66\ \mu\text{m}$, and $1.24\ \mu\text{m}$, and brightness temperature differences in the thermal
85 bands (e.g., Gao and Kaufman, 1995; Gao et al. 2002a, 2002b; Roskovensky and Liou,
86 2003; Roskovensky et al., 2004). In order to scale the effect of water vapor absorption,
87 reflectance at a second channel is usually required in the practical algorithms (Gao et al.,
88 2002b). A ratio between the MODIS apparent reflectance at bands $1.38\ \mu\text{m}$ and $0.66\ \mu\text{m}$
89 was preferred over other satellite-derived cirrus screening parameters for detecting cirrus
90 over Southeast Asia during the cirrus prevailing season (Huang et al., 2011).

91

92 Therefore, as an extension of a detailed regional study in the Biomass-burning Aerosols
93 in South East-Asia: Smoke Impact Assessment (BASE-ASIA) campaign (Huang et al.,
94 2011), this study aims to:

- 95 • Investigate the consistency and comparability of detecting cirrus using MPLNET and
96 CALIPSO
- 97 • Investigate the susceptibility of ground aerosol measurements to cirrus contamination
98 and to quantify its influence at additional AERONET sites. This goal is achieved by
99 exploring the susceptibility of valid and quality assured aerosol retrievals to
100 identifying thin cirrus in the following pairs of matched up data: AERONET vs.
101 MPLNET; AERONET vs. CALIPSO, and AERONET vs. MODIS
- 102 • Evaluate the relative contributions of cirrus optical depth to aerosol observations for
103 those cirrus contaminated cases and to examine the corresponding changes in the
104 Ångström exponent

- 105 • Discuss various factors that impact the data match up schemes used in this study and
106 to recommend solutions for future studies.

107 This paper is arranged as follows. Section 2 lists the main datasets used in this study,
108 followed by a detailed demonstration of results given in Section 3. Lastly, section 4
109 presents our main findings and conclusions.

110

111 **2. Data and Data Processing**

112

113 Because the main focus of the study is on ground measurements, the primary datasets for
114 this study are concurrent ground aerosol and cirrus observations, complemented by cirrus
115 observations from satellites. For aerosol retrievals, we used aerosol products from
116 AERONET; for cirrus identification, we employed data from MPLNET, CALIPSO
117 vertical feature mask (VFM) and the MODIS-derived thin cirrus parameter.

118

119 **2.1. AERONET**

120

121 The AERONET provides a long-term, continuous and readily accessible public domain
122 database of aerosol optical, microphysical and radiative properties for aerosol research
123 and characterization, validation of satellite retrievals, and synergism with other databases
124 (Holben et al., 1998). For the current AERONET aerosol optical depth (AOT) cloud
125 screening, a series of procedures are adopted by examining the temporal variability of
126 measured AOT (Smirnov et al., 2000), including the AOT variability from three
127 consecutive measurements (triplet) over a one-minute time interval, the standard

128 deviation of the remaining AOT (500 nm) data points over a day, and observations of
129 AOT (500 nm) and Ångström exponent with variability higher than three standard
130 deviations within the daily intervals.
131 For this study, only cloud-screened and quality-assured Level 2.0 data were used for the
132 highest operational quality. An AOT temporal variability based three-step approach is
133 adopted in the current operational cloud screening (Smirnov et al., 2000). We use the
134 level 2.0 AOT measurements at 440 nm to validate against concurrent cirrus observations
135 for computing susceptibility statistics.

136

137 **2.2. MPLNET**

138

139 The collocated MPLNET and AERONET super sites provide both column and vertically
140 resolved aerosol and cloud data, such as: optical depth, single scatter albedo, size
141 distribution, aerosol and cloud heights, planetary boundary layer (PBL) structure and
142 evolution, and profiles of extinction and backscatter (Welton et al., 2001;
143 <http://mplnet.gsfc.nasa.gov>). Out of 16 collocated MPLNET and AERONET sites, 13
144 sites with overlapping temporal data coverage were selected. We primarily use MPLNET
145 Level 1.0 normalized relative backscatter (L1.0 NRB) data for cirrus visualization and
146 cirrus flag derivation. The NRB-derived cirrus flag is used for automated cirrus
147 identification purposes. It is generated based on the statistical characterization of the
148 NRB data in each time-space window (300-m in range and 10-minute in time). To be
149 discriminated from a more theoretical based cirrus flag, this cirrus flag is named as
150 ‘Statistical Cirrus Flag’ (SCF) in this paper. Although MPLNET has both day and night

151 observations and noise level generally increases in daytime, we had to use daytime data
152 because AERONET data are daytime measurements. The following criteria were applied
153 in each time-space window of the NRB data to identify the existence of cirrus cloud and
154 to minimize the influence from noise: 1) the total number of samples has to exceed 30; 2)
155 the averaged NRB value has to exceed 0.35 and 3) cloud base height has to be higher
156 than 8 km. The selection of the threshold values were based on visual inspections of
157 many cases by comparing the cirrus flag to the NRB profiles to ensure the cirrus features
158 were separated from surrounding noise and from the aerosol and low cloud layers
159 underneath. It is noteworthy, however, that for the Monterey and Trinidad-Head sites, the
160 trans-pacific aerosol layers can be as high as cirrus base heights (e.g. Eguchi et al., 2009).
161 In such circumstances, we increased the cirrus cloud base height of the NRB-derived
162 cirrus flag to 10 km to avoid misidentifying aerosol layers at high altitude as cirrus.
163 Although this conservative solution may underestimate the occurring frequency of cirrus
164 clouds, it gives us more confidence on cirrus detection.

165 Moreover, once SCF identifies cirrus during a 10-minute window, a cirrus persistence
166 flag (CPF) is designed to count the continuity of NRB samples that have NRB values
167 exceeding 0.35 at each 1-minute MPL sampling step within the 10-minute time window.
168 The threshold value was determined based on its effectiveness to distinguish cirrus
169 features from ambient noise. CPF will be used to test the persistence of cirrus during each
170 10-minute window. The effectiveness of SCF and CPF in cirrus detection will be
171 elaborated in Section 3.

172 Cirrus case identification highly depends on selection criteria. Based on the SCF and

173 CPF, we will test four sets of cirrus selection criteria based on cirrus existence and
174 persistence within different time window (TW): ‘TW10 existence’, ‘TW30 existence’,
175 ‘TW30 overall persistence’ and ‘TW30 strong persistence’, from less strict to most strict,
176 respectively.

177 1) ‘TW10 existence’ uses SCF at each 10-minute time window without any additional
178 cirrus persistence testing;

179 2) ‘TW30 existence’ uses SCF at three consecutive 10-minute time windows, without
180 any additional cirrus persistence testing;

181 3) ‘TW30 overall persistence’ uses both SCF and CPF at three consecutive 10-minute
182 time windows and requires CPF values higher than 20 out of 30 samples at each one-
183 minute MPL sampling resolution within the 30-minute time window;

184 4) ‘TW30 strong persistence’ is the strictest, and it uses both SCF and CPF at three
185 consecutive 10-minute time windows and requires CPF values higher than 9 out of
186 the 10 samples within each 10-minute time window, and such requirements have to
187 be met for all three consecutive windows. The difference in the results of these four
188 settings will be discussed when they are used for the AERONET-MPLNET match up
189 in Section 3.3.

190

191 **2.3. CALIPSO**

192

193 CALIPSO combines an active lidar instrument (CALIOP) with passive infrared and
194 visible imagers to probe the vertical structure and properties of clouds and aerosols over
195 the globe (Vaughan et al., 2005, 2009). It provides a unique capability to closely examine

196 the vertical profiles of aerosol and clouds from space. For this study, the Level 3.0
197 CALIPSO vertical feature mask (VFM) v3.01, that includes a ‘transparent thin cirrus’
198 cloud subtype (Vaughan et al., 2005, 2009; Liu et al., 2009), were used as baseline for
199 cirrus cloud detection. For comparison to concurrent AERONET aerosol measurements
200 in terms of cirrus contamination evaluation, only daytime CALIPSO data were used. For
201 comparison to MPLNET in terms of cirrus detection, both daytime and nighttime
202 CALIPSO data were used.

203

204 **2.4. MODIS**

205

206 For this study, only Aqua MODIS data were used to identify thin cirrus.. The primary
207 datasets for cirrus screening are the MYD021KM level 1B collection 5 data that has
208 apparent reflectance at 1.38 μm (R1.38) and its derived reflectance ratio between bands
209 1.38 μm and 0.66 μm (RR1.38/0.66) to be used as indicators for thin cirrus at relatively
210 large scale (Huang et al., 2011).

211

212 **3. Results**

213

214 **3.1 Thin Cirrus Climatology from CALIPSO**

215

216 Thin cirrus climatology and its seasonal and regional variability are crucial to
217 understanding their links to data uncertainties in aerosol products. In this study, thin
218 cirrus occurrence frequency is calculated solely based on CALIPSO VFM. The following

219 three criteria were set accordingly to ensure the classification of cirrus clouds is
220 appropriate:

- 221 1) The confidence level for the feature type in VFM has to exceed 70 in the cloud-aerosol
222 discrimination (CAD) score, which signifies high confidence on cloud rather than
223 aerosol;
- 224 2) The feature type should be ‘cloud’, and the sub feature type should be ‘cirrus clouds
225 transparent’; and
- 226 3) Surface return signal should be detected. This is because if the lidar signal is totally
227 attenuated and there is no surface return detected, clouds are too thick (optical thickness
228 higher than 3.0) to be classified as thin cirrus (Sassen et al. 2008).

