

1 **Analysis of improvements in MOPITT observational coverage over Canada**
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10
11 **Abstract**
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13 The Measurements of Pollution in the Troposphere (MOPITT) satellite instrument has been
14 measuring global tropospheric carbon monoxide (CO) since March 2000, providing the longest
15 nearly continuous record of CO from space. During its long mission, the data processing algo-
16 rithms have been updated to improve the quality of CO retrievals and the sensitivity to the lower
17 troposphere. Currently, MOPITT retrievals are only performed for clear-sky observations or over
18 low clouds for ocean scenes. The cloud detection scheme was modified in the new V9 product,
19 resulting in an improvement in observational coverage, especially over land. Comparison of the
20 spatial and seasonal variations of the data coverage in V9 and V8 shows differences with
21 significant geographical and temporal variability, with some regions such as Canada and the Am-
22 azon exhibiting a doubling of data in winter. Here we conducted an analysis of Moderate Resolu-
23 tion Imaging Spectroradiometer (MODIS) cloud heights and cloud mask products along with
24 MOPITT retrieval cloud flag descriptors to understand the impact of cloud conditions on the
25 MOPITT observational coverage, with a particular focus on observations over Canada. The
26 MOPITT CO total column (TC) data were modified by turning off the cloud detection scheme to
27 allow a CO retrieval result regardless of their cloud status. Analyses of the standard V8 CO TC
28 product (cloud filtered) and non-standard product (non-cloud masked) were conducted for selected
29 days. Results showed some coherent structures that were observed frequently in the non-masked
30 CO product that was not present in the V8 product and could potentially be actual CO features.
31 Many times, these CO plumes were also seen in the Infrared Atmospheric Sounding Interferometer

32 (IASI) CO TC product. The MODIS cloud height analysis revealed that a significant number of
33 low cloud CO retrievals were discarded in the V8 product. Most of the missed CO plumes in the
34 V8 product are now detected in the new V9 product as a result of the dependence of MOPITT
35 radiance ratio (MRT) test over land. Comparisons of the MRT and MODIS cloud height data in-
36 dicate a remarkable negative correlation. As a result of modified V9 cloud detection algorithm, a
37 significant portion of the low cloud CO retrievals is now incorporated in the new V9 MOPITT
38 product. Consequently, the observational coverage over Canada is significantly improved, which
39 benefits analyses of regional CO variability, especially during extreme pollution events. We also
40 conducted a comparison of MOPITT and IASI CO TC and found generally good agreement, with
41 about a 5-10% positive bias that is more pronounced in highly polluted scenes.

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43

44 **1. Introduction**

45 Carbon monoxide (CO) in the atmosphere has a medium lifetime (weeks to months), which is
46 long enough to track atmospheric physical and chemical processes over a range of spatial scales
47 from space (Jiang et al., 2011, Edwards et al., 2006; Duncan et al., 2007). Hence, satellite meas-
48 urements of atmospheric CO are useful for studying both transported and local sources of pollution
49 as well as atmospheric chemistry.

50 The Measurements of Pollution in the Troposphere (MOPITT) satellite instrument provides
51 the longest dataset of CO from space. It has been measuring tropospheric CO using gas filter cor-
52 relation radiometry (GFCR) since March 2000 (Drummond et al., 1996, Drummond et al., 2010,
53 Deeter et al., 2017), with a footprint of $22 \text{ km} \times 22 \text{ km}$ and global coverage every 3 days (Deeter
54 et al., 2003). It is on board the Terra satellite, which is in a sun-synchronous polar orbit at 705 km
55 of altitude and crosses the equator at 10:30 local time (Drummond et al., 1996). Furthermore, it is
56 the only satellite instrument that measures CO in both the thermal infrared (TIR, $4.7 \mu\text{m}$) and near
57 infrared (NIR, $2.3 \mu\text{m}$). This long-term data record provides a unique opportunity for analyzing
58 interannual variability and long-term trends in the distribution of CO, atmospheric transport, and
59 tropospheric chemistry that are associated with human activity and climate change (Worden et al.,
60 2013; Strode et al., 2013, Buchholz et al., 2021).

61 During MOPITT's long mission, data processing algorithms have been updated considerably
62 to improve the quality of the CO retrievals and their sensitivity to the lower troposphere. However,

63 MOPITT cannot “see” through cloud and this represents a significant obstruction to measurement
64 spatial coverage. The current cloud detection algorithm, using both MOPITT and Moderate Reso-
65 lution Imaging Spectroradiometer (MODIS) information (Warner, et al., 2001), rejects pixels with
66 a significantly amount of cloud cover, thereby reducing the number of pixels retrieved. This leads
67 to global maps with gaps in CO data where clouds are present.

68 Retrieving CO gas in cloudy conditions represents a major challenge. The presence of clouds
69 in the observed scene enhances reflectivity and blocks the atmosphere below the clouds for cloudy
70 scenes compared to cloud-free sky scenes. The albedo and in-cloud absorption effects enhance the
71 sensitivity to trace gases above the clouds, while the shielding effect impacts the vertical sensitivity
72 of the measurement which results in an inaccurate estimation of the trace gas column. Various
73 techniques have been proposed to cope with this problem depending on the spectral range of the
74 measurements. These techniques can be grouped into the following four approaches.

75 The first approach is the threshold method, where only observations under clear sky conditions
76 or weakly cloud contaminated scenes (determined by using threshold-based algorithms to detect
77 clouds and develop cloud masks) are considered (Ackerman et al., 1998; Deeter, 2003; Warner, et
78 al., 2001). The second approach, referred to as cloud clearing, is to reconstruct clear column radi-
79 ances that would have been present if there were no clouds. Cloud clearing is used for Atmospheric
80 Infrared Sounder (AIRS) atmospheric CO retrievals where a reconstructed pixel consisting of a 3
81 x 3 array (9 pixels are used) is produced, resulting in 45 km spatial resolution (Susskind et al.,
82 2003; Li et al., 2005). Both of these approaches avoid the need for complex modeling of cloud
83 effects, but have the added complexity of characterizing errors resulting from un-modeled cloud
84 fields. The third approach is to solve for the radiative effects of clouds directly in the inversion
85 process. This approach is used for retrieving profiles (Kulawik et al. 2006) from measurements
86 from the Tropospheric Emission Spectrometer (TES). The fourth approach is utilized for CO re-
87 trievals over land and ocean in the presence of low-altitude clouds from measurements from the
88 TROPOspheric Monitoring Instrument (TROPOMI). In this approach, shortwave infrared (SWIR)
89 measurements of methane TC are used to filter out observations with high and optically thick
90 clouds to retrieve the trace gas information (Vidot et al. 2012, Landgraf et al., 2016).

91 For MOPITT, due to the lack of spectral information and collocated methane data, only the
92 first two approaches are possible and, unfortunately, the results of the reconstructed clear column
93 radiances using two adjacent pixels are not sufficiently precise for viable retrievals. Consequently,

94 adjustments to the current MOPITT cloud detection scheme is the only one of the four approaches
95 that can be employed.

96 Deeter et al., (2021) recently made significant changes to the cloud detection scheme resulting
97 in a new MOPITT product V9. Those changes impacted the MOPITT coverage rate, especially
98 over land. Hence, the aim of this study is to conduct an analysis of MODIS cloud heights and cloud
99 mask products along with MOPITT retrieval cloud flag descriptors to understand the impact of
100 cloud conditions on the MOPITT observational coverage, with a particular focus on observations
101 over Canada.

102

103 **2. Data and Methodology**

104 This study uses data from three satellite instruments, MOPITT, IASI, and MODIS. MODIS,
105 and MOPITT are all onboard the Terra satellite (with an equatorial crossing time of 10:30 am local
106 time (LT)), which facilitates the collocation of observations in space and time. IASI on MetOp-A
107 has an equatorial crossing time of 9:30 am LT.

108 **2.1 MOPITT**

109 The MOPITT instrument is onboard the NASA Terra, which is a Sun-synchronous polar-
110 orbiting satellite. It has a spatial resolution of 22×22 km with a swath width of 640 km which
111 covers the globe every 3–4 days. MOPITT Version 8 and Version 9 (V8 and V9) Level 1 (L1)
112 and Level 2 (L2) TIR products are used in this study. L1 data corresponds to all of the radiance
113 observations that are obtained in MOPITT swaths. They are used subsequently as input to the
114 algorithms that retrieve the CO vertical profiles and total column (TC) amounts, which are referred
115 to as L2 data. The MOPITT L2 products that are utilized here are the CO total column (TC) abun-
116 dances and two cloud diagnostics contained in the MOPITT L2 files: the MOPITT cloud descrip-
117 tion index and the MODIS cloud diagnostics vector.

118

119 **2.2 MODIS**

120 The MODIS products used in this study are the Collection-6 1-km cloud mask (MOD35)
121 and the cloud height 5-km resolution (MOD06) data. MODIS measures radiances at 36 wave-
122 lengths, including infrared and visible bands with spatial resolution from 250 m to 1 km. The
123 MODIS cloud mask algorithm uses up to 19 MODIS spectral bands for better cloud detection

124 (Ackerman et al., 2008, 1998). The MODIS cloud height is derived using 5 thermal infrared bands
125 (both day and night) at 5 km spatial resolution.

126

127 **2.3 IASI-A**

128 IASI-A is a Fourier Transform Spectrometer on the European space agency (EPS)/MetOp-A
129 satellite launched in 2006 with a spectral coverage range from 3.62 to 15.5 μm (645 to 2760 cm^{-1})
130 including the CO 2140 cm^{-1} TIR band. It views the ground through a cross-track rotary scan mirror
131 with a horizontal resolution of 12 km diameter at nadir, which increases at the larger viewing
132 angles. The width of the swath is ~ 2200 km with a total of 120 views. The IASI instrument takes
133 measurements day and night which gives a global coverage twice a day with some gaps between
134 orbits around the equator. However, clouds in the field of view can obstruct the measurements and
135 hence reduce the number of the observations (Clerbaux et al., 2009). This study used L2 IASI-A
136 CO TC values that were retrieved by LATMOS (Laboratoire Atmosphères, Milieux, Observations
137 Spatiales) using a retrieval code, FORLI (Fast Optimal Retrievals on Layers for IASI), developed
138 at ULB (Université Libre de Bruxelles) (<https://iasi.aeris-data.fr/co/>). Data are retrieved for a
139 cloud fraction of less than 25 % (Clerbaux et al., 2009).

140 **3. MOPITT cloud detection scheme**

141 The MOPITT retrieval algorithm only performs retrievals in clear-sky conditions. The
142 MOPITT procedures for identifying clear-sky retrievals from cloud-contaminated pixels involves
143 a threshold method that makes use of two independent tests, (1) a MOPITT radiance ratio threshold
144 and (2) a MODIS cloud mask threshold within the MOPITT field of view (Warner et al., 2001,
145 Deeter, 2011), which are described below.

146

147 **MOPITT radiance threshold**. Radiance from the MOPITT 4.7 μm thermal channel radiance is
148 compared to the a priori clear-sky radiance calculated by The MOPITT Operational Fast Forward
149 Model (MOPFAS) (Edwards et al., 1999) for each pixel. If the measured/calculated radiance ratio
150 is ≥ 1.0 for V8 and V9 and ≥ 0.955 for other versions (V7 and before), then the observation is
151 considered “clear”. For this test however, the threshold value may be exceeded under temperature
152 inversion conditions where clouds are warmer than the underlying surface. This threshold method

153 is not applicable to polar regions due to the frequent temperature inversions at night, and to avoid
154 the effect of possible snow and ice coverage on the daytime signals (Warner et al., 2001).

