Response to Reviewer #2: Dr. Rebecca Adams-Selin

Thank you for your careful and thorough reading of this manuscript and your thoughtful comments and suggestions. Our responses follow your comments (in *Italics*).

This article details the development of a highly useful convective climatology for the eastern two-thirds of the continental U.S. Considerable effort is expended explaining the datasets used, potential sources of error and mitigation strategies, and the complex processing steps involved. Future applications for the dataset are described. I am concerned about the design of the algorithm not separating organized from unorganized isolated convection, potentially leading to impacts in the precipitation intensity calculations. Pending responses to my comments enumerated below, I recommend acceptance bending major revisions.

Major comments:

1. *The IDC category is potentially lumping unorganized isolated convection in with highly organized isolated convection such as supercells. I can certainly see the authors' points that MCSs are larger systems than all IDC, and thereby should result in larger transport, circulation, and accumulated precipitation impacts (e.g., Lines 80-82), but citation of a few studies in the literature to that effect would be useful so as to not argue from intuition alone.*

Reply:

We had references for the larger transport and circulation effects of MCSs than IDC in Lines 75 – 77 in the revised main manuscript and have added another reference from

Bigelbach et al. (2014). We think you meant the sentence in Lines 85 – 87 in the revised main manuscript: ‘Compared to IDC, MCSs tend to occur in more favorable environmental conditions, such as higher convective available potential energy (CAPE) and wind shear (French and Parker, 2008), potentially making them more conducive to hazardous weather.’ We have changed this sentence with more details. We intended to emphasize the different environmental conditions associated with MCS and IDC, but the old sentence misrepresents the results of Rowe et al. (2012) and French and Parker (2008). Now the sentences are as follows.

‘Rowe et al. (2012) also suggested that the enhanced rainfall from MCSs might be associated with more favorable environmental conditions, such as higher convective available potential energy (CAPE) and wind shear. CAPE and wind shear can impose different impacts on the initiation and evolution of IDC and MCSs (French and Parker, 2008).’

Severer precipitation impacts can also be reflected by our citation of Rowe et al. (2012).

> *Regarding severe weather, however, including tornados and large hail, MCSs are not the primary generators. Instead, supercells are (e.g., Wurman et al. 2011 BAMS). Furthermore, supercells are increasingly recognized as producers of heavy and extreme rainfall (e.g., Hitchens and Brooks 2013 AR; Smith et al. 2001 JHM). The conflation of two dynamical storm classes when evaluating the impacts of IDCs has potential impacts on the authors’ discussion of precipitation intensities (e.g., Figs.3, S9; Sections 3.2.1, 3.2.2). The precipitation intensity distribution for IDC events is in all likelihood a bimodal distribution, containing output from isolated*

non-supercells and supercells (e.g., Hitchens and Brooks 2013 AR).

Can the authors examine the IDC portion of their climatology to determine if there is indeed a bimodal distribution captured within? If not, why do the authors think that the FLEXTRKR algorithm failed to capture heavy/extreme rain events from supercells?

Is it possible to add an additional class to the FLEXTRKR algorithm to detect supercells specifically? How likely is it that supercells will be classified as IDC within this climatology? Supercells do frequently grow upscale into an MCS (e.g., Reif and Bluestein 2017): in such a situation, would the entire storm track be classified as an MCS in this climatology? How would these "misclassifications" impact the results?

Reply:

Thank you for your suggestions. However, a supercell is defined from another perspective but not based on the size and duration of convective systems used to separate MCS from IDC in this study. Supercell characteristics include hook echoes, bounded weak-echo regions, and the presence of strong rotation updrafts (Lynn, 2002; Naylor et al., 2012). Rotation recognition (or rotation-related variables, such as vertical vorticity, low-level-shear, azimuthal shear, etc.) is necessary for the automatic identification of supercells (Lakshmanan and Smith, 2009; Lynn, 2002; Smith et al., 2012; Stumpf et al., 1998). Therefore, the current FLEXTRKR algorithm cannot identify supercells. Also, high spatiotemporal-resolution radar radial velocity data are needed to calculate rotation-related variables. Gridrad V3.1 only provides hourly reflectivity data. So, the source datasets used in our study is not sufficient to identify supercells either. We find that the Multi-Radar Multi-Sensor radar dataset mentioned below provides half-hourly rotation data, which can be used for supercell identification by using corresponding algorithms.