229 Based on these criteria, we calculated daytime thin cirrus occurrence frequency as shown
230 in Figure 1. Only daytime statistics were shown because aerosol retrievals are only
231 available at daytime. A global average of 18% in Figure 1(a) is comparable to 15% in
232 Sassen et al. (2008) where they also constrained cloud top temperature to be less than -
233 40°C from CloudSat data in order to distinguish pure ice clouds from mixed phase
234 clouds. Cirrus average height and its latitudinal dependence in Figure 1(b) are also
235 similar to Sassen et al. (2008). While the global distribution of cirrus occurrence is highly
236 consistent to Sassen et al (2008), it is noteworthy that the Tibet Plateau features much
237 higher thin cirrus occurrence frequency than that in Sassen et al. (2008), which might be
238 attributable to their additional control of cloud top temperature. The seasonal migrations
239 of thin cirrus prevailing regimes are also clearly seen in the thin cirrus occurrence
240 frequencies in four seasons.

241

242 3.2. MPLNET versus CALIPSO

243

244 Before comparing concurrent aerosol and cirrus observations, it is intriguing to compare
245 the cirrus detection capability of ground lidar and its spaceborne counterpart, by
246 crosschecking the effectiveness of MPLNET NRB-derived cirrus flag and the CALIPSO
247 vertical feature mask. A quantitative direct comparison between MPLNET and CALIPSO
248 may be challenging (Berkoff et al., 2008) however an indicative qualitative comparison
249 in terms of cirrus existence is feasible. The most challenging issue remains to be the
250 distance between the MPLNET sites and CALIPSO overpass tracks. Another challenge is
251 that, in some cases, the CALIPSO overpass time is close to the MPL shutdown time
252 when the MPL was turned off around solar noon to avoid strong sunlight from entering
253 the telescope, which is more critical for tropical sites that have very small solar zenith
254 angle around high noon (Welton, personal communication). Additionally the CALIPSO
255 16-day repeat cycle also significantly reduces the sample size of MPLNET-CALIPSO
256 collocation.

257

258 A first-step crosscheck between MPL and CALIPSO is the cirrus occurrence seasonality.
259 We selected four AERONET-MPLNET sites (GSFC, COVE, Trinidad_Head and
260 NCU_Taiwan) that exhibit the longest multiple year data coverage to give equal sampling
261 weight to different seasons. Table 1 tabulated the cirrus occurrence seasonality as
262 observed from both MPLNET and CALIPSO. For MPLNET data, we calculated cirrus
263 occurrence frequency as a percentage of MPLNET detected cirrus cases at each 10-
264 minute time window over the total number of MPLNET 10-minute time windows during

265 the one-hour period +/- 30 minutes around the averaged CALIPSO local overpass time
266 (around 13-14 local hour). The values for CALIPSO are thin cirrus occurrence frequency
267 observed from all CALIPSO tracks that overpass and are within the $1^{\circ} \times 1^{\circ}$ degree grid
268 centered at each site. The frequencies for all four seasons were calculated with the annual
269 mean shown in Figure 1. For each season and annual mean, the thin cirrus occurrence
270 frequency values at the closest grid to the site were used in Table 1.

271 Overall, the annual mean of cirrus frequency from MPLNET and CALIPSO are
272 comparable in their order of magnitudes: 14.10 vs. 18.56, 12.62 vs. 16.56, 8.13 vs. 16.12,
273 5.36 vs. 8.66 percent for GSFC, COVE, Trinidad_Head and NCU_Taiwan, respectively.

274 For all four sites, the MPLNET and CALIPSO agreed on the thin cirrus peak seasons:
275 GSFC, COVE and NCU for JJA, and Trinidad_Head for MAM. Three out of the four
276 sites agreed on the least cirrus occurrence frequency (COVE for SON, Trinidad_Head for
277 JJA, and NCU for DJF) except GSFC where MPLNET exhibited a low cirrus season for
278 MAM but for CALIPSO the low cirrus season was SON. Although they both agree on the
279 cirrus peaks seasons, the discrepancy is also significant: the CALIPSO detected cirrus
280 frequencies for the peak seasons were generally higher than those for the MPL: 20.30%
281 vs. 15.65%, 24.33% vs. 13.95%, 32.65% vs. 12.27%, and 17.66% vs. 9.59% for GSFC,
282 COVE, Trinidad_Head and NCU sites, respectively. There are two possible reasons for
283 such discrepancies: First, the CALIPSO's 'top-down' viewing geometry allows better
284 detection of high clouds before the lidar signal become attenuated; However, in the
285 MPL's 'bottom-up' viewing geometry, lidar signals could be attenuated by aerosol layers
286 and low clouds significantly before it reaches high clouds. Secondly, noontime
287 measurements are always difficult for ground lidar, because the noise levels are usually

288 much higher when the solar zenith angle is low which makes automated cirrus detection
289 more challenging. Moreover the MPL lidar noontime shut-down protective measure also
290 prevents continuous observations of thin cirrus around local noontime. This second factor
291 is expected to have a bigger impact on tropical sites during boreal summer time, such as
292 NCU_Taiwan with a 17.66% vs. 9.59% difference.

293

294 To gain more insight on the comparability between MPLNET and CALIPSO, we further
295 matched up 9 MPLNET-AERONET collocated sites (See Table 2). To ensure a one-to-
296 one match up of the data, we only chose those data pairs with the closest distance of
297 CALIPSO track to the site and the closest MPLNET data collection time (within ± 5
298 minutes) to the CALIPSO overpass. Because CALIPSO overpass tracks shift slightly
299 within a range of ~ 15 - 20 km between tracks during the 16-day repeat cycle at each site,
300 the distance between the sites and CALIPSO tracks also varies in range. Seen from Table
301 2, among the 9 sites, some sites (i.e. Gosan_SNU) have a distance range less than 10 km,
302 but other sites (i.e. GSFC) can have larger ranges up to 90 km. Despite all the challenges
303 and the limited sample size of collocated cases, close examination of all cirrus cases from
304 June 2006 to December 2010 indicated that, in terms of cirrus detection, for the 8 sites
305 (except Singapore) that have more than 20 matchups (\sim one year of day or night data
306 coverage considering 16-day CALIPSO data cycle), MPLNET and CALIPSO reached a
307 percentage agreement of 71-88% when both daytime and nighttime cases were counted.
308 The agreement results are not much different between daytime and nighttime. This not
309 only proves the general comparability of the MPLNET L1.0 SCF and the CALIPSO
310 VFM in terms of cirrus detection, but it also demonstrates the effectiveness of MPL L1.0

311 SCF for detecting cirrus without significant impacts from large noise during the daytime.
312 A very noteworthy point is that when MPLNET cirrus criteria were set much tighter, for
313 example, from “TW10 existence” to “TW30 strong persistence”, the number of cirrus
314 cases decreased significantly. Such sensitivity to cirrus detection criteria impacts the
315 AERONET-MPLNET match up significantly, which contributes to the discrepancy
316 between the results from the AERONET-MPLNET match up and the results from the
317 AERONET-CALIPSO match up, in addition to the already existing temporal and spatial
318 differences of matched up samples. This sensitivity will be further discussed in the
319 following sections.

320

321 **3.3. AERONET versus MPLNET**

322

323 ***3.3.1. AERONET-MPLNET Match up***

324 The AERONET Aerosol optical thickness (AOT) retrievals were paired up with the
325 MPLNET NRB-derived SCF and CPF to calculate susceptibility percentage (% SP), an
326 indicator of how many percentages of best quality assured L2.0 AOT retrievals are
327 potentially contaminated by cirrus. Results about SP will be discussed in Section 3.3.2.

328 The MPLNET SCF and CPF calculations and the four MPLNET cirrus detection criteria
329 settings were discussed in Section 2.2. Additional requirements for the one-to-one
330 AERONET-MPLNET match up are:

331 1) At each of the four MPL cirrus settings, AERONET has to have valid quality assured
332 L2.0 AOT retrievals at 440 nm within the central MPL SCF 10-minute time window, to
333 be counted as being potentially susceptible to cirrus contamination;

334 2) At each match up, the solar zenith angle (SZA) has to be less than 20° . This is because
335 the micro-pulse lidar is looking upright through the atmosphere for aerosol-cloud features
336 while sunphotometer is always looking at the sun for AOT retrievals. The less the solar
337 zenith angle, the atmospheric paths as observed by both instruments are better matched
338 up. They never exactly overlap however, because the micro-pulse lidar cannot look into
339 the sun.

340

341 To further elaborate on the AERONET-MPLNET match up, Figure 2 shows the MPL
342 NRB, SCF, and CPF in their respective (a)-(c) panels for the cirrus case over the COVE
343 site on June 7, 2007. The persistent cirrus layer around 11-12 km altitude was clearly
344 seen from the NRB profile (Figure 2a). After statistical analysis, both SCF and CPF
345 showed their consistent results with the NRB observations. SCF in Figure 2(b) shows the
346 corresponding NRB values when cirrus existence was identified at each 10-minute time
347 window. In comparison to Figure 2(a), Figure 2(b) shows that the SCF filtering process
348 removed most of ambient noise effectively, demonstrating that SCF is capable of
349 distinguishing cirrus layers from noise very effectively. CPF in Figure 2(c) on the other
350 hand described the continuity of the cirrus layers that had persistent strong lidar
351 scattering signals ($\text{NRB} > 0.35$). Therefore when low cloud attenuated the lidar signals
352 significantly, for example the case around 10:40AM, the CPF number decreased
353 correspondingly because of the weaker NRB strength. The corresponding AERONET
354 measurements, including AOT (440 nm), AOT (500 nm), Ångström exponent (440-675
355 nm) susceptible to cirrus contamination, and solar zenith angle, are also shown in Figure
356 2(d). It is noteworthy however that the aerosol measurements around 9AM local hour

357 were not counted as cirrus contaminated cases because SZA was 41° , which did not pass
358 the $SZA < 20^\circ$ test.