155 **The MODIS Cloud threshold.** The MODIS swath (2330 km) is much wider than the MOPITT
156 swath (640 km), so it provides complete overlap for MOPITT passes. The MODIS cloud mask
157 (MOD35 L2) product (Ackerman et al., 2008) that is used here has 1 km horizontal resolution at
158 nadir (Ackerman et al., 1998). Therefore, each MOPITT pixel can encompass ~ 480 MODIS 1
159 x 1 km pixels. After co-location, relevant MODIS cloud mask parameters of the MODIS are gath-
160 ered and averaged for each MOPITT pixel. MOD35_L2, containing data collected from the Terra
161 platform is used to get the cloud count at each MOPITT pixel and if the MODIS cloud percent is
162 less than 5%, then the MOPITT pixel is considered clear.

163 In the previous MOPITT products (V8 and before), the MODIS test value supersedes the
164 MOPITT value over land, i.e., if the MODIS test is “clear” and the MOPITT test is “cloudy”, then
165 the MOPITT pixel will be considered “clear” (Warner et al., 2001, Marey et al., 2018). However,
166 if the MOPITT test identifies the pixel as clear and the MODIS test identifies the pixel as cloudy,
167 then a low cloud test is done. The low cloud test exploits the MODIS IR and visible reflectance
168 (Warner et al., 2001; Deeter et al., 2017). To assign low clouds for daytime observations, an aver-
169 aged MODIS IR threshold test value should be ≥ 0.9 and an averaged MODIS visible reflectance
170 test value should be ≤ 0.95 . For nighttime observations, a MODIS IR temperature difference test
171 value ≥ 0.9 is interpreted as low clouds (Warner et al., 2001, Marey et al., 2018). While for ocean
172 scenes even if the low cloud test did not pass, the pixel is considered clear based on either the
173 MOPITT or MODIS test result (Deeter et al., 2017).

174 For the V9 product, the modified cloud detection algorithm (Deeter et al., 2021) allows CO
175 retrievals over land when the MOPITT radiance ratio test indicates the pixel is clear although the
176 MODIS cloud mask test assigns the pixel as cloudy. Hence, a cloud index value of 6 (Table 1) is
177 now applied for both ocean and land areas (Deeter et al., 2017 and 2021).

178 The final clear/cloudy decision for each MOPITT pixel is based on set of rules summarized
179 in six cloud indices as follows: The pixel is assigned to be clear and hence retrieved if:

- 180 1: MODIS data are missing but the MOPITT radiance threshold is passed (rare).
- 181 2: MODIS data are clear and the MOPITT radiance threshold is passed. (most confidently clear)
- 182 3: MODIS data are clear but MOPITT radiance threshold is failed. The MODIS result overrides
183 the MOPITT result.

184 4: MODIS data are cloudy but the MOPITT radiance threshold is passed. In this case, the MODIS
185 low cloud test is applied and in the case of a low cloud, the pixel is treated as clear (occurs mostly
186 over ocean scenes).

187 5: Polar regions only ($> 65^\circ$ N or S latitude): MODIS data are clear. MOPITT test is not used.

188 6: Ocean and land scenes for V9 no MODIS low cloud: MODIS data are cloudy and the
189 MOPITT radiance threshold is passed. This was introduced in V7 for ocean scenes to correct for
190 an observed degradation in MODIS cloud products (Moeller and Frey, 2017).

191 If the pixel does not pass any of these tests, then no retrieval is performed. The six cloud
192 indices are reported in Level 2 MOPITT files in the “Cloud Description” diagnostic as presented
193 in Table 1.

194

195 Table 1. MOPITT Cloud Descriptor Values in L2 CO retrievals

Descriptor value	MOPITT assignment	MODIS assignment	Notes
1	clear	missing	MODIS data are not available
2	clear	clear	
3	cloudy	clear	
4	clear	cloudy, low clouds	
5	Not used	clear	Used only in polar regions
6	clear	cloudy, no low clouds	Introduced in MOPITT V7, for ocean observations only

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197

198 4. Results and Discussion

199

200

4.1 Assessment of the successful MOPITT CO retrievals

201 To assess the successful MOPITT CO retrievals in terms of data coverage, the statistics of
202 the L2 data from 2000 to 2020 for V9 and V8 are computed. Buchholz et al. (2017) recommended

203 avoiding the use of MOPITT above 60°N as the sea ice may not be correctly accounted for in the
204 retrievals. The fraction of daily valid data between 90°S–90°N and 60°S–60°N (for land and ocean
205 combined) are shown in Figure 1. The successful rate is calculated by taking the ratio of the num-
206 ber of daily CO data retrievals (L2) to the total number of daily radiance measurements (L1). For
207 the 90°S–90°N, the successful retrieval rate of V8 and V9 varies between 27%–33% and 35%–
208 40%, respectively. While the 60°S–60°N domain has a successful retrieval rate between 34%–
209 42% and 40%–50%, for V8 and V9 respectively. Therefore, the number of daytime V9 MOPITT
210 retrievals has increased by 15-20% for 90°S–90°N and 60°S–60°N relative to Version 8 product.
211 However, the gain in data coverage varies significantly on spatial level.

212 Figures 2-5 show the seasonal spatial coverage rate per day (the fraction of the successful
213 retrievals, L2 to the total number of radiance measurements, L1) using 2014 as a representative
214 year gridded in 1° × 1° bins. The top and the bottom figures present V9 and V8 daily coverage
215 rate, respectively while the middle ones indicate V9-V8 percent. It is apparent that some regions
216 exhibit high coverage rates (close to 100%) in all seasons for both V8 and V9, such as northern
217 Africa, so there are no added observations over such regions as it is indicated by the middle panels
218 (V9-V8). While other regions exhibit large gain in retrievals compared to V8 product which varies
219 seasonally. For example, in Canada, the data coverage of V8 (bottom panel of Figure 4) reached
220 50% in summer (e.g. Hudson Bay), but drops to less than 10% in winter (bottom panel of Figure
221 2) due to high cloud cover. Interestingly, V9 successful retrievals (top panels) for Canada demon-
222 strated significant data enhancement, especially in winter (top panel of Figure 2) where observa-
223 tions in some areas has doubled relative to V8 as shown in Figure 2. Additionally, the Amazon
224 region experienced significant data increase compared to V8, especially in JJA months as shown
225 in Figure 4. The increase in retrieval yield over the Amazon region has been investigated in more
226 details by Deeter et al. (2021).

227 Here we focus on daytime data, and therefore there is a cut off at high northern latitudes in
228 the northern-hemisphere winter, and at high southern latitudes in the southern-hemisphere winter.
229 In general, high latitude regions (poleward of 65°) have strong seasonal variations in data cover-
230 age, with the northern high latitudes showing the highest coverage rates for both V9 and V8 in
231 June, July, and August, and the southern high latitudes exhibiting the highest rates in December,
232 January, and February as a result of less cloud in the summer. However, V9 successful retrievals

233 of spring (February, March, and April) and fall (September, October and November) seasons ex-
234 perience a significant coverage gain in comparison to V8. Hence, the cloud detection scheme
235 modifications in the new V9 product resulted in an improvement in observational coverage, espe-
236 cially over land (Deeter et al., 2021).

237

238 **4.2 Analysis of standard and non-standard MOPITT product**

239 In this section, we present an analysis of Moderate Resolution Imaging Spectroradiometer
240 (MODIS) cloud heights and cloud mask products along with MOPITT retrieval cloud flag de-
241 scriptors to understand the impact of cloud conditions on the MOPITT observational coverage,
242 with a particular focus on observations over Canada.

243 CO TC were retrieved for a selected number of dates and locations by suppressing the cloud
244 detection scheme, so that all MOPITT L1 data were used to produce the L2 product regardless of
245 the cloud conditions. This non-cloud masked product will be referred to here as the non-standard
246 product. Analysis of the CO TC V8 L2 standard (cloud filtered) and non-standard product (non-
247 cloud masked) were performed for some selected cases. Figures 6a and 6b show the standard and
248 non-standard CO product on 16 August 2018, respectively, over the region between 78°W–92°W
249 and 44°N–60°N, which covers Ontario, Canada, near Hudson Bay. The standard (cloud masked)
250 product indicates that about 60% of the data are missing. Comparing it to the non-standard (non-
251 masked) product, some features can be observed in the non-standard product over the regions that
252 were missing data in the V8 standard product. A coherent structure is present between 50°N–54°N
253 (as it is indicated by pink and purple colors). The IASI TC for the same area and time was analyzed
254 to corroborate whether the features in the non-cloud-masked product are actual CO plumes
255 (Figures 6c). Comparing IASI CO TC on 16 August 2018 (Figures 6c) to the corresponding
256 MOPITT (Figure 6b) illustrate a strong CO plume around 50-55 °N and -94: -84 °W that is
257 apparent in both IASI and MOPITT. In the next section the MODIS cloud height product was used
258 to diagnose the cause of the missing (not retrieved in the V8 standard product) CO features.

259 **4.3 Regional analysis of MODIS cloud height and MOPITT data**

260

261 The MODIS swath (2330 km) is much wider than the MOPITT swath (640 km), so it
262 provides complete overlap for MOPITT passes. The MODIS cloud height (MOD6 L2) product
263 (Ackerman et al., 2008) has 5 km horizontal resolution at nadir (Ackerman et al., 1998). Therefore,
264 each MOPITT pixel can encompass ~ 20 MODIS 1 x 1 km pixels. After co-location, relevant
265 MODIS cloud height values are gathered and averaged for each MOPITT pixel.

266

267 Figures 6d depicts the V8 MOPITT cloud index (see Table 1), for the case on 16 August
268 2018. Retrievals were assigned cloud index 2 (MODIS and MOPITT clear, grey color), 3 (MODIS
269 clear and MOPITT cloudy, dark blue), and 4 (low clouds, cyan color). Figures 6d shows that the
270 V8 L2 data on 16 August 2018 case were retrieved based on clear and low cloud conditions as
271 indicated by flag number 2 and flag number 4. Figure 6e displays the MODIS cloud height (and
272 cloud mask for the same swath on 16 August 2018. Comparing the low cloud retrieval area (cyan
273 color) to the corresponding MODIS cloud height (Fig. 6e) and cloud mask (Figure 6f), it can be
274 seen that this area has cloud percent (the term “cloud” encompasses water clouds and aerosols) by
275 more than 90% and has cloud heights less than 1 km, as illustrated by the grey color (Figure 6e).
276 The MODIS cloud height also shows other areas that have low clouds (grey and blue colors) where
277 there were no retrievals in the V8 standard product. Those pixels collocate with the coherent
278 pattern region (between 52°N–54°N) that were shown in the non-masked product (Figure 6b).
279 Therefore, it appears that some of the potential retrievals were missed in the V8 standard retrieval
280 due to misidentification of low cloud pixels. It is necessary to examine additional cases using the
281 same approach to determine whether these findings are widespread.