Since supercell is defined differently, there are no direct relationships between MCS/IDC and supercell. That is to say, both MCS and IDC events can contain supercell features sometimes during their lifetimes (French and Parker, 2008). Supercell can exist in both the MCS and IDC categories in our data product. Our examination of MCS/IDC hourly rain rate probability density functions (PDFs) does not show a significant bimodal shape (Figure R3). The interesting point is that although the PDF shapes between MCS and IDC are very similar, MCS PDF shows slightly larger values in high rain rates, reflecting relatively more pixels with larger rain rates for MCSs. Figure R3 does not mean that supercells do not have higher precipitation intensities than non-supercells. Since supercells only account for a small portion of all convective events, mixing them with other IDC/MCS events in a single PDF would conceal the feature of supercells. We need a supercell PDF to display its uniqueness compared to other convective systems, similar to what Hitchens and Brooks (2013) did.

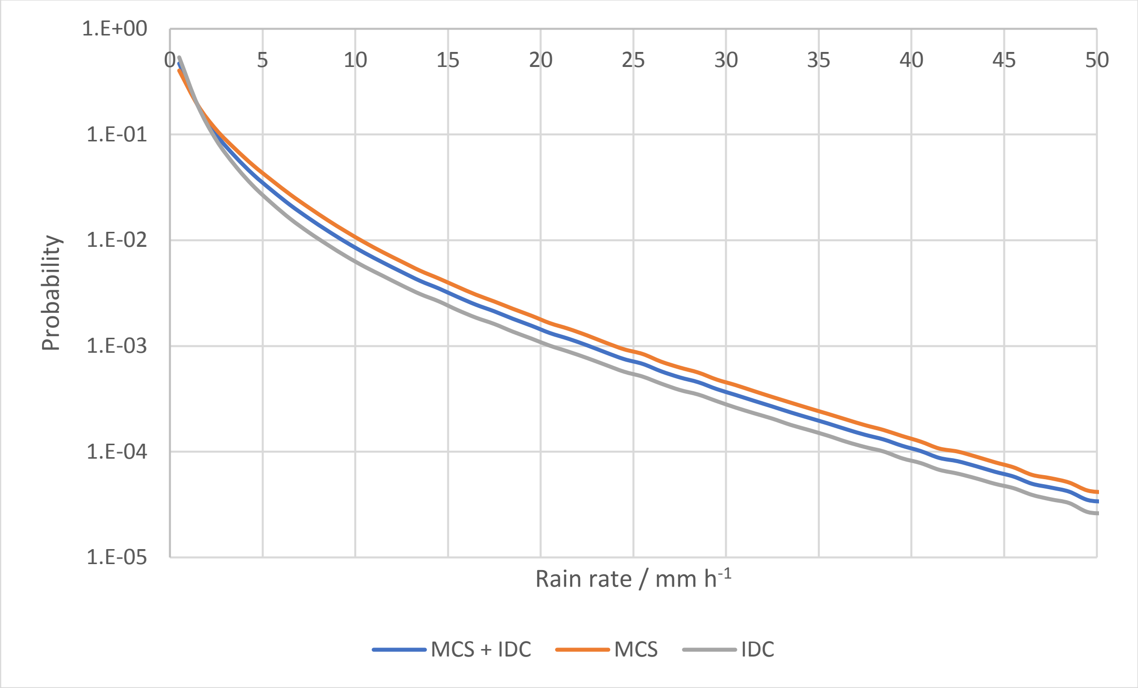

Figure R3. PDFs of pixel-level hourly rain rates for MCS and IDC events during 2004 – 2017. The orange line is for MCS, the gray line is for IDC, and the blue line is for MCS + IDC. We do not consider rain rates larger than 51 mm h^{-1} in this figure. However, the number of those pixels with rain rates > 51 mm h^{-1} only accounts for about 0.03% of the total number. Excluding them should have little impact on the PDFs.

As we mentioned, the current FLEXTRKR algorithm cannot detect supercells by merely adding a supercell class. To identify supercells, we need to add rotation-related variables in FLEXTRKR and make some other changes to the algorithm. Theoretically, FLEXTRKR can be used to detect supercells if enough contents are added. However, this is not necessary. The advantage of our data product is that we store a lot of information for each MCS/IDC track. Supercells can be further identified by combining our data product with other datasets. For example, we know the location and time information of an MCS in our data product. The Multi-Radar Multi-Sensor radar dataset can provide rotation data over the location during the time of that MCS. We can determine whether the MCS shows supercell features or not based on the coincident rotation data (may need some calculations, derivations, and coding). It is much easier than modifying FLEXTRKR.

For the last question, the answer much depends on the researchers and the purposes. In the study of Hitchens and Brooks (2013), they defined hours as instances of supercell thunderstorms if a storm showed supercell features at that hour. If the FLEXTRKR could identify supercell features, we would define an MCS/IDC track as supercell if it showed supercell features at any time during its lifetime. Or we could set some fraction thresholds: an MCS was defined as a supercell track only when the fraction of hours showing supercell features was larger than a threshold. Ultimately, this depends on the specific purpose of the research. Our data product is not intended for supercell research specifically.