359

360 **3.3.2. Susceptibility Percentage (SP)**

361 Susceptibility percentage (SP) is defined as the percentage of aerosol retrievals that are
362 susceptible to cirrus contamination to the total numbers of quality aerosol retrievals.

363 Because match up criteria can be less strict or very strict, SP values change with different
364 settings of match up criteria. Table 3 summarizes the sensitivity of SP to cirrus existence
365 and persistence criteria settings, time window selections, and SZA, for all 13 sites with
366 their temporal coverage sorted in order. As seen in Table 1, changes in SP can be an
367 order of magnitude simply because of different cirrus selection criteria. For example, the
368 SP values at GSFC were 7.74%, 3.61%, 3.44% and 1.55% for ‘TW10 existence’, ‘TW30
369 existence’, ‘TW30 overall persistence’ and ‘TW30 strong persistence’ respectively. The
370 reasons are twofold: one is the actual spatial and temporal variability of cirrus clouds, the
371 other is the way that lidar looks upright for high cloud detection and gets attenuated along
372 the atmospheric path. Although cirrus usually occur at synoptic scales, low clouds,
373 aerosol and the atmosphere can significantly attenuate the MPL lidar signal, before it
374 reaches more than the 10 km height to detect cirrus. Therefore any occurrence of heavy
375 low or middle cloud or heavy aerosol could prevent continuous observation of cirrus.
376 Note that this impact gets particularly stronger around noontime when noise levels
377 usually increase significantly (See Figure 2(a)), which makes cirrus detection even more
378 challenging as it requires relatively stronger lidar signals in order to discriminate cirrus
379 from ambient noises. Moreover, the MPL lidar shutdown around high noon at low SZA

380 hours also prevented continuous observations of cirrus persistence, particularly for
381 tropical sites. Thus additional strong persistence testing (e.g., ‘TW20 strong persistence’)
382 resulted in much lower SP values than relatively weaker persistence testing (e.g., ‘TW10
383 existence’). SP values for the top 10 AERONET-MPLNET sites from the ‘TW30 overall
384 persistence’ testing are plotted on top of the CALIPSO thin cirrus occurrence frequency
385 map in Figure 3. With the ‘TW30 overall persistence’ testing and the SZA filtering
386 ($SZA < 20^\circ$), all 10 sites have SP values less than 5% and 4 of them (40%) are actually less
387 than 1% (Figure 3); but for the ‘TW10 existence’ testing, 6 out of 10 sites (60%) have SP
388 values within 4-10%, and the other 4 (40%) within 1-3%. Similarly in Table 3, when the
389 time window becomes larger, for example, changing cirrus detection from 15-minute
390 time window to 30-minute or 60-minute time windows, the requirements for cirrus strong
391 persistence also become higher, thus less cirrus cases were detected, and SP values
392 become lower correspondingly. For example, at GSFC, the SP values for TW15, TW30
393 and TW60 were 3.10%, 1.55% and 1.20% respectively.

394

395 Viewing geometry differences between the sunphotometer and micro-pulse lidar can
396 affect the SP assessment dramatically. For example for GSFC, the SP value increases
397 significantly from 1.55% to 3.29% when the SZA constraint changes from $SZA < 20^\circ$ to
398 all SZA applying the ‘TW30 strong persistence’ test (See Table 3). The ‘ $SZA < 20^\circ$ ’
399 control is conducted to account for the viewing geometry differences between
400 sunphotometers and lidar instruments. A ‘ $SZA < 20^\circ$ ’ criterion ensures a better matchup.
401 On the downside however, a ‘ $SZA < 20^\circ$ ’ screening significantly reduced the sample sizes.
402 For comparison, ‘all SZA’ match ups had many more cirrus cases detected than

403 ‘ $SZA < 20^\circ$ ’. For example, the number of cirrus cases for ‘TW60’ at GSFC (Table 2) was
404 found to be 730 versus 7.. However, it is worthwhile to emphasize that the AERONET-
405 MPLNET match ups that sample at higher SZA (i.e. $SZA > 20$) are less indicative of
406 cirrus contamination in the AERONET measurements because the two instruments were
407 more likely looking at different atmospheric paths when their viewing angles were widely
408 separated.

409

410 Seasonal variability was also found in the SP statistics. The derived SP values shown in
411 Figure 3 and tabulated in Table 3 features strong seasonal signals. Table 4 compares
412 cirrus statistics of SP values and samples for their seasonality over the 13 sites. For
413 example, cirrus cases occurred more frequently in boreal spring for Pimai and in boreal
414 summer for GSFC and COVE (also see Table 1). All the 10 cirrus cases in the ‘TW30
415 strong persistence’ testing over GSFC were from boreal summer. Both ‘TW10 existence’
416 and ‘TW30 overall persistence’ tests indicate similar seasonality of cirrus occurrence at
417 each site.

418

419 ***3.3.3. Cirrus Optical Depth Calculation for Selective Cases***

420 We further investigated each individual cirrus case identified in the AERONET-
421 MPLNET match up for more details. With given NRB and molecular backscatter
422 profiles, molecular optical depth can be calculated from molecular extinction profiles
423 based on NCEP vertical temperature and pressure profiles, thus theoretically cirrus
424 optical depth can also be calculated:

425 $P_1=C\times\beta_{m1}\times e^{[-2(\tau_{m1}+\tau_{c1})]}$ (1)

426 $P_2=C\times\beta_{m2}\times e^{[-2(\tau_{m2}+\tau_{c2})]}$ (2)

427 Where subscripts 1 and 2 denote cirrus base and top, respectively. P, β and τ are NRB,
 428 molecular backscatter and optical depth respectively, while m and c stand for molecular
 429 and cirrus. C is a coefficient that counts for lidar performance and lidar signal attenuation
 430 due to other aerosol or cloud layers beneath cirrus. All these parameters are retrieved at
 431 cirrus base and cirrus top heights. From (1) and (2), cirrus optical depth can be calculated
 432 as:

433 $\Delta\tau_c = \tau_{c2} - \tau_{c1}=0.5\times[\ln(P1/P2)-\ln(\beta_{m1}/\beta_{m2})]-(\tau_{m2}-\tau_{m1})$ (3)

434 The challenge however comes from the following two influential factors that prevent
 435 precise measuring of NRB values at high altitude in daytime: 1) Ground lidar signal
 436 becomes extremely weak when it reaches an altitude higher than 10 km where cirrus
 437 layers reside, particularly after being further attenuated by cirrus; 2) during daytime,
 438 particularly around local noon time when the AERONET-MPLNET match up requires
 439 the closeness of viewing geometries from both instruments ($SZA<20^\circ$), noise level also
 440 increases significantly (see Figure 2(a)). Therefore operational cirrus optical depth
 441 estimation based on the MPL dataset faces extreme difficulties. In this work, we selected
 442 a very limited numbers of quality cirrus cases for testing an empirical approach for
 443 calculating cirrus optical depth, in the scope of evaluating relative contribution of cirrus
 444 optical depth to total optical depth observed by the sunphotometer. We assessed all cases
 445 for lidar operational stability, lidar signal strengths before and after cirrus layers, and

446 persistence of cirrus layers. Results from two test cases over the GSFC site on June 7th
447 2007 are shown in Figure 4.
448
449 Figure 4(a) shows a very persistent cirrus layer lasting for more than 8 hours over GSFC
450 on June 7th 2007. To overcome the influence from noise, we used the data distribution
451 pattern from the concurrent molecular backscatter profile to proxy the NRB data
452 distributions beneath and above cirrus layers (Figure 4(b) and (c)). The assumption is that
453 in the clear portions of the atmosphere (i.e. above aerosol and low clouds but below
454 cirrus clouds), the data distribution pattern of the NRB profile is similar to the data
455 distribution pattern of the molecular backscatter profile. Such data similarity, indicating
456 molecular scattering profiles without cloud and noise interference, has been broadly
457 discussed in previous literatures (e.g. Sassen et al., 1989; Vaughan et al., 2005, 2009).
458 This assumption was further verified from MPLNET night scene observations when
459 noise levels were significantly low. For these two particular cases, the measured NRB
460 profile data from 4 km to 10 km and the collocated molecular backscatter profile data
461 were trained to find a best linear fit function between the two datasets. This best fit
462 function was then applied to the molecular backscatter data to approximately calculate
463 the NRB data right beneath and just after cirrus layers. Then, cirrus optical depth can be
464 calculated in equation (3) by using the approximated NRB values, the molecular
465 backscatter and molecular optical depth data as inputs. The molecular backscatter and
466 optical depth were calculated from a Rayleigh radiative model based on inputted NCEP
467 reanalysis temperature and pressure profiles. Results show roughly 30-50% relative
468 contributions from cirrus to the possibly ‘cirrus-contaminated’ AOT retrievals at 527 nm,

469 0.0926 vs. 0.270 for 16:12UTC case, and 0.123 vs. 0.253 for the 16:22UTC case.
470 However, despite the residual profile-fitting uncertainties, this level of cirrus optical
471 depth did not seem to decrease Ångström exponent significantly to a very low value,
472 while the Ångström exponents were still as high as 1.0 for both cases even under cirrus
473 contaminations.