282

283 **4.4 Analysis of V8 cases under different cloud and pollution conditions**

284 In this section, additional cases are investigated by analyzing the cloud filtered (V8 standard)
285 and the non-cloud masked, along with the MODIS cloud height and cloud mask products. Figure
286 7 shows the results over Canada, on 12 April 2010 and it indicates that, about 70% of the data are
287 missing in the standard retrievals (Figure 7a). However, the non-cloud masked product (Figure 7b)
288 captures notable features between 54°N–56°N and 90°W–98°W (as indicated by the red colors in
289 Figure 7b). The MOPITT cloud flag description on 12 April 2010 (Figure 7d) reveals that all L2
290 data were retrieved under clear conditions (MODIS cloud percent less than 5%) as indicated by

291 the flag number 2 (grey color) and the MOPITT diagnostics data (Figure 7c). However, the
292 corresponding MODIS cloud height (Figure 7e) showed an area of very low cloud heights that are
293 less than 500 m (around 54°N–56°N), where the MOPITT measurements were not retrieved
294 completely in the V8 standard product as they were considered cloudy (with more than 5% cloud
295 cover, see Figure 7f). Comparing this area to the collocated non-masked CO product (Figure 7b),
296 it can be noted that it exactly matches the coherent pattern that was observed between 54°N–56°N.
297 Looking to IASI CO TC for the same time and location on 12 April 2010 (Figures 7c), it can be
298 seen that most of the CO features in the area of 52-56 latitude and -100: -92 longitudes (Figure 7b)
299 are not captured as well due to their cloud detection scheme.

300 An unusually active forest fire season occurred in the vicinity of Fort McMurray, Alberta, in
301 May 2016. Figures 8a and 8b display the V8 standard and non-standard CO TC on 6 May (day),
302 respectively. Again, the non-standard CO product exhibits a notable coherent pattern over some
303 areas that were not retrieved in the standard product. On 6 May 2016, there is a CO plume around
304 50°N–52°N and 108°W–112°W longitude that is indicated by the purple colors (Figure 8b) and it
305 is completely missed in the V8 standard product. On the other hand, IASI shows a consistency
306 with the non-masked MOPITT product where a prominent CO plumes was observed around 50-
307 56 latitude and -112: -104 longitudes which coincide the corresponding MOPITT (Figure 8b).

308 The elevated CO values on 6 May 2016 is likely to be a result of Fort McMurray fire
309 emissions in northern Alberta (as indicated by MODIS fire images, not shown). Considering the
310 low cloud detection during the Fort McMurray fires, the MODIS cloud height data of the
311 corresponding MOPITT pixels on 6 May 2016 (Figure 8e) suggest that none of the low cloud (blue
312 colors) pixels were retrieved in the standard product as it is implied by the MOPITT flag number
313 (Figure 8d) (all values are 2).

314

315 **4.5 MODIS height comparison with MOPITT radiance ratio**

316

317 As it is mentioned in section 3 the MOPITT retrieval algorithm only retrieve CO in clear-
318 sky conditions. The cloud detection scheme utilizes information from both MODIS cloud mask
319 product and the MOPITT's thermal-channel radiances (Warner et al., 2001). Radiance from the
320 MOPITT 4.7 μm thermal channel radiance is compared to the calculated model for each pixel. If

321 the measured/calculated radiance ratio is greater than the threshold (which is one for V8), then the
322 observation is considered “clear”.

323 In MOPITT V8 and before, the MODIS test value supersedes the MOPITT test value over
324 land, i.e., the MOPITT pixel will be considered “clear” if the MODIS test is “clear” and the
325 MOPITT test is “cloudy”. However, the MOPITT pixel will be considered “cloudy” if the
326 MOPITT test identifies the pixel as clear and the MODIS test identifies the pixel as cloudy. Hence
327 V8 level 2 retrievals are processed over land just if the MODIS test passes. For the MOPITT V9
328 product, Deeter et al., (2021) modified the cloud detection algorithm by allowing CO retrievals
329 when the MOPITT radiance ratio (MRT) test indicates the pixel is clear although the MODIS cloud
330 mask test assigns the pixel as cloudy. Deeter et al., (2021) modified the cloud detection algorithm
331 by allowing CO retrievals when the MOPITT radiance ratio test indicates the pixel is clear alt-
332 hough the MODIS cloud mask test assigns the pixel as cloudy.

333 To understand how the new V9 cloud detection scheme improved the coverage rate, an anal-
334 ysis of the MRT and MODIS cloud height has been conducted for many cases over Canada. The
335 data on 6 May 2016 are presented here as a case study and are shown in Figure 9. It can be seen
336 that there is a negative correlation between the MRT and MODIS cloud height with a slope of -
337 0.06 and a correlation of $R = 0.68$.

338 A Box and Whisker plot of MRT and the corresponding MODIS cloud heights for various
339 groups are displayed in Figure 9b. Since the modified cloud detection scheme of V9 relies on the
340 MRT threshold test (the threshold value is one), it is expected that, most of the observations with
341 cloud heights up to 3 km are incorporated in V9 retrievals as illustrated Figure 9b.

342 Figures 9c and d in the bottom panel depict the histograms density of MODIS cloud heights of
343 the corresponding MOPITT clear/MODIS clear observations and MOPITT clear/MODIS cloudy,
344 respectively on 6 May 2016. The successful retrievals using MOPITT clear/MODIS clear pixels
345 and MOPITT clear/MODIS cloudy are 45.4%, and 14.2%, respectively.

346 Since MRT correlates negatively with the low cloud heights (as indicated above in Figure 9a),
347 the low cloud cases are included in V9 (Figure 9d) with high proportion of heights less than 3 km.
348 Hence, adding low cloud observations as a result of considering MRT values of greater than 1
349 enhances the MOPITT coverage percentage by 14.2% compared to 45.4% successful retrievals
350 without considering the low cloud cases. The total coverage rate is about 60% with about a 30%
351 (14.2/45.4) gain in data coverage. Therefore, using the MRT cloud test independently in V9 cloud

352 detection scheme resolved the problem of low cloud miss-detection over land, which results in a
353 significant data coverage increase, especially over the region of Canada.

354

355 **4.6 MOPITT and IASI comparison**

356 We examine the impact of the increased observational coverage in the MOPITT TIR V9
357 product in comparison to IASI data over Canada for three case studies. The first and third cases
358 are associated with biomass burning emissions (6 May 2016 and 16 August 2018), while the se-
359 cond case represents typical conditions with no extreme air pollution (12 April 2010). Figure 10
360 shows maps of 1-day/morning overpasses of CO total columns measured by MOPITT and IASI
361 on 6 May 2016. Figures 10a and 10b show MOPITT V9 and V8 data, respectively, while Figures
362 10c and 10d show the corresponding IASI data (collocated with MOPITT) and the entire IASI CO
363 field (gridded in $0.25^\circ \times 0.25^\circ$ bins), respectively. As seen in Figures 10a and 10b, there is a gap
364 with missing MOPITT data in V8 that extends across Alberta and Saskatchewan between 110°W
365 and 100°W , but the data are present in V9 as a result of the improved retrievals in low cloud
366 conditions (as indicated by the MODIS cloud heights in Figure 8e). The high CO total column
367 values that are added in MOPITT V9 product coincide with the high AOD and OMI UV Aerosol
368 Index (UVAI) values (not shown) from the Fort McMurray fire emissions. Smoke was transported
369 from the eastern part of Alberta, moving into Saskatchewan and central Alberta in the vicinity of
370 the high CO values. Interestingly, the added retrievals in V9 exhibit a pattern that is consistent
371 with the IASI data (Figure 10c). Since IASI has daily global coverage compared to MOPITT's 3-
372 day global coverage, the entire smoke plume is captured by IASI (Figure 10d).

373 Figure 11 depicts the scatter plots of IASI and MOPITT TIR V9 and V8 retrievals over
374 Canada on 6 May 2016 and for the entire month of May 2016 (monthly average). IASI and
375 MOPITT data are gridded in 0.25×0.25 deg., then the daily collocated data are selected for the
376 analysis.

377 In general, IASI and MOPITT retrievals are consistent to a large extent with a correlation
378 coefficient of 0.98-0.99 and 0.97-0.98 for V8 and V9, respectively. However, IASI has higher
379 values than MOPITT over Canada, with the slope varying from 1.04 to 1.06. Total CO column
380 biases for V9 are somewhat larger than for V8 products; with a slope for V9 of 1.05 and 1.06,
381 whereas for V8 it is 1.04 and 1.05 for data on 6 May 2016 and for all of May 2016, respectively.

382 These discrepancies occur at high CO values, and since the added data in V9 are mainly in heavily
383 polluted regions, the IASI bias is greater for V9 than V8.

384 For the second case analysis on 12 April 2010, V9 (shown in Figure 12a) exhibited greater
385 data coverage relative to V8 (Figure 12b) around 126°W, 56-60°N, 90°W, 56-60°N, and 80°W,
386 44°N as a result of retrievals of low cloud height pixels (Figure 7e). Figure 12c shows generally
387 good agreement between IASI CO total column values and corresponding MOPITT retrievals. As
388 this time of year has no extreme air pollution sources (such as forest fire emissions), the CO total
389 column values over land are in the range of 20-30 10^{17} molecules/cm², which can be seen in the
390 whole IASI CO total column field in Figure 12d. Consequently, as shown in Figure 13, the IASI
391 biases with MOPITT V8 and V9 are generally similar, with comparable correlations and slopes.

392 Comparison of MOPITT V9 and V8 on 16 August 2018 over Canada, in Figure 14, shows the
393 greater number of successful MOPITT retrievals in V9 that were discarded in V8. The added data
394 in V9 are around 80°W-90°W, and 50°N-56°N and 100°W-117°W, 54°N-56°N. Those regions are
395 associated with cloudy areas of relatively low cloud heights as indicated by the MODIS cloud
396 mask and height (Figure 6e and 6f). As shown in Figure 14c, the IASI observational pattern is
397 generally consistent with the corresponding MOPITT CO total columns. However, there is an ap-
398 parent positive IASI bias around 80°W-90°W and 54°N where IASI CO values exceed 50×10^{17}
399 molecules/cm² compared to 30×10^{17} molecules/cm² for MOPITT. These high CO values are as-
400 sociated with the dense pollution plume that extends across Canada as shown in the map in Figure
401 14d with the whole IASI observational scene and in Figure 15a with the MODIS Terra image
402 overlaid with the thermal anomaly spots.

403 The scatterplots of CO total column values between IASI and MOPITT TIR V9 and V8 for
404 August 2018 are shown in Figure 15b. The slopes of the relationship between IASI and MOPITT
405 V8 data on 16 August 2016 and for all of August are 1.09 and 1.07, respectively. Since the added
406 MOPITT retrievals in V9 are associated with higher CO total column values, the slopes increase
407 to 1.12 and 1.1, respectively, with smaller correlation coefficients. CALIPSO total attenuated
408 backscatter at 532 nm on 16 Aug. 2018 for the two yellow swaths shown in Figure 15a are pre-
409 sented in Figures 15c and 15d. The smoke aerosols were observed at altitudes between 2 km and
410 6 km, as measured by CALIPSO, indicating that convective lofting may have elevated the fire
411 emissions above the boundary layer into the free troposphere. The large CO enhancements ob-
412 served by IASI around -80°W-90°W and 54°N (Figure 14c) are collocated with the maximum

413 aerosol backscatter coefficient at ~3 km detected by the CALIPSO lidar (Figure 15d). However,
414 CO in this area is underestimated by MOPITT TIR relative to IASI (Figure 14b) resulting in 12%
415 overall bias over Canada on 16 August 2018 (as indicated by the slope of 1.12).