2. *I had trouble following exactly how the SL3D algorithm output was incorporated into the climatology. Given its introduction at the start of section 2.2 I had first assumed its classifications were important to the FLEXTRKR algorithm in identifying the CCFs and PFs. After reading I'm no longer convinced it is used in that effort at all, but instead just incorporated into the climatology after the fact. How are the five SL3D categories, listed in lines 221-222, used to identify the CCFs and PFs (if they are)? If not, how are those categories used? On a display note, how does the data shown in Fig. 2e correspond to the five categories listed?*

Reply:

Thank you for your comments. The usage of the SL3D outputs can be reflected in the definitions of CCF and PF (Lines 238 – 243 in the revised main manuscript). CCF is a continuous updraft/convective area with precipitation > 0 mm h^{-1}, and PF is a continuous updraft/convective/precipitating-stratiform area with precipitation > 1 mm h^{-1}. Here, updraft (convective updraft), convective, precipitating-stratiform are the categories from SL3D (Table S2). The SL3D algorithm can determine the type of radar echo (five categories or missing value) of each pixel in Figure 2e (we have added explanations to the values in Figure 2e in Lines 327 – 328 in the revised main manuscript: 1, convective updraft; 2, convective; 3, precipitating stratiform; 4, non-precipitating stratiform; 5, anvil). Therefore, after we identify a CCS track, we know the echo type (five categories) and Stage IV hourly precipitation of all the pixels in the CCS track at any time. Among these pixels, we identify continuous areas satisfying specific criteria, such as CCFs and PFs. That is to say, the convective/stratiform status is from SL3D outputs, which is necessary for the FLEXTRKR algorithm to determine MCS and IDC tracks.

3. *How is rain rate calculated? Is it based on assumed Z-R relationships from the GridRad data (which introduces a host of problems), or is it calculated by subtracting accumulated Stage-IV rainfall at successive hours? If calculated by subtracting rainfall accumulations, that has the unfortunately side effect of evenly distributing rainfall over the full hour, lessening peak intensities that occur over shorter periods of time. Given the temporal resolution of the datasets used here, that issue can't be avoided, but the authors should include a few sentences qualifying their discussion on precipitation intensity (beyond the issues already noted in major comments #1.)*

Reply:

Thank you for your comments. All precipitation values and associated variables are derived from the Stage-IV data, which represents hourly accumulated precipitation. As the temporal resolution of all the source datasets and the MCS/IDC data product is 1 hour, we do not need to make any subtractions to Stage-IV rainfall at consecutive hours. Rain rate or precipitation intensity just denote mean hourly precipitation. Anyway, we agree with you that the 1-hour resolution may reduce peak precipitation intensities occurring in minutes. However, since Sections 3.1 and 3.2 talks about climatological mean characteristics, we do not expect the sub-hour heterogeneity will affect the results in Sections 3.1 and 3.2. We mentioned the limitation of the 1-hour temporal resolution in Section 4.3 from the perspective of Gridrad reflectivity, which only includes reflectivities within ± 3.8 minutes of each hour. Considering the 1-hour temporal resolution of our study, we cannot find a suitable place to add discussions about the sub-hour precipitation variations.

4. *Figures S1 and S5 are key to understanding the descriptions in the text and should be moved to the main article.*

Reply:

Thanks. We have moved the two figures to the main manuscript (Figures 3 and 4). All figure numberings have been changed accordingly in the revised main manuscript and supplement.

Minor comments:

- *Lines 39-45: This is a nice summary of the wide-reaching impacts of deep convection. On a minor note, should multiple citations within one reference be provided in chronological order?*

Reply:

Thanks. According to the reference format of ESSD on https://www.earth-system-science-data.net/submission.html#references, in-text citations can be sorted chronologically or alphabetically or based on relevance, depending on the author's preference. There is no specific requirement for it. References listed at the end of the manuscript should be sorted alphabetically under the first author's name, except for those with the same first author. Our current in-text citation format follows the rule of reference listing at the end of the manuscript.

- *Line 49: "deep convection associated thunderstorms" –> deep convective thunderstorms*

Reply:

Have corrected. Please see Line 51 in the revised main manuscript.

- *Line 201: Is the "neareststod" method essentially nearest neighbor? A brief one-line description would be helpful.*

Reply:

Yes. There are two types of nearest neighbor methods in the ESMF regrid module:

“neareststod” and “nearestdtos.” The “neareststod” method maps each destination point to the closest source point, while the “nearestdtos” method maps each source point to the destination point. In the “nearestdtos” approach, it is noteworthy that some destination points may not be mapped to any source points, which cannot be used in our study. We have added a sentence to explain the “neareststod” method in Lines 187 – 188 in the revised main manuscript, just as follows.