474

475 **3.4. AERONET versus CALIPSO**

476

477 Another approach for assessing cirrus contamination in the AERONET AOT retrievals
478 is to pair them up with CALIPSO cirrus observations. The complication, however, comes
479 from the limited CALIPSO temporal coverage at each site because of the 16-day
480 repeating cycle and the distant between the CALIPSO overpass tracks and most
481 AERONET sites. To address these issues, we first sorted the distances between the
482 locations of 522 AERONET sites that have L2.0 AOT retrievals and the CALIPSO's 16-
483 day cycle of global overpass tracks during the first 16 days of 2010 (January 1-16, 2010).
484 Then we selected the top 56 sites whose distances to CALIPSO tracks are within 30 km.
485 At these 56 sites, we collocated CALIPSO cirrus flags with AERONET L2.0 AOT
486 retrievals. Because CALIPSO tracks fluctuate from one 16-day global track to another,
487 actual distances from these AERONET sites to the CALIPSO tracks were calculated for
488 each match up data pair. We further constrain the calculated (actual) distance to be less
489 than 10 km. Moreover, the one-to-one data match up was further constrained by limiting
490 the CALIPSO overpass time to be within +/-10 minutes of the AERONET data collection
491 time. To ensure sufficient statistical reliability, the total sample size of matched-up data

492 has to exceed 20 for each AERONET site, roughly corresponding to about one-year of
493 CALIPSO and AERONET paired data, considering CALIPSO's 16-day cycle. After
494 matching up the data, the resulting SP values for the 18 AERONET sites that passed time
495 and space filtering are presented in Figure 5, superimposed on an annual mean thin cirrus
496 occurrence frequency map. About half (8 out of 18) sites have SP values less than 10%,
497 which means there is a relative low level of susceptibility of AOT retrieval to thin cirrus
498 contamination (Figure 5(a)). This level of SP values is relatively comparable in the order
499 of magnitude to the AERONET-MPLNET 'TW10 Existence' testing (See Table 3).
500 However, some sites showed much larger SP values, for example, 33% for CARTEL,
501 23% for CEILAP-BA, and 21% for Xianghe that are outside of the cirrus prevailing
502 regions, and 25% for Ilorin which is within the tropical cirrus region. Because the
503 background cirrus occurrence frequencies (Figure 5) for those sites outside of the cirrus
504 prevailing regions are not high, more strict cloud screenings in the AERONET
505 observations at these sites are recommended. Statistics were also calculated for four
506 boreal seasons separately but sample sizes are rather limited. Similar to the AERONET-
507 MPLNET comparison, strong seasonal and regional variability were also found for the
508 distributions of SP values over these sites, which tend to be higher during the local thin
509 cirrus prevailing seasons. Statistics also indicate that sample size issues can affect SP
510 values significantly. For example, if we increase the sample size requirement to 40
511 (equivalent to about two years of CALIPSO and AERONET matched-up data) instead of
512 20, only 6 sites would have passed the threshold and all of them would have SP values
513 less than 15%, which is closer to the AERONET-MPLNET evaluation results from the
514 'TW10 existence' testing.

515 The SP values from the majority of sites in the AERONET-MPLNET and the
516 AERONET-CALIPSO match ups are comparable in the order of magnitude. For
517 example, 60% of the sites have SP values of 4-10% in the ‘TW10 existence’ testing
518 shown in Table 3, and about half the sites with less than 10% in Figure 5 (note that all
519 sites have SP values less than 15% if the sample size requirement is set to 40). However
520 the discrepancy between AERONET-MPLNET (Tables 3-4 and Figure 3) and
521 AERONET-CALIPSO (Figure 5) was also observed. Possible explanations are the
522 following: 1) The AERONET-MPLNET and AERONET-CALIPSO match ups are based
523 on different spatial-temporal domains. The former and latter are related more to
524 time/distance constraints, respectively; 2) MPL and CALIPSO observe cirrus occurrence
525 frequency differently, while the MPL usually has lower values than CALIPSO during
526 cirrus peak seasons, as explained in Section 3.2 (Table 1); and 3) The SP values are
527 highly sensitive to the selection of cirrus detection criteria (see Table 2-4). The tighter the
528 cirrus detection requirements are the less cirrus cases were identified.

529

530 **3.5 AERONET-MPLNET-CALIPSO 3-Way Matchup**

531 To extend investigations in susceptibility percentage discrepancies between AERONET-
532 MPLNET and AERONET-CALIPSO beyond the match ups of MPLNET-CALIPSO
533 ((Section 3.2), AERONET-MPLNET (Section 3.3), and AERONET-CALIPSO (Section
534 3.4), it is intriguing to see whether we can identify sufficient samples for a 3-way
535 AERONET-MPLNET-CALIPSO match up. Such data matching is only valid for daytime
536 because AERONET aerosol data are only measured during daytime. A two-step match up
537 procedure was adopted: 1) match up MPLNET-CALIPSO as described in Section 3.2,

538 and identify the MPLNET data collection times that are closest to the CALIPSO
539 overpass; 2) match up AERONET aerosol data around the MPLNET data collection time
540 identified in Step 1. Two different temporal limitations were tested for comparison: 1)
541 any AERONET aerosol AOT 440 nm measurements within 0.5 hour of MPLNET cirrus
542 cases matched up with CALIPSO overpass were considered ‘cirrus susceptible’; 2) any
543 AERONET aerosol measurements within 1 hour of MPLNET cirrus cases matched up
544 with CALIPSO overpass were considered ‘cirrus susceptible’. Unfortunately very few
545 ‘cirrus susceptible’ cases were found from the 3-way comparison for the 9 sites. For the
546 GSFC site, 27 AERONET-MPLNET-CALIPSO matchup cases were identified, where
547 both MPL and CALIPSO agreed on four cirrus cases. Of the four cases, one AERONET
548 matchup was identified as ‘cirrus susceptible’ using the ‘TW30 overall persistence’
549 testing for the 1-hour time allowance, and none were identified for the 0.5-hour time
550 allowance. It is noted that the numbers are not statistically significant due to the
551 insufficient sample sizes. However, the study successfully demonstrates the 3-way match
552 up approach, which will prove to be more valuable as longer CALIPSO datasets become
553 available and there are more MPLNET-AERONET collocated sites. Collective
554 information resulting from a 3-way data yields improved constraints for cirrus
555 susceptibility testing because it provides two independent verification channels for
556 concurrent cirrus detection.

557

558 **3.6. AERONET versus MODIS**

559

560 One of the important objectives of this study is to investigate the feasibility of using
561 satellite derived cloud screening parameters for cloud screening of AERONET aerosol
562 retrievals around the satellite overpass time. Therefore, it is essential to explore the
563 susceptibility of AERONET retrievals to cirrus contamination at AERONET sites during
564 the MODIS overpass times. . Because RR1.38/0.66 is indicative of thin cirrus
565 (Roskovensky and Liou, 2003; Huang et al., 2011), AERONET AOT and Fine Mode
566 Fraction (FMF) measurements were collocated with the MODIS-derived RR1.38/0.66
567 over select AERONET sites. The 15 AERONET sites were chosen according to their
568 L2.0 AOT data availability and their representativeness on a global map: 4 of them have
569 5+ year data records and the other 11 have 7+ year data records. Further spatial and
570 temporal constraints for the collocations are: 1) Spatially, considering the 1 km resolution
571 of MODIS L1B data, the closest RR1.38/0.66 value are retrieved within 1 km distance
572 from each AERONET site; 2) temporally, the closest AERONET data points are
573 collected within a ± 30 minute time window centered at the MODIS overpass time.

574

575 Figure 6 shows overall susceptibility levels of AERONET AOT and FMF data at the 15
576 sites. For both AOT and FMF, there are 13 (93%) sites having the SP value less than
577 10%, a comparable SP level to the previous comparisons in AERONET vs. CALIPSO,
578 indicating the effectiveness of current AERONET cloud screening schemes.

579

580 Because cirrus cloud particle sizes are larger than aerosols, potential cirrus contamination
581 can be reflected in the changes of the aerosol's particle size distribution; and this
582 phenomenon should become more significant over aerosol emission regions where fine

583 aerosol particles (such as smoke) usually prevail. In order to see the changes of AE and
584 FMF transitioning from cirrus-free to cirrus-contaminated cases, we selected three
585 representative AERONET sites having the longest L2.0 AOT data record over three
586 smoke predominant regions during their peak smoke seasons respectively: Alta_Floresta
587 in Amazon during SON, 2004-2009; Mukdahan in Southeast Asia during MAM, 2004-
588 2009; Mongu in Southern Africa during JJA, 2003-2010. The changes in the PDF of AE
589 and FMF in response to high RR1.38/0.66 at these three sites are shown in Figure 7.
590 Because there were no MPLNET data available at these sites, the collocated MODIS
591 reflectance ratio RR1.38/0.66 was used to distinguish cirrus-contaminated cases from
592 cirrus-free cases. A threshold value of $RR1.38/0.66 = 0.1$ was used for cirrus cloud
593 identification. Systematic PDF shifting in AE and FMF were observed for all three sites.
594 In comparison to cirrus-free cases, AE and FMF in cirrus-contaminated cases tend to
595 have smaller values, indicating more frequent presence of large particles as a result of
596 possible cirrus contamination. Kosmogorov-Smirnov tests, which are usually used for
597 testing the significance level of differences between two data distributions, indicate that
598 the data distributions of AE and FMF in cirrus-free and cirrus-contaminated cases, as
599 shown in Figures 7, are significantly different at a confidence level of 95%. These
600 evidences are consistent with the theoretical prediction that thin cirrus contamination in
601 the aerosol retrieval would lead to larger retrieved particle sizes, more evidence of
602 potential thin cirrus contamination in AERONET aerosol retrievals.
603
604 Such tests of collocating AERONET AOT (or FMF) with the MODIS RR1.38/0.66 cirrus
605 detection parameterization suggests feasible operational routines that can be used to

606 crosscheck aerosol and cirrus retrievals from AERONET and operational satellites.. This
607 becomes more important for satellite product calibration/validation field campaigns
608 where in-situ measurements are closely examined along with collocated satellite
609 observations in near real-time to verify the atmospheric environment and to validate
610 satellite retrievals.