416 Similar results were found by Turquety et al. (2009) as their study revealed that IASI CO is on
417 average 35% higher than MOPITT in regions of elevated CO concentrations during extreme fire
418 events. There are many factors that could explain the discrepancies between IASI and MOPITT
419 during pollution events. One of them is the different horizontal resolution of the two instruments
420 (22 km × 22 km for MOPITT and a 12-km diameter for IASI), especially above inhomogeneous
421 scenes. A second major factor that could contribute to the differences between the MOPITT and
422 IASI retrievals is the a priori used in the retrievals. IASI uses a fixed a priori while MOPITT has
423 variable a priori profiles. George et al. (2015) examined the impact of the a priori on the IASI and
424 MOPITT data and found that using the same a priori constraints slightly improved the correlation
425 between the two data sets and reduced the large discrepancies (total column biases over 15 %)
426 observed at some places by a factor of 2 to 2.5. However, other regions did not show any bias
427 reduction. A third factor is the difference in vertical sensitivity between the two instruments, as
428 reflected by their averaging kernel matrices (the sensitivity of the retrieval to the abundance of CO
429 at different altitudes). The instruments have different degrees of freedom for signal (DOFS), which
430 is given by the trace of the averaging kernel matrix; the DOFS of the MOPITT retrievals is lower
431 than the corresponding IASI retrievals (not shown). Although both instruments in general have
432 good sensitivity in the middle troposphere, IASI's averaging kernel indicating greater sensitivity
433 in the upper troposphere as well. The difference in averaging kernels for the instruments can be
434 attributed to instrumental and retrieval factors (George et al., 2015). For example, surface emis-
435 sivity and water vapor are treated differently in the two retrieval algorithms. The MOPITT algo-
436 rithm retrieves emissivity simultaneously with CO but uses a fixed water vapor profile from
437 NOAA/National Centers for Environmental Prediction (NCEP), while IASI assumes a fixed emis-
438 sivity but estimates the water vapor amount (Barré, J., et al., 2015). Understanding how the factors
439 discussed here, as well as others, potentially contribute to the discrepancies between MOPITT and
440 IASI will be further investigated in future work

441

442 **5. Conclusion**

443 In this study, an analysis has been performed to understand the improvements in observa-
444 tional coverage over Canada in the new MOPITT V9 product. Temporal and spatial analysis of
445 V9 indicates a general coverage gain of 15-20% relative to V8 which vary regionally and season-
446 ally. For example, the number of successful MOPITT retrievals in V9 was doubled over Canada
447 in winter.

448 The standard (cloud filtered) V8 CO TC (L2) product was compared with a non-standard
449 (non-cloud masked) version of the retrievals for selected days to understand the observation gain
450 in V9 relative to V8. The results reveal some coherent structures of CO plumes that were observed
451 frequently in the non-cloud masked product but which were missing in the standard the V8 prod-
452 uct. Those features are not captured in V8 standard product because the cloud detection scheme
453 did not properly detect many low cloud cases over land.

454 The modified V9 cloud detection scheme utilizes MRT test (threshold value of 1) individu-
455 ally which allow CO retrievals when the MRT test indicates the pixel is clear although the MODIS
456 cloud mask test assigns the pixel as cloudy. Since MRT correlates negatively with the low cloud
457 heights, most of low cloud observations (up to 3 km) are included in V9 L2 retrievals. Hence, the
458 incorporation of the MRT test over land will resolve the low cloud detection issue as it is demon-
459 strated by MODIS cloud height correlation. Hence, adding low cloud observations as a result of
460 considering MRT values of greater than 1 enhances the MOPITT coverage percentage.

461
462 The improved V9 cloud detection scheme benefits regions that are often characterized by
463 high aerosol concentrations (e.g. biomass burning emissions). An analysis of MOPITT and IASI
464 CO are conducted for three cases. The first and third cases are associated with biomass burning
465 emissions, while the second case represents typical conditions with no extreme air pollution. The
466 added retrievals in V9 exhibit a pattern that is generally consistent with the corresponding IASI
467 data. In general, the IASI MOPITT comparison indicated discrepancies at high CO values. Since
468 the added data in V9 are mainly characterized by high aerosol load (low cloud cases) that are
469 usually associated with high CO values as a result of fire emissions, the IASI bias is greater for
470 V9 than V8. So, IASI MOPITT CO TC comparison indicated generally good agreement with about
471 5-10% positive bias which increases in highly polluted scenes.

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473

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487 **6. References**

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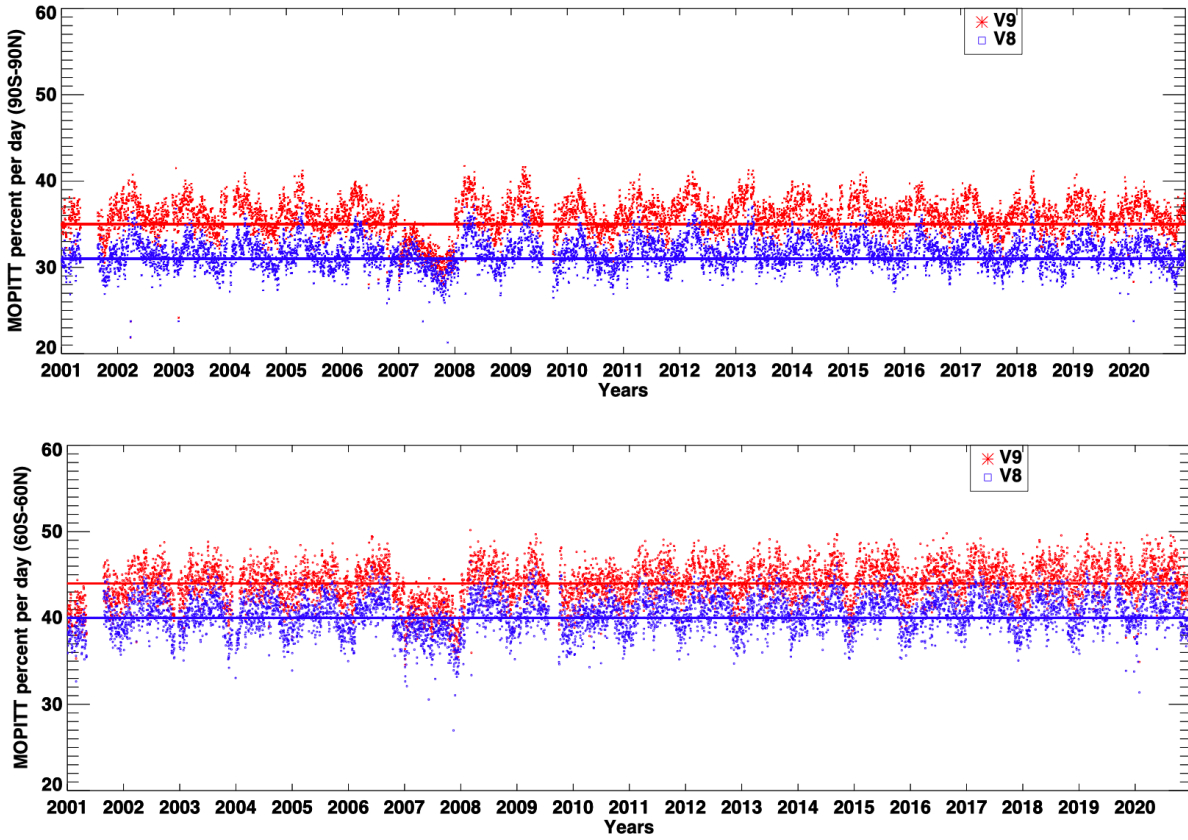
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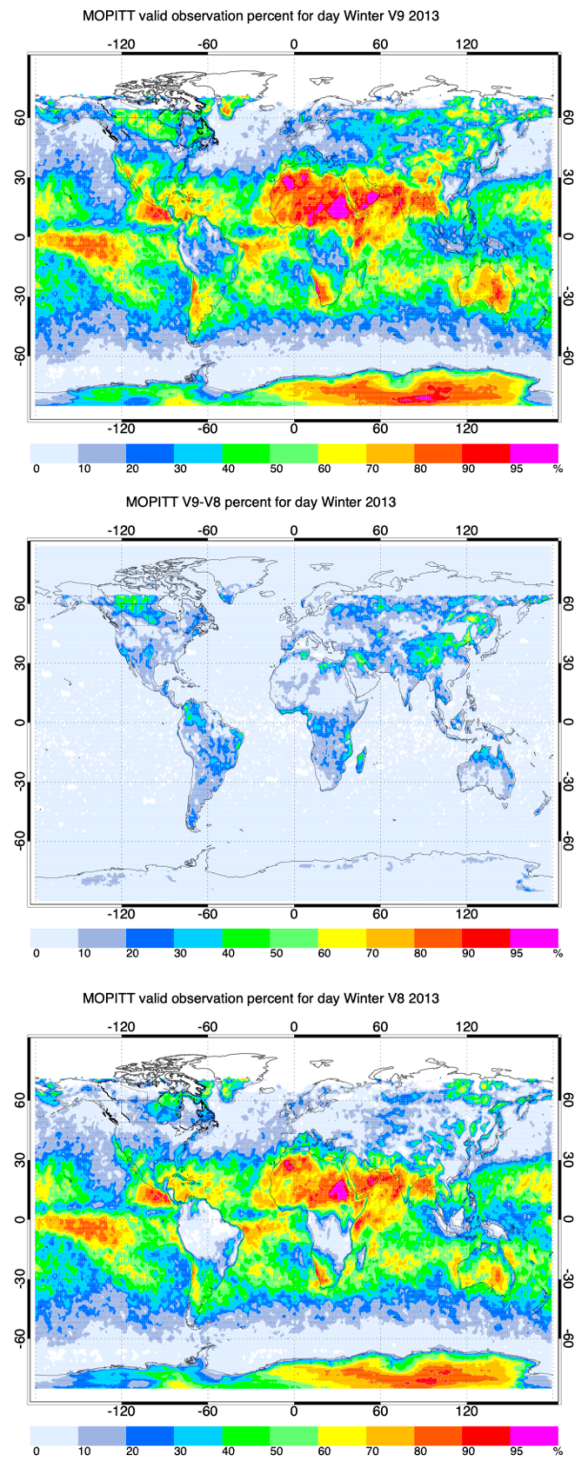
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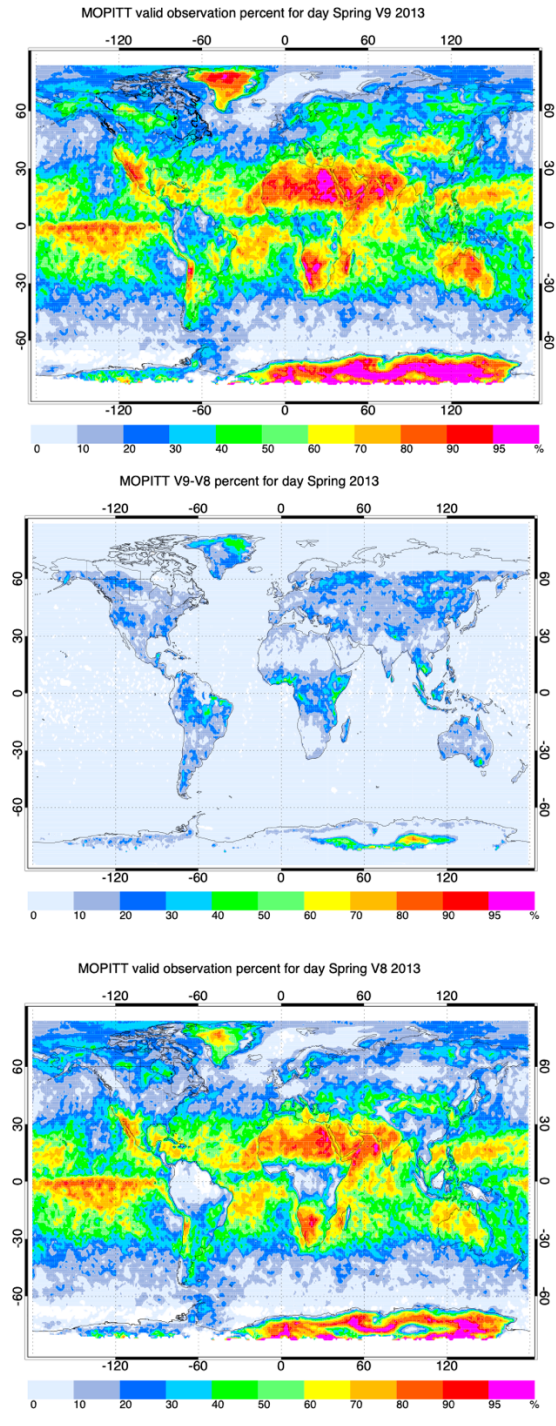
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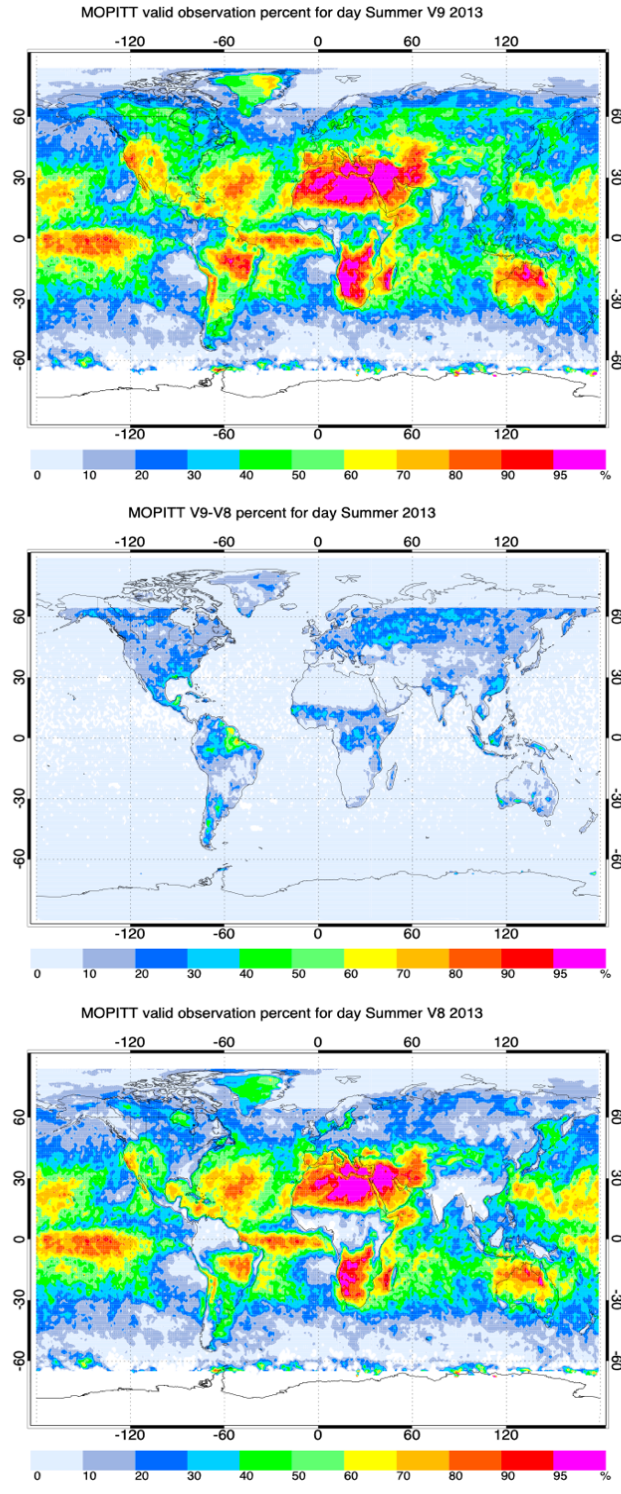
598 Figure (1) The percentage of successful daily MOPITT retrievals between 90°S–90°N and 60°S–
599 60°N from 2000 to 2020 for V9 and V8. The solid lines represent the average successful retrieval
600 for the entire period.



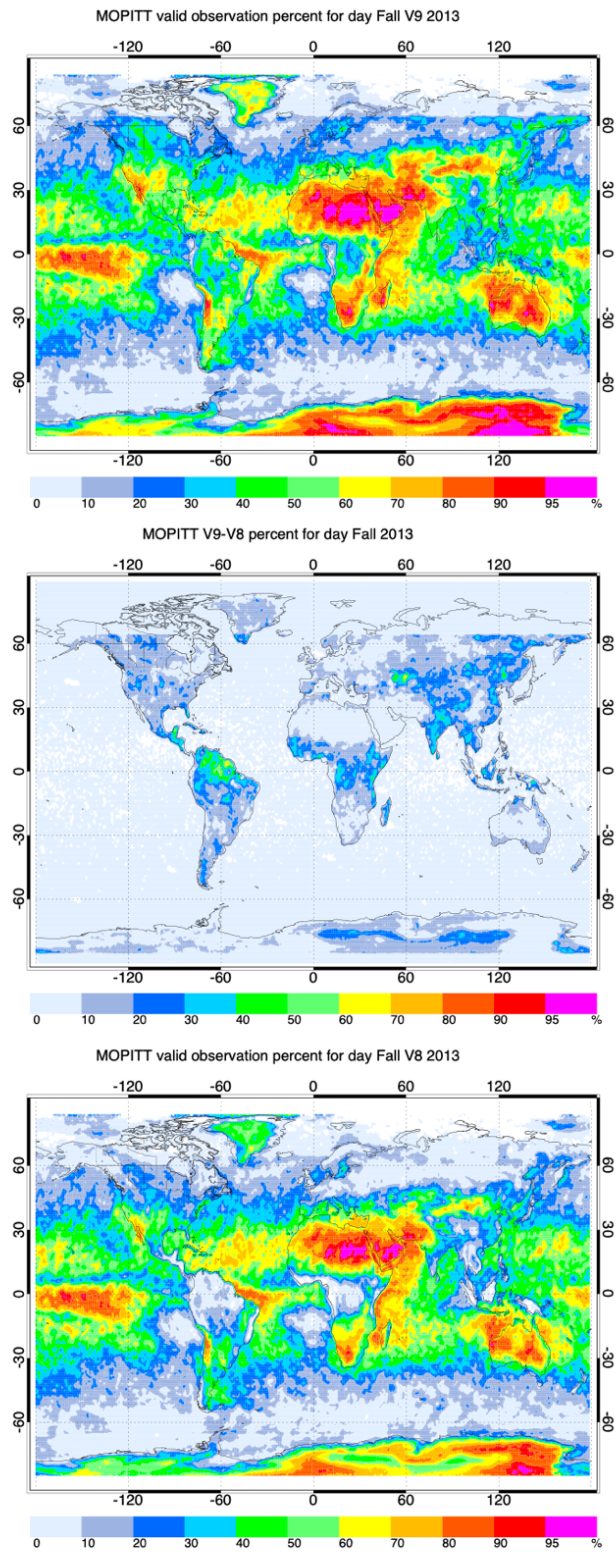
601
 602 Figure (2) Seasonally averaged spatial distribution of the successful MOPITT retrievals in winter
 603 2013 for V9 (top panel), V8 (bottom panel) and V9-V8 (middle panel). Data were aggregated
 604 into $1^\circ \times 1^\circ$ bins.



605
 606 Figure (3) The same as Figure 2 but for spring season.

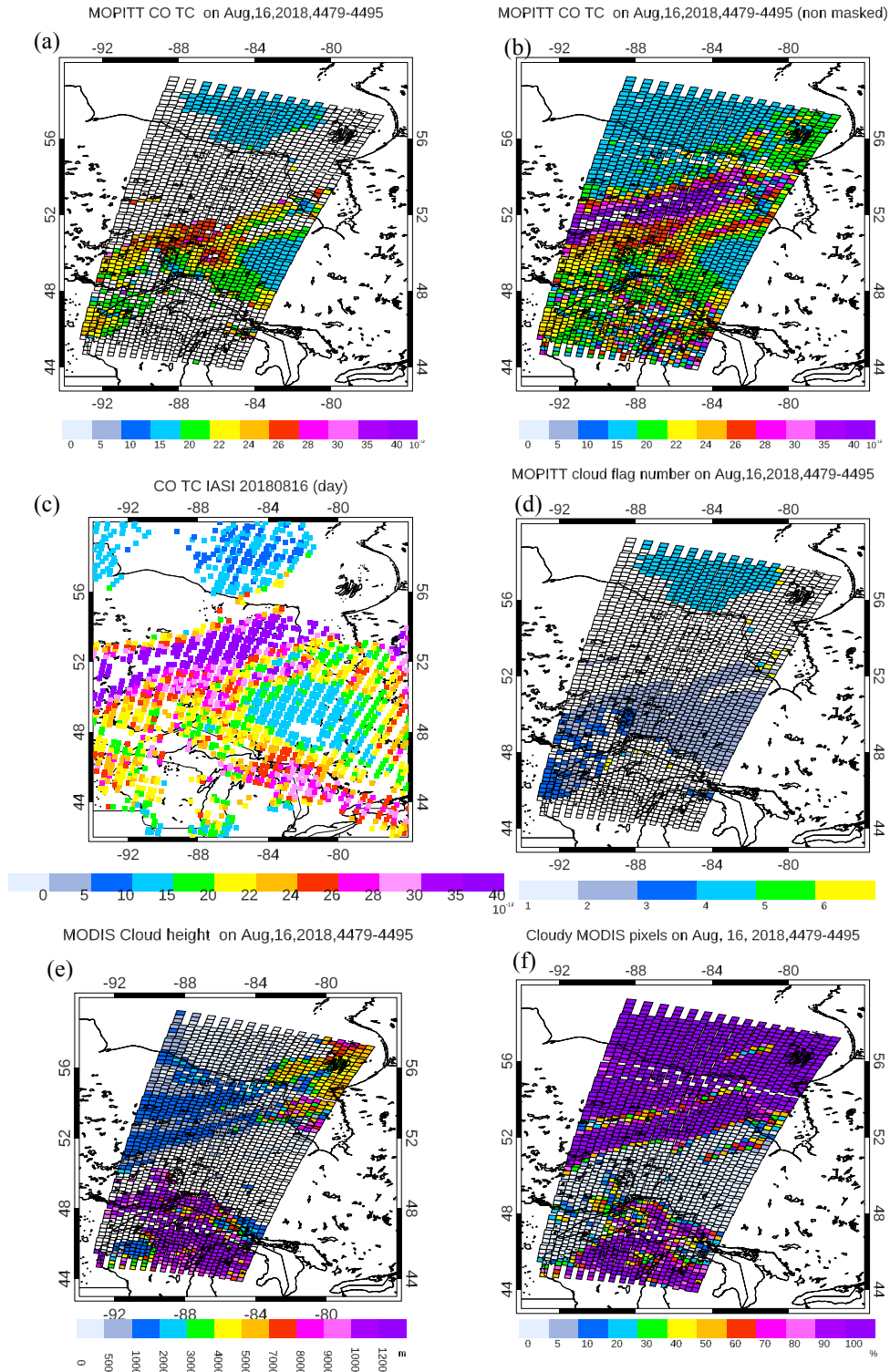


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 608 Figure (4) The same as Figure 2 but for summer season.
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612 Figure (5) The same as Figure 2 but for fall season.