611

612 **4. Summary and discussions**

613

614 Concurrent aerosol and cirrus observations from ground measurements and satellites
615 were used to evaluate the susceptibility of ground aerosol retrievals to thin cirrus
616 contamination. We first compared MPLNET and CALIPSO in terms of their cirrus
617 detection capabilities. Their agreement rate is about 71-88% for both day and night match
618 up cases. For the cirrus occurrence frequency, both agreed on the cirrus peak seasons at
619 four selective sites; however, MPLNET detected relatively lower cirrus frequency than
620 CALIPSO during the cirrus peak seasons.

621

622 To quantify the susceptibility of the AERONET aerosol products to cirrus contamination,
623 the following pairs of datasets were matched up: 1) AERONET versus MPLNET, 2)
624 AERONET versus CALIPSO, and 3) AERONET versus MODIS. In the AERONET-
625 MPLNET match up, challenges come from the different viewing geometries of the two
626 instruments and difficult cirrus observations at high altitude when the lower atmosphere
627 significantly attenuates lidar signals. For a ‘SZA<20° and TW30 overall cirrus
628 persistence’ testing, all susceptibility percentages at 10 collocated AERONET and

629 MPLNET sites are less than 5%, and 40% of the sites are less than 1%; for the ‘SZA<20°
630 and TW10 existence’ testing, 6 out of 10 sites (60%) have SP values within 4-10%, and
631 the other 4 (40%) within 1-3%. The SP values are sensitive to different cirrus detection
632 criteria, such as cirrus persistence test settings, time window selections, and solar zenith
633 angle constraints. An empirical approach for cirrus optical depth calculation based on
634 MPLNET NRB profiles was established and successfully implemented for selective cases
635 to roughly estimate the relative contribution of thin cirrus contamination to AOT
636 retrievals.

637

638 Despite various challenges in collocating AERONET with CALIPSO, such as
639 insufficient sampling and distance between CALIPSO daytime tracks and AERONET
640 sites, about half of the 18 AERONET-CALIPSO collocated sites also have a
641 susceptibility percentage less than 10%, a similar order of magnitude to the AERONET-
642 MPLNET match up of data. A promising 3-Way AERONET-MPLNET-CALIPSO match
643 up scheme was established during this study. As CALIPSO lifespan extends and the
644 number of the AERONET-MPLNET supersites increases, the 3-Way comparison will
645 become more valuable when sufficient matchup samples are available. AERONET
646 aerosol retrievals were also paired up with MODIS cirrus parameters, such as
647 RR1.38/0.66, to test the ground-satellite match up techniques in terms of using satellite
648 derived cirrus detection to evaluate cirrus contamination in ground aerosol retrievals. The
649 AERONET-MODIS showed 93% sites having the SP value less than 10%, a comparable
650 SP level to the AERONET-CALIPSO match up. For three smoke dominant regions
651 during their biomass burning seasons, cirrus-free cases and cirrus-contaminated cases

652 were discriminated from each other using the MODIS cirrus parameter, Smaller
653 AERONET Ångström exponents and Fine Mode Fractions were also found in their
654 probability data distributions for ‘cirrus-contaminated’ cases than in the ‘cirrus-free’
655 cases, another indication that thin cirrus potentially contaminates the AERONET aerosol
656 retrievals.

657

658 Statistical results from this study demonstrated the effectiveness of the current cloud
659 screening schemes in the AERONET retrieval although residual cirrus contaminated
660 cases may still exist. It is also noteworthy that the susceptibility evaluation is highly
661 dependent on both season and region. Moreover, influential factors, such as viewing
662 geometry differences between sunphotometers and micro-pulse lidars when AERONET
663 and MPLNET are compared, and the sample size threshold values when AERONET and
664 CALIPSO data are compared, can significantly impact the susceptibility percentage.

665 From a cirrus contamination perspective, this study improves our understanding of data
666 uncertainties of ground aerosol products. Similar evaluations on satellite aerosol
667 retrievals are underway. Further improvement of ground aerosol product quality is
668 valuable for calibration and validation of satellite aerosol retrievals, and also very
669 important for any consequential aerosol-related climate research.

670

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817 **Table and Figure List**

818 Table 1. A comparison between MPLNET and CALIPSO on the seasonality of daytime
819 thin cirrus occurrence frequency (%). The values for MPLNET are the percentage of
820 cirrus cases over the total MPLNET measurements during +/-30 minutes around the
821 CALIPSO daytime overpass time. The values for CALIPSO are thin cirrus occurrence
822 frequency observed from all CALIPSO track overpasses at each site within the 1x1
823 degree grid centered at each site. The highest and lowest seasons are highlighted for each
824 site.

825 Table 2. Statistics on the MPLNET-CALIPSO match up over the 9 AERONET-
826 MPLNET collocated sites during daytime (the left outlined data block) and nighttime (the
827 right outlined data block)

828 Table 3. Susceptibility percentage (SP, %) of AERONET Level 2.0 AOT retrievals to
829 thin cirrus contamination, and its sensitivity to cirrus existence and persistence criteria
830 settings, time window (TW) and solar zenith angle (SZA), in the left, middle and right
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832 Table 4. Seasonality of susceptibility percentage (SP, %) of AERONET Level 2.0 AOT
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834 persistence criteria settings. Two types of cirrus persistence criteria settings (TW10
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836 outlined data blocks respectively.

837 Figure 1. (a) Daytime thin cirrus occurrence frequency (%) and (b) Daytime thin cirrus
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839 (December 2006 – November 2007).

840 Figure 2. An example cirrus occurrence case over COVE AERONET and MPLNET site
841 on June 7, 2007: (a) MPL L1.0 normalized relative backscatter (NRB) higher than 0.35;
842 (b) MPL statistical cirrus flag (SCF); (c) MPL statistical cirrus persistence flag (CPF);
843 and (d) AERONET AOT and Ångström exponent measurements, and solar zenith angle
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846 Figure 3. Susceptibility percentage (SP, %) of AERONET L2.0 AOT retrievals to thin
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849 Figure 4. Cirrus optical depth estimation for cirrus cases over GSFC on June 7, 2007: (a)
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851 highlighted by vertical lines; (b) cirrus optical depth calculation results for the case of
852 16:12UTC; and (c) cirrus optical depth calculation results for the case of 16:22UTC.

853 Figure 5. Susceptibility percentage (SP, %) tests of AERONET L2.0 AOT retrievals
854 against the CALIPSO vertical feature mask. Refer to Section 3.4 for more details of the
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856 Figure 6. Susceptibility percentage map of AERONET aerosol retrievals against MODIS
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858 with 5+ years of L2.0 AOT data record; and all the remaining sites were selected with 7+
859 years of L2.0 AOT data records available. SP values (%) in red are for AOT and yellow
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861 Figure 7. PDF of AE and FMF for cirrus and non-cirrus cases over three representative
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863 right: Alta_Floresta in Amazon during SON, 2004-2009; Mukdahan in Southeast Asia
864 during MAM, 2004-2009; Mongu in Southern Africa during JJA, 2003-2010). Top panels
865 (a-c) are for AE and bottom panels (d-f) are for FMF. RR1.38/0.66>0.1 was used for thin
866 cirrus case identification.

867

868 **Tables**

869 Table 1. A comparison between MPLNET and CALIPSO on the seasonality of daytime
 870 thin cirrus occurrence frequency (%). The values for MPLNET are the percentage of
 871 cirrus cases over the total MPLNET measurements during +/-30 minutes around the
 872 CALIPSO daytime overpass time. The values for CALIPSO are thin cirrus occurrence
 873 frequency observed from all CALIPSO track overpasses at each site within the 1x1
 874 degree grid centered at each site. The highest and lowest seasons are highlighted for each
 875 site.
 876

Site	UTC	MPLNET (%)					CALIPSO (%)				
		MAM	JJA	SON	DJF	4-Season	MAM	JJA	SON	DJF	4-Season
GSFC	18.0-19.0	11.37	15.65	15.24	14.14	14.10	17.88	20.30	12.40	13.02	18.56
COVE	17.9-18.9	11.94	13.95	10.35	13.24	12.62	15.21	24.33	11.90	15.24	16.56
Trinidad_Head	20.7-21.7	12.27	3.38	7.27	11.34	8.13	32.65	9.09	10.51	17.08	16.12
NCU_Taiwan	5.0-6.0	5.33	9.59	5.31	0.76	5.36	9.38	17.66	5.27	3.48	8.66

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880 Table 2. Statistics on the MPLNET-CALIPSO match up over the 9 AERONET-
881 MPLNET collocated sites during daytime (the left outlined data block) and nighttime (the
882 right outlined data block)