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615 Figure 6. (a) Standard (cloud masked), (b) non-standard (non-cloud masked) CO TC, (c) IASI CO
616 TC, (d) MOPITT cloud flag number, (e) MODIS cloud height, and (f) cloud mask on 16 August,
617 2018. The faint black squares represent MOPITT pixels (22 km x 22 km) for all L1 observations.

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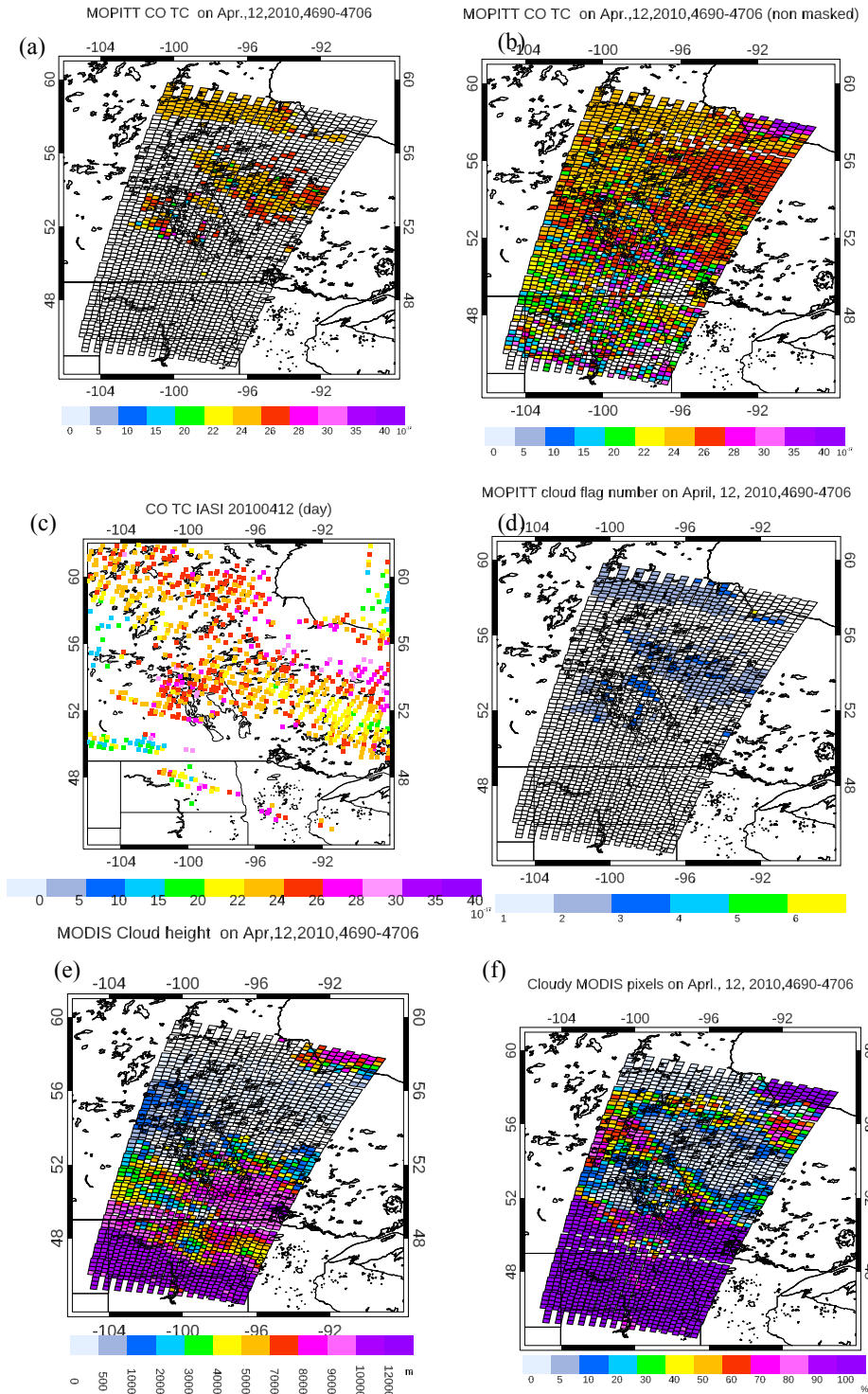
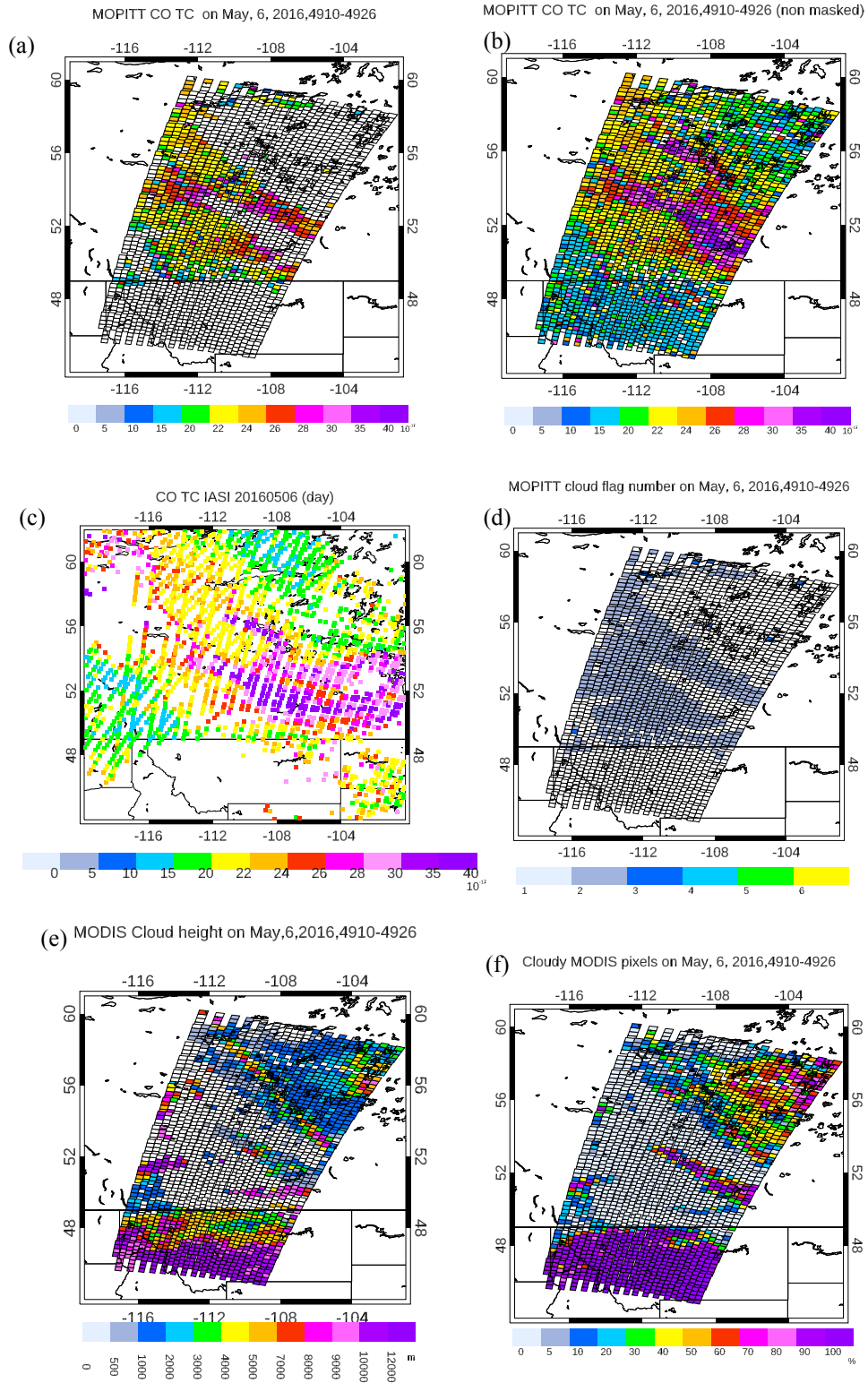


Figure (7) The same as Figure 3, but for 12 April 2010.

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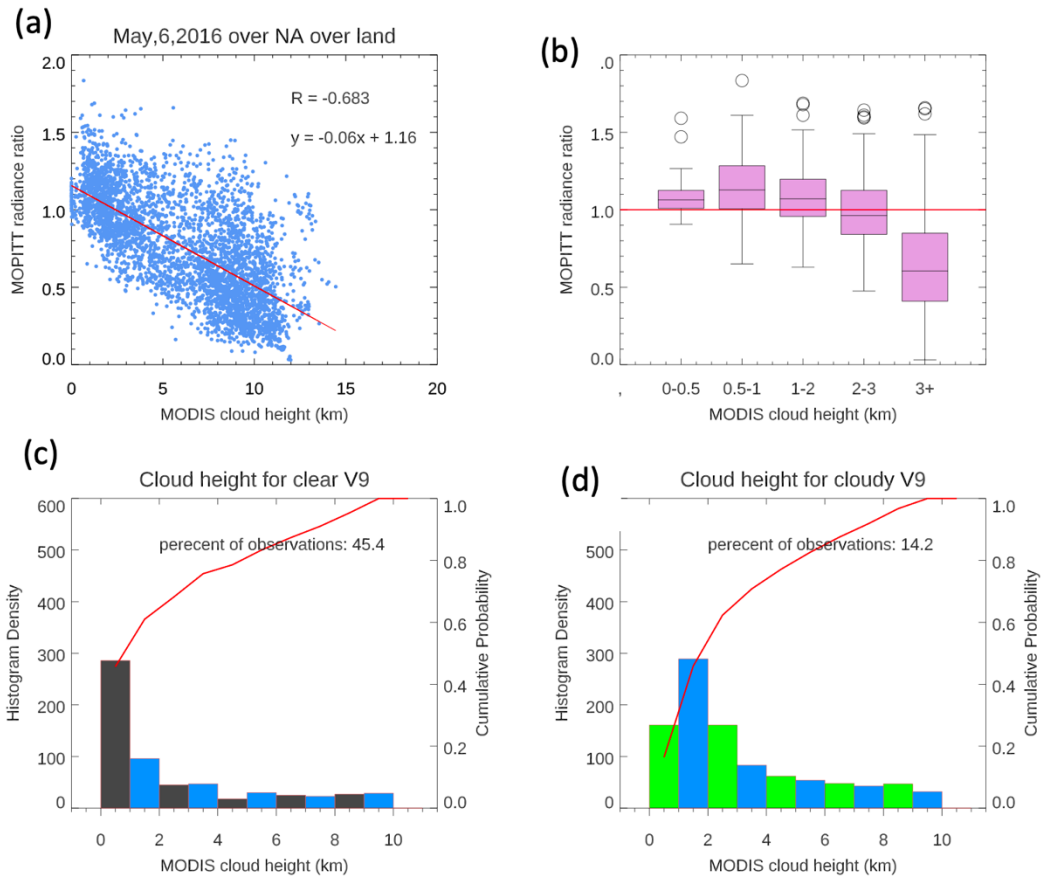
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624 Figure (8) The same as Figure 3, but for 6 May 2016.