Site	Cases	Day	MPL	VFM	Both	Agreement % (Day)	Night	MPL	VFM	Both	Agreement % (Night)	Agreement % (Day&Night)
GSFC	Cirrus	90km	5 (1)	5	4 (1)		40km	10 (3)	14	5 (3)		81.82%
	Non-Cirrus		22	22	21			51	47	42		
	Total Cases		27	27	25	92.59%		61	61	47	77.05%	
COVE	Cirrus	50km	24 (0)	13	8 (0)		20km	15 (3)	23	9 (3)		70.92%
	Non-Cirrus		48	59	43			54	46	40		
	Total Cases		72	72	51	70.83%		69	69	49	71.01%	
NCU	Cirrus	30km	2 (0)	7	1 (0)		70km	5 (1)	7	2 (1)		87.60%
	Non-Cirrus		60	55	54			54	52	49		
	Total Cases		62	62	55	88.71%		59	59	51	86.44%	
Trinidad_head	Cirrus	30km	2 (0)	2	1 (0)		40km	8 (3)	7	4 (2)		83.63%
	Non-Cirrus		20	20	19			25	26	22		
	Total Cases		22	22	20	90.91%		33	33	26	78.79%	
Gosan_SNU	Cirrus	10km	5 (0)	9	2 (0)		No samples.					79.17%
	Non-Cirrus		43	39	36							
	Total Cases		48	48	38	79.17%						
Monterey	Cirrus	30km	4 (0)	7	1 (0)		20km	4 (2)	8	4 (2)		84.14%
	Non-Cirrus		36	33	30			38	34	34		
	Total Cases		40	40	31	77.50%		42	42	38	90.48%	
Barbados	Cirrus	80km	0 (0)	0	0 (0)		50km	12 (3)	21	10 (3)		72.92%
	Non-Cirrus		1	1	1			35	26	24		
	Total Cases		1	1	1	100%		47	47	34	72.34%	
Singapore	Cirrus	80km	2 (0)	4	1 (0)		No samples.					66.67%
	Non-Cirrus		10	8	7							
	Total Cases		12	12	8	66.67%						
Kanpur	Cirrus	35km	4 (2)	3	1 (1)		70km	2 (0)	3	2 (0)		81.25%
	Non-Cirrus		21	22	19			5	4	4		
	Total Cases		25	25	20	80%		7	7	6	85.71%	

883 Notes: In the 'MPL' column, the numbers outside brackets are from the 'TW10 existence' tests, and the numbers inside
884 brackets are from the 'TW30 strong persistence' tests. Similarly, in the 'Both' row, the numbers are the corresponding MPL
885 cases that agreed with the CALIPSO VFM cirrus testing. In the last column, 'agreement %' is the percentage of MPL and
886 CALIPSO agreed cases over the total matchup cases. The distance (km) in the 'Day' and 'Night' columns are allowance
887 thresholds of the distance between the site and the CALIPSO overpass tracks.

888 Table 3. Susceptibility percentage (SP, %) of AERONET Level 2.0 AOT retrievals to thin cirrus contamination, and its sensitivity to
 889 cirrus existence and persistence criteria settings, time window (TW) and solar zenith angle (SZ), in the left, middle and right thick
 890 line outlined data blocks respectively. Samples are from all seasons.

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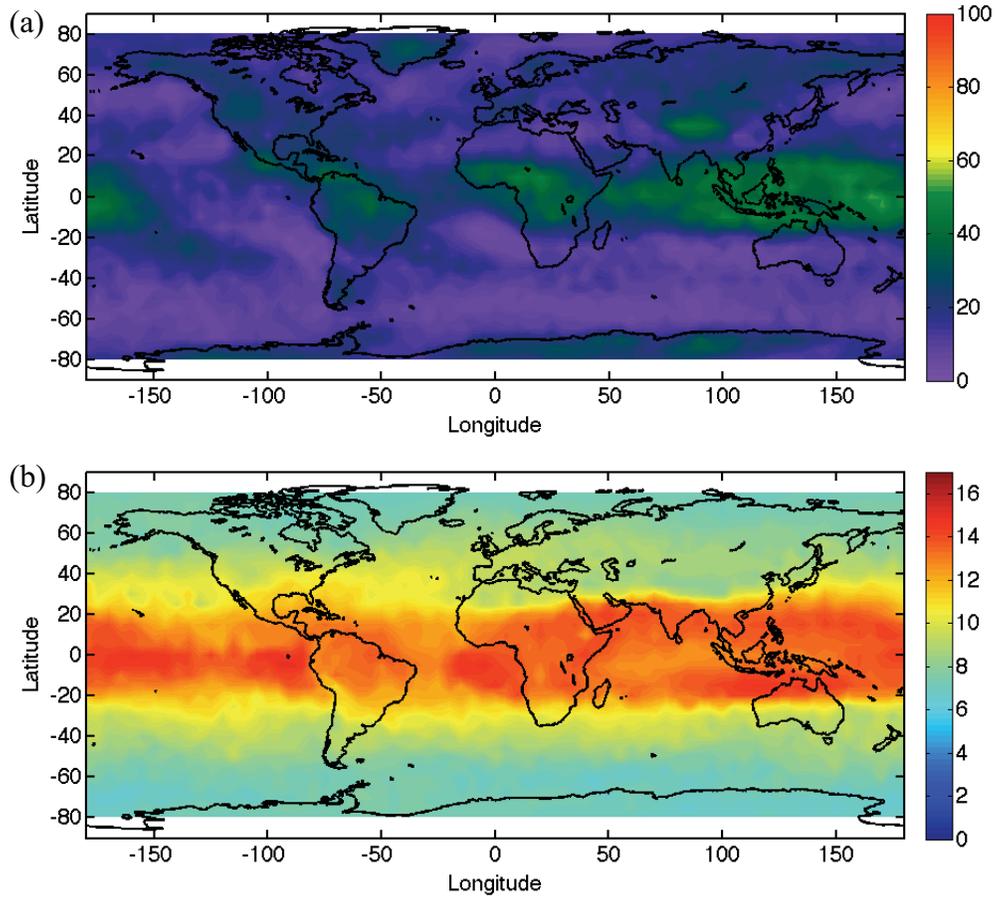
Site Name	MPLNET Coverage	Sensitivity of SP (%) to cirrus existence and persistence criteria settings (Sample Size N: cirrus/total)				Sensitivity of SP (%) to time window (Sample Size N: cirrus/total)			Sensitivity of SP (%) to SZ (Sample Size N: cirrus/total)	
		SZA<20° TW10 Existence	SZA<20° TW30 Existence	SZA<20° TW30 Overall persistence	SZA<20° TW30 Strong persistence	SZA<20° TW15 Strong persistence	SZA<20° TW30 Strong persistence	SZA<20° TW60 Strong persistence	SZA<20° TW30 Strong persistence	All SZA TW30 Strong persistence
GSFC	2001.11-2010.06	7.74 (45/581)	3.61 (21/581)	3.44 (20/581)	1.55 (9/581)	3.10 (18/581)	1.55 (9/581)	1.20 (7/581)	1.55 (9/581)	3.29 (1265/38437)
COVE	2004.05-2010.09	4.44 (11/248)	2.82 (7/248)	2.42 (7/248)	2.82 (7/248)	4.03 (10/248)	2.82 (7/248)	2.82 (7/248)	2.82 (7/248)	2.21 (186/8409)
Trinidad_Head	2005.05-2010.09	1.14 (2/175)	0 (0/175)	0 (0/175)	0 (0/175)	0 (0/175)	0 (0/175)	0 (0/175)	0 (0/175)	2.10 (223/10612)
NCU_Taiwan	2005.01-2009.10	4.00 (6/150)	0.67 (1/150)	0.67 (1/150)	0.67 (1/150)	1.33 (2/150)	0.67 (1/150)	0.67 (1/150)	0.67 (1/150)	4.10 (139/3394)
Gosan_SNU	2007.04-2010.02	4.76 (5/105)	0.95 (1/105)	0.95 (1/105)	0.95 (1/105)	1.90 (2/105)	0.95 (1/105)	0 (0/105)	0.95 (1/105)	0.68 (11/1620)
Monterey	2003.04-2003.10 2004.01-2004.04 2007.03-2009.04	2.44 (19/780)	1.41 (11/780)	1.41 (11/780)	0.26 (2/780)	1.41 (11/780)	0.26 (2/780)	0 (0/780)	0.26 (2/780)	2.80 (537/19152)
Ragged_Point	2008.06-2011.09	1.95 (16/819)	0.49 (4/819)	0.49 (4/819)	0.49 (4/819)	0.98 (8/819)	0.49 (4/819)	0.24 (2/819)	0.49 (4/819)	4.17 (344/8242)
Singapore	2009.09-2011.09	6.35 (24/378)	2.65 (10/378)	2.65 (10/378)	0.79 (3/378)	2.91 (11/378)	0.79 (3/378)	0 (0/378)	0.79 (3/378)	4.85 (239/4923)
Kanpur	2009.05-2010.09	2.36 (9/381)	1.31 (5/381)	1.31 (5/381)	1.31 (5/381)	1.60 (6/375)	1.31 (5/381)	1.60 (6/375)	1.31 (5/381)	2.74 (127/4634)
Pimai	2006.02-2006.05	8.33 (14/168)	3.57 (6/168)	3.57 (6/168)	2.38 (4/168)	5.52 (9/163)	2.38 (4/168)	0 (0/163)	2.38 (4/168)	8.65 (148/1711)
Skukuza	1999.08-1999.09 2000.08-2000.09	--	--	--	--	--	--	--	--	0.26 (3/1176)
Mongu	2000.08-2000.09	0 (0/16)	0 (0/16)	0 (0/16)	0 (0/16)	0 (0/16)	0 (0/16)	0 (0/16)	0 (0/16)	0.72 (7/978)
XiangHe	2005.02-2005.05	--	--	--	--	--	--	--	--	1.74 (21/1207)

892 (Note: the numbers inside brackets are the sample size of 'cirrus cases' over the total sample size of 'cirrus and non-cirrus cases', as the calculations of SP
 893 values. The SP values with the 'TW30 overall persistence' tests were plotted in Figure 3).

894 Table 4. Seasonality of susceptibility percentage (SP, %) of AERONET Level 2.0 AOT
 895 retrievals to thin cirrus contamination, and its sensitivity to cirrus existence and
 896 persistence criteria settings. Two types of cirrus persistence criteria settings (TW10
 897 existence and TW30 overall persistence) are shown in the left and right thick line
 898 outlined data blocks respectively.

Site Name	MAM SP%	JJA SP%	SON SP%	DJF SP%	All Seasons, SP (%)	MAM SP%	JJA SP%	SON SP%	DJF SP%	All Seasons, SP (%)
	SZA<20° TW10 Existence	SZA<20° TW10 Existence	SZA<20° TW10 Existence	SZA<20° TW10 Existence	SZA<20° TW10 Existence	SZA<20° TW30 Overall Persistence	SZA<20° TW30 Overall Persistence	SZA<20° TW30 Overall Persistence	SZA<20° TW30 Overall Persistence	SZA<20° TW30 Overall Persistence
GSFC	7.09 (9/127)	7.93 (36/454)	--	--	7.74 (45/581)	0.79 (1/127)	4.19 (19/454)	--	--	3.44 (20/581)
COVE	2.54 (3/118)	6.15 (8/130)	--	--	4.44 (11/248)	0.85 (1/117)	4.10 (5/122)	--	--	2.42 (7/248)
Trinidad_Head	0 (0/2)	1.16 (2/173)	--	--	1.14 (2/175)	0 (0/2)	0 (0/173)	--	--	0 (0/175)
NCU_Taiwan	11.1 (4/36)	2.04 (2/98)	(0/16)		4.00 (6/150)	2.78 (1/36)	0 (0/98)	0 (0/16)	--	0.67 (1/150)
Gosan_SNU	0 (0/59)	10.87 (5/46)	--	--	4.76 (5/105)	0 (0/59)	2.17 (1/46)	--	--	0.95 (1/105)
Monterey	5.88 (11/187)	1.35 (8/593)			2.44 (19/780)	4.28 (8/187)	0.51 (3/593)	--	--	1.41 (11/780)
Ragged_Point	1.32 (4/303)	1.11 (4/360)	5.13 (8/156)	--	1.95 (16/819)	0.33 (1/303)	0.28 (1/360)	1.28 (2/156)	--	0.49 (4/819)
Singapore	5.56 (3/54)	9.33 (7/75)	6.81 (13/191)	1.72 (1/58)	6.35 (24/378)	1.85 (1/54)	2.67 (2/75)	3.66 (7/191)	0 (0/58)	2.65 (10/378)
Kanpur	1.43 (2/140)	2.90 (7/241)	--	--	2.36 (9/381)	0.71 (1/140)	1.66 (4/241)	--	--	1.31 (5/381)
Pimai	8.33 (14/168)	--	--	--	8.33 (14/168)	3.57 (6/168)	--	--	--	3.57 (6/168)
Skukuza	--	--	--	--	--	--	--	--	--	--
Mongu	--	--	0 (0/16)	--	0 (0/16)	--	--	0 (0/16)	--	0 (0/16)
XiangHe	--	--	--	--	--	--	--	--	--	--

899 **Figure**



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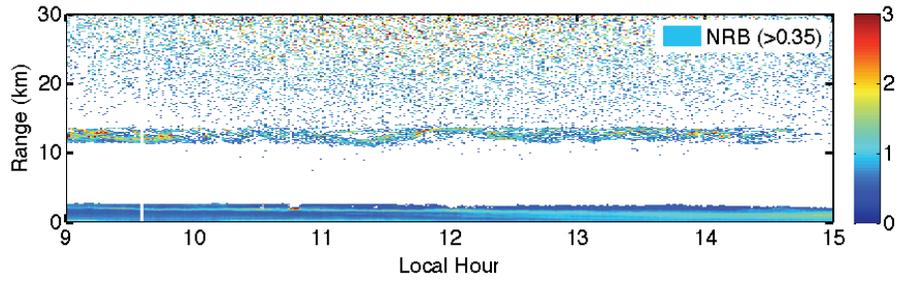
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904 (December 2006 – November 2007).

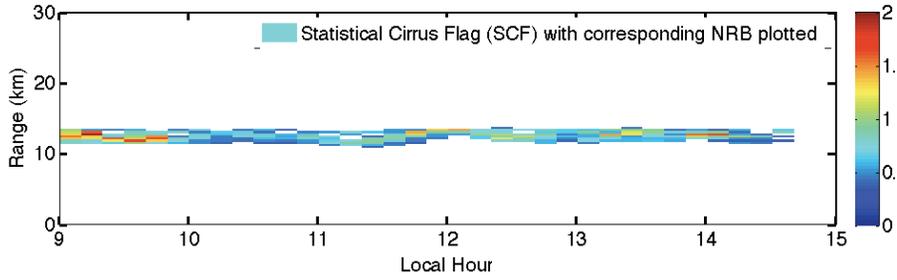
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906 (a)



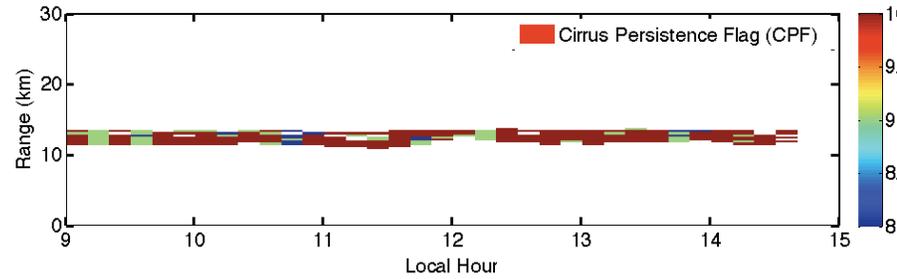
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(b)



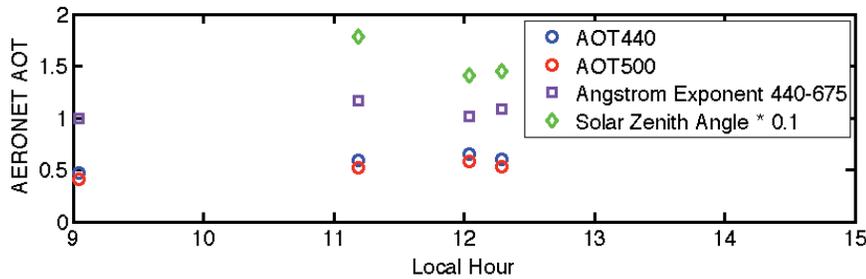
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914 Figure 2. An example cirrus occurrence case over COVE AERONET and MPLNET site

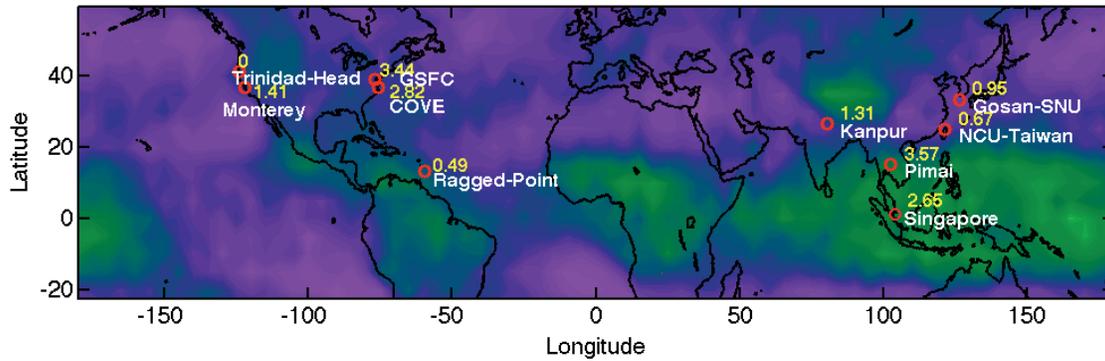
915 on June 7, 2007: (a) MPL L1.0 normalized relative backscatter (NRB) higher than 0.35;

916 (b) MPL statistical cirrus flag (SCF); (c) MPL statistical cirrus persistence flag (CPF);

917 and (d) AERONET AOT and Ångström exponent measurements, and solar zenith angle

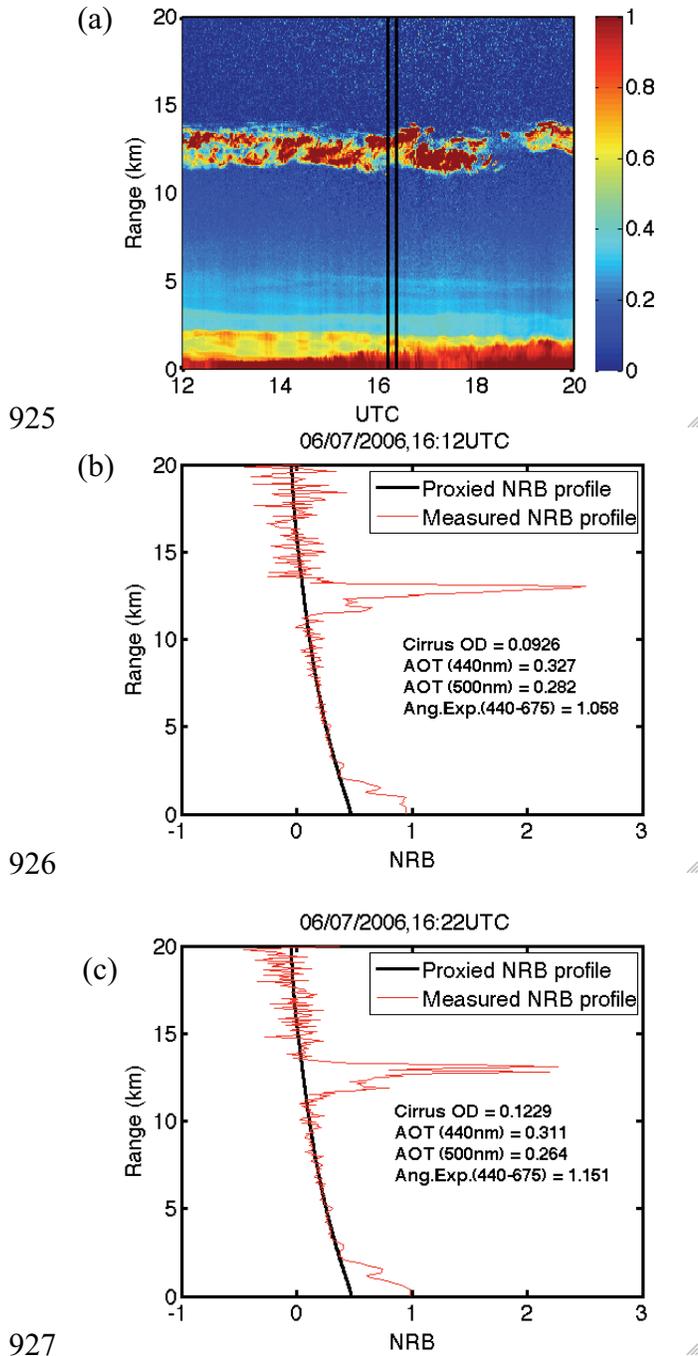
918 (SZA) (note the SZA for the data measurement around 9am was 41°, which did not pass