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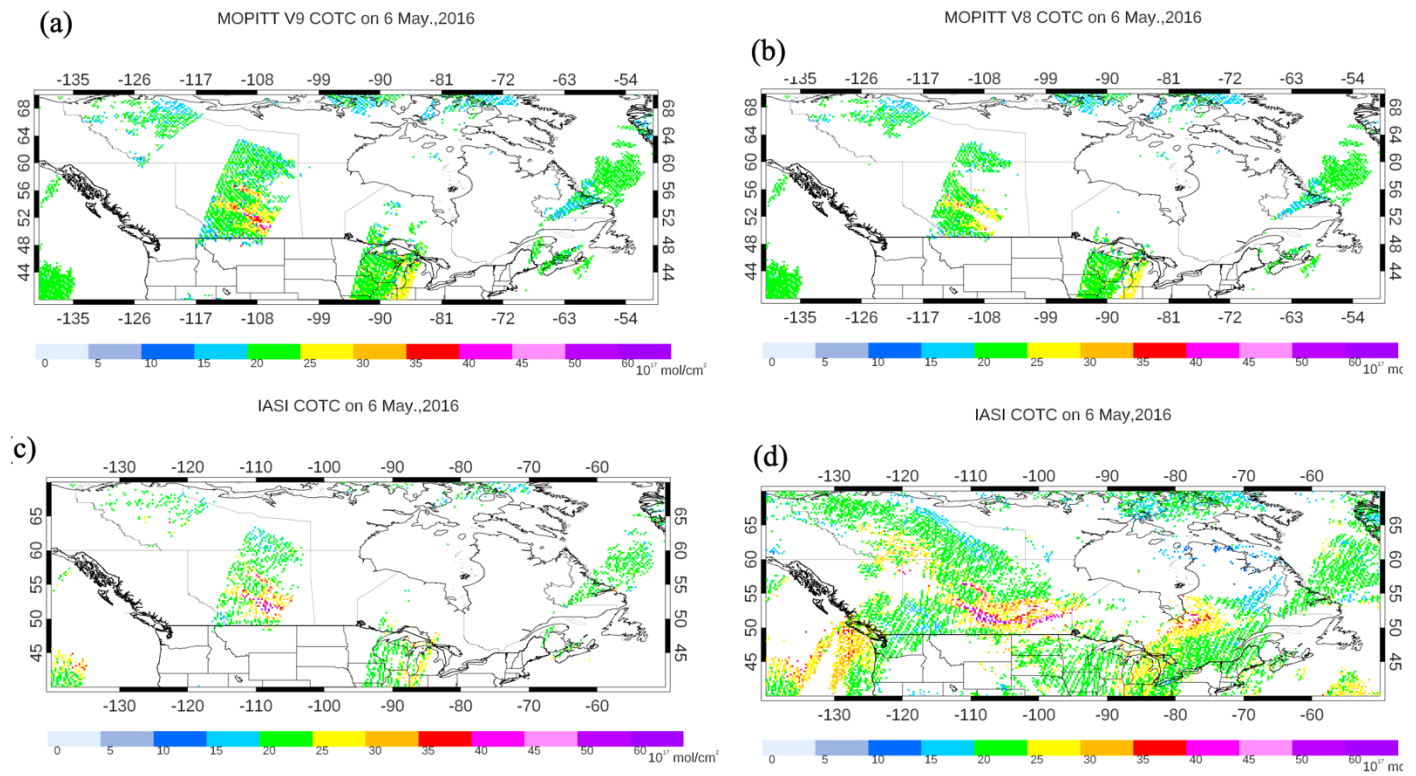
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629 Figure (9) (a) scatter plot correlation between MOPITT radiance ratio (MRT) and MODIS cloud
630 height, (b) A *Box and Whisker plot* of MRT and various MODIS cloud height groups, (c) The
631 histogram density of MODIS cloud heights of MOPITT clear/MODIS clear observations, (d) The
632 histogram density of MODIS cloud heights of MOPITT clear/MODIS cloudy observations on 6
633 May 2016.

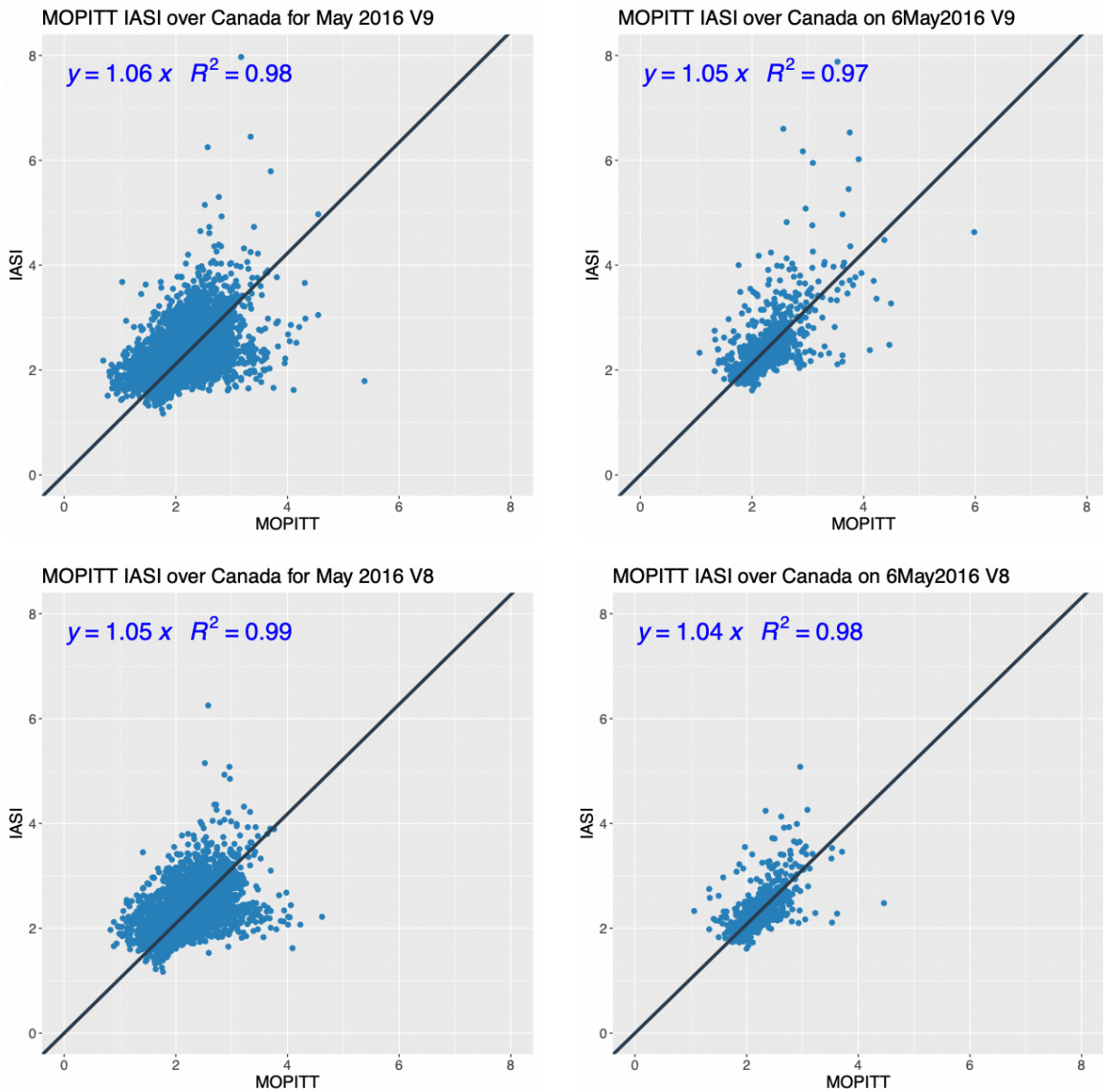


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635 Figure (10) MOPITT CO total column for V9 (a) and V8 (b). IASI CO total column observations

636 of the corresponding with MOPITT (c) and the entire IASI CO retrievals (d) on 6 May 2016.