919 the SZA < 20° test and is therefore off the chart).

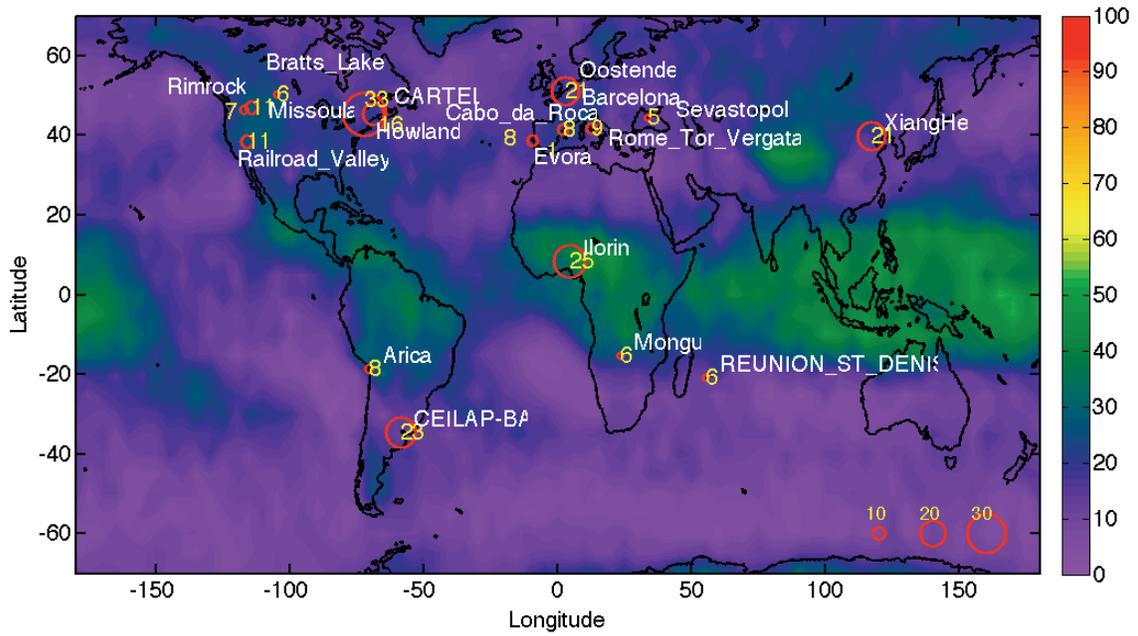


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Figure 3. Susceptibility percentage (SP, %) of AERONET L2.0 AOT retrievals to thin cirrus contamination as tested against the MPLNET statistical cirrus flag. Refer to Sections 2.2 and 3.3.1 for more details of match up criteria.

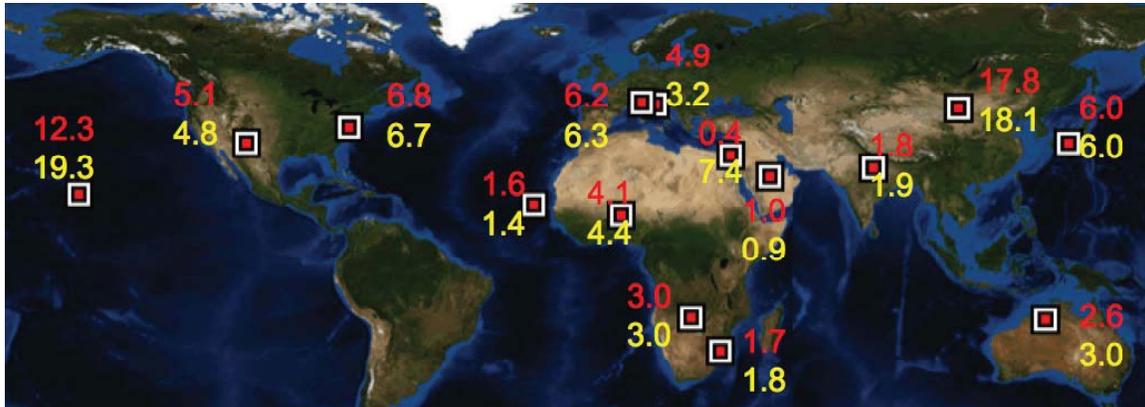


928 Figure 4. Cirrus optical depth estimation for cirrus cases over GSFC on June 7, 2007: (a)
 929 NRB profile from 12 to 20 UTC (local 7am to 5pm). The two matchup cases are
 930 highlighted by vertical lines; (b) cirrus optical depth calculation results for the case of
 931 16:12UTC; and (c) cirrus optical depth calculation results for the case of 16:22UTC.
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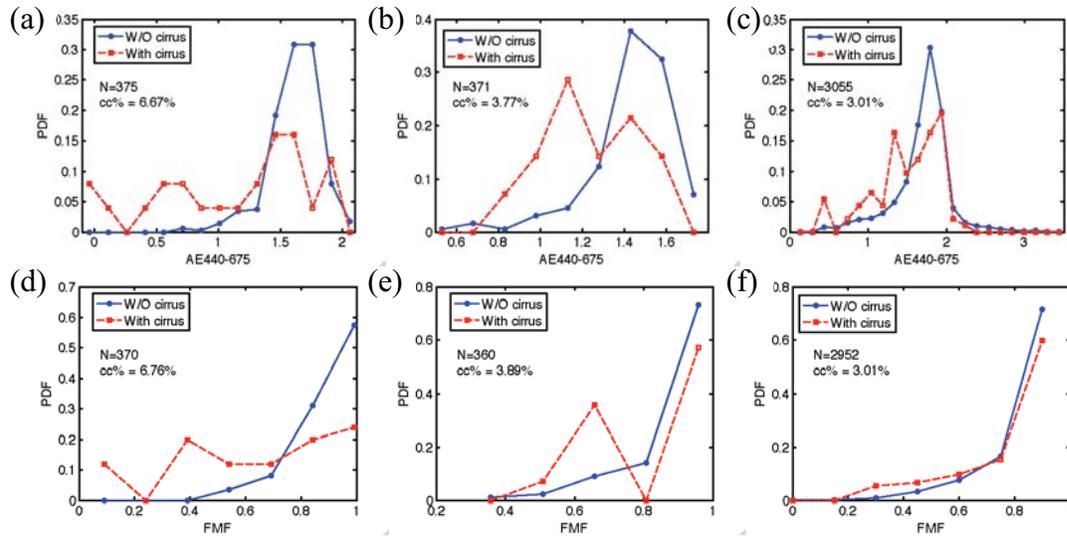
Figure 5. Susceptibility percentage (SP, %) of AERONET L2.0 AOT retrievals as tested against the CALIPSO vertical feature mask. Refer to Section 3.4 for more details of the one-to-one match up criteria.



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940 Figure 6. Susceptibility percentage map of AERONET aerosol retrievals against MODIS
 941 derived RR1.38/0.66 over 15 AERONET sites. The four eastern most sites were selected
 942 with 5+ years of L2.0 AOT data record; and all the remaining sites were selected with 7+
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951 during MAM, 2004-2009; Mongu in Southern Africa during JJA, 2003-2010). Top panels
952 (a-c) are for AE and bottom panels (d-f) are for FMF. $RR_{1.38/0.66} > 0.1$ was used for thin
953 cirrus case identification.
954

955 **Acronyms/Abbreviation LIST**

Acronyms/Abbreviation	Full Name
AE	Ångström exponent
AERONET	Aerosol Robotic Network
AOT	Aerosol Optical Thickness
BASE-ASIA	Biomass-burning Aerosols in South East-Asia: Smoke Impact Assessment field campaign
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CPF	Cirrus Persistence Flag
DJF	December-January-February
FMF	Fine Mode Fraction
JJA	June-July-August
MAM	March-April-May
MODIS	Moderate Resolution Imaging Spectroradiometer
MPL	Micro-Pulse Lidar
MPLNET	Micro-Pulse Lidar Network
NCEP	National Centers for Environmental Prediction
NRB	Normalized Relative Backscatter
RR	Reflectance Ratio
SCF	Statistical Cirrus Flag
SON	September-October-November
SP	Susceptibility Percentage
SZA	Solar Zenith Angle
TW	Time Window
VFM	Vertical Feature Mask

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