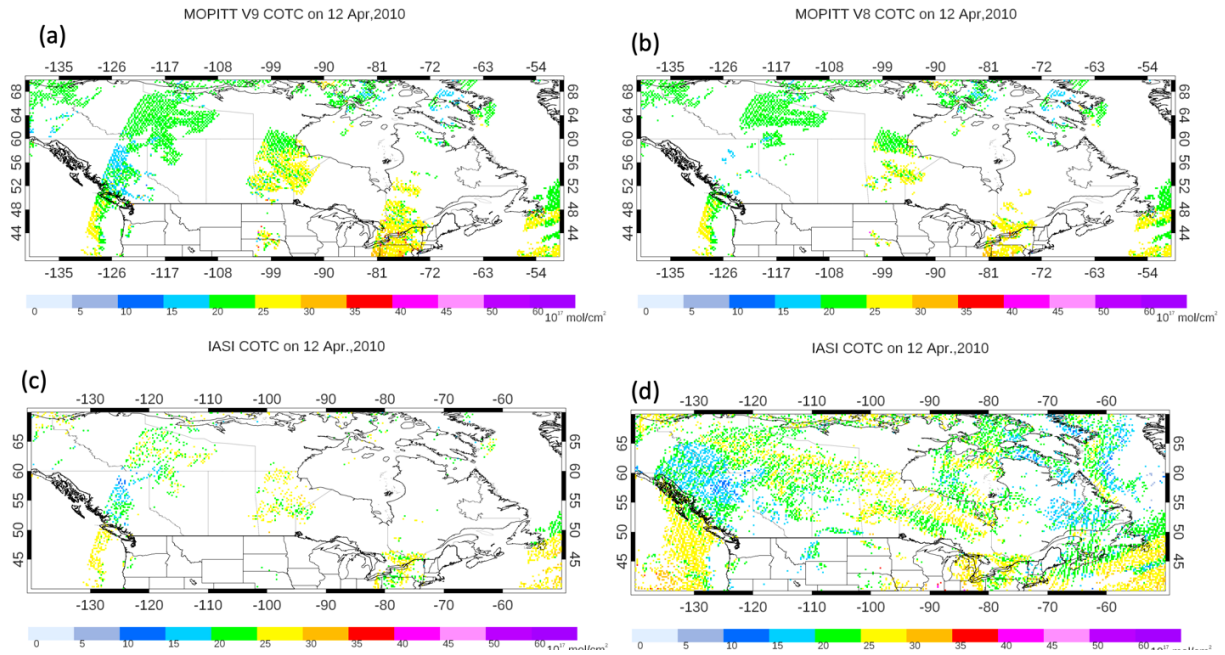
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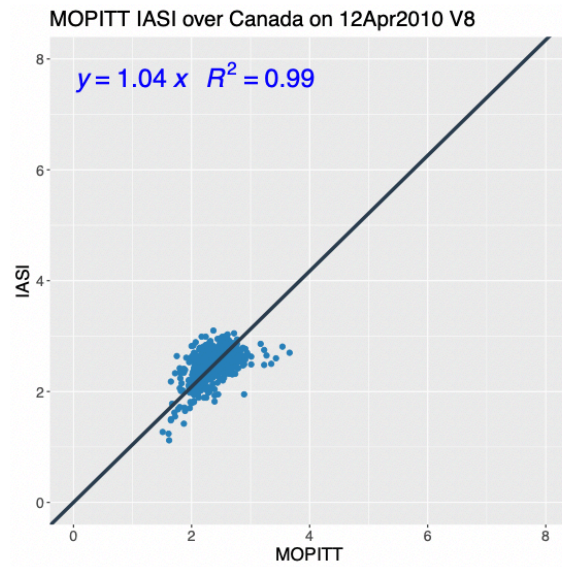
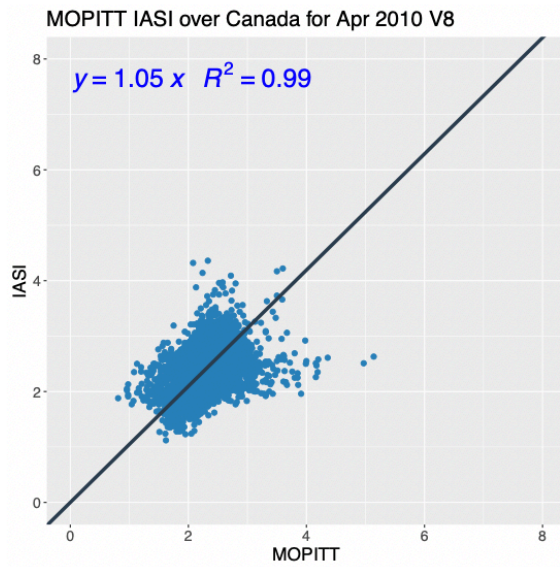
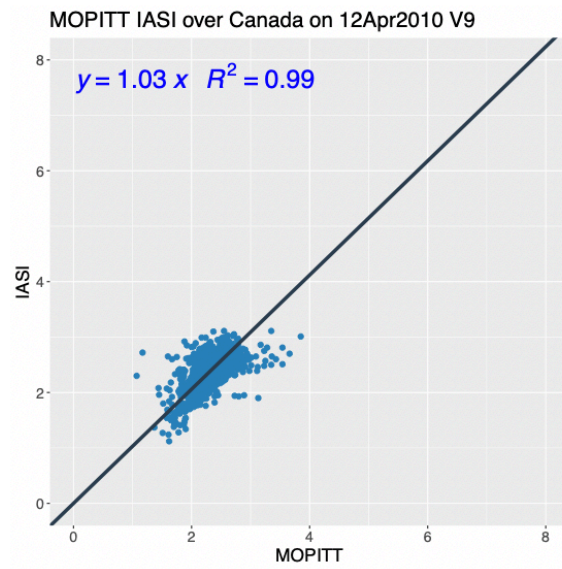
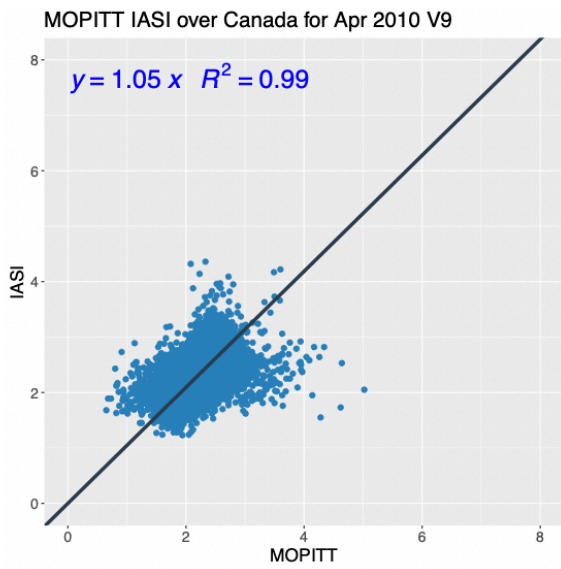
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639 Figure (11) Scatter plots of the IASI and MOPITT CO retrievals in 10^{18} molecules/cm², for 6 May
 640 2016 and the monthly averaged May 2016. The correlation coefficient and the regression slope are
 641 reported.

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 644 Figure (12) The same as Figure 10, but for 12 April 2010.
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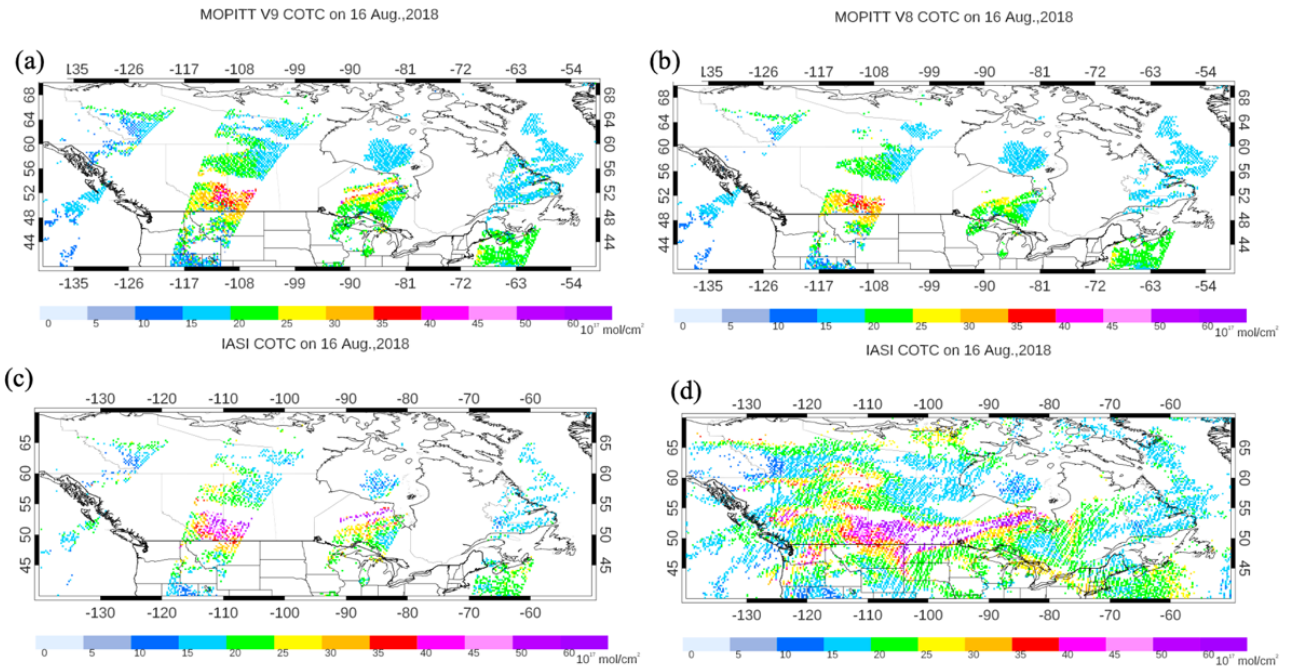


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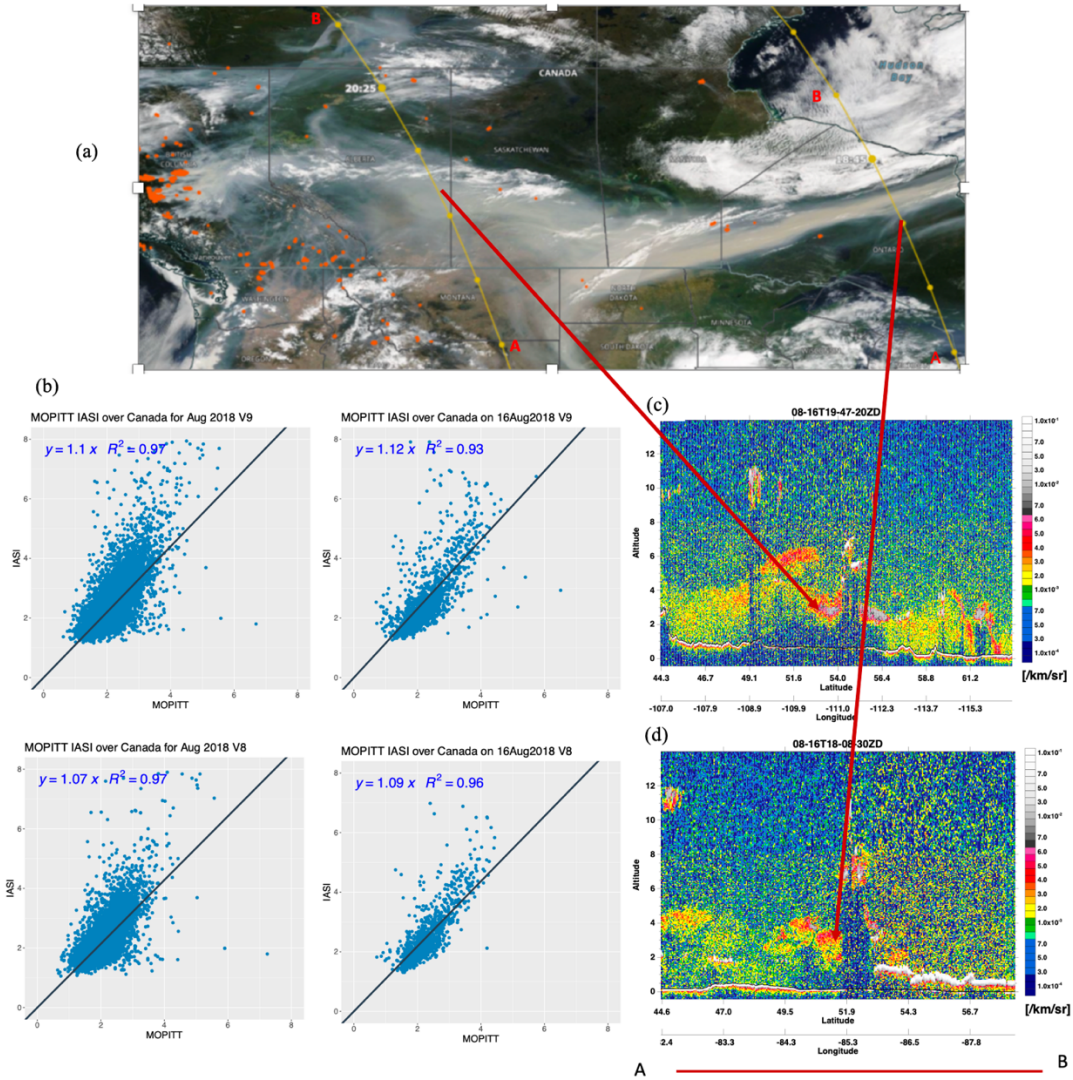
648 Figure (13) The same as Figure 11, but for 12 April 2010.

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651 Figure (14) The same as Figure 10, but for 16 August 2018.



652

653 Figure (15) (a) MODIS Terra overlaid with fire points (red points), (b) scatter plots between IASI

654 and MOPITT TIR V9 and V8 and (c-d) daytime CALIPSO 532nm total attenuated backscatter on

655 16 August 2018.