‘The “neareststod” method maps each destination point to the closest source point.’

- *Lines 229-231: A few sentences describing, theoretically, how CCFs and PFs differ, and what kind of features each of these is intended to represent, would be helpful. It wasn’t always clear to me why essentially two separate datasets were being developed.*

Reply:

As defined in Lines 238 – 243 in the revised main manuscript, CCF is a continuous updraft/convective area with precipitation > 0 mm h^{-1}, and PF is a continuous updraft/convective/precipitating-stratiform area with precipitation > 1 mm h^{-1}. The difference between PF and CCF can be clarified in Figure 3 in Lines 336 – 337 in the revised main manuscript. In the last row of Figure 3, the red color indicates CCF, and the green color indicates PF. Theoretically, PF represents areas with significant precipitation (> 1 mm h^{-1}), while CCF represents convective cores. They are somewhat spatiotemporally overlapped, as generally convective cores have substantial precipitation. There is another variable used in the definition: intense convective cell, which is convective cells with column maximum reflectivity ≥ 45 dBZ and precipitation > 1 mm h^{-1} (pink areas in Figure 3) (Lines 271 – 272 in the revised main manuscript), representing the strongest convection activity (other values may be used in other studies, such as 40 dBZ in Bigelbach et al. (2014)). In the definition of MCS, we use PF and intense convective cells, while in the definition of IDC, we use PF and CCF. PF is intended to denote the size of a convective system. However, PF cannot be used solely in the MCS/IDC definitions, as PF may contain no convective precipitation but just stratiform precipitation. Intense convective cells and CCF are used to confirm that a track is convective. Specifically, intense convective cells are also used in the MCS definition to ensure that the MCS convection activity is strong enough. Our idea of using two different types of variables to separate different convective systems is similar to Bigelbach et al. (2014), which used an areal variable to represent the size of the convective object and a reflectivity threshold to confirm convection. A similar definition approach was also found in Geerts (1998).

Now the question is whether we can only use CCF or intense convective cells to define MCS and IDC. The answer is Yes. Rowe et al. (2011) and Rowe et al. (2012) used cell features to separate MCS and IDC events. Their cells required reflectivity (the only dataset used in their tracking algorithm) to be larger than 35 or 45 dBZ, which are similar to convective cores in our study. In their studies, IDC is defined as a track with cell major axis length < 100 km and aspect ratio less than 5:1; while an MCS is defined as a track with cell major axis length > 100 km. However, this kind of definition may be problematic in some cases when multiple convective cores of an MCS are somewhat separated by weaker precipitating stratiform clouds, making it unable to satisfy the size criterion. The significant large precipitating-stratiform area associated with some convective systems, especially for MCSs (Parker and Johnson, 2000), may cause CCF or intense convective cells unable to represent the actual sizes of the convective systems. Since there are no precise definitions of MCS or IDC and many studies used different source datasets and definition criteria, using CCF or intense convective cell solely in the MCS or IDC definition is practically possible, but the limitations should be understood.

Finally, CCS is another variable to determine the size of the convective systems in our study. However, cold-top upper-level clouds do not always contain precipitation, and CCS cannot represent the size of the precipitating area. So, we used CCS and PF together in the definition. This is another reason why we use several different variables in the definition of MCS and IDC: we hope to minimize the false identification of MCS and IDC events by combining different datasets.

We have added some explanations about our purposes to use PF, CCF, and intense convective cells in the updated FLEXTRKR algorithm in Lines 239 – 240, 242 – 243, and 272 in the revised main manuscript.

- *Lines 290-293, Fig. 2: I was only able to understand the descriptions of the pixel-level information by reading the caption of Fig. 2. I'd move the description in the caption into the text and expand lines 290-293 by referencing each subfigure individually.*

Reply:

Thank you for your suggestions. We have added more detailed explanations to Figures

2f-2i in Lines 302 – 311 in the revised main manuscript. Now, the sentences are as follows.

‘Figures 2f – 2i give an example of the pixel-level MCS/IDC information at 2005-07-04T03:00:00Z. Figure 2f displays the spatial coverages of MCS/IDC tracks at that time at pixel scale and the corresponding unique numbers of these tracks. From Figure 2f, we know whether a pixel belongs to an MCS/IDC track and the number of the track if the pixel belongs to a track. We can further determine whether the track is an MCS or IDC event from Figure 2g, which shows the types (MCS or IDC) of the tracks in Figure 2f at the pixel scale. Figures 2h and 2i are similar to Figures 2f and 2g, respectively. The difference is that Figures 2h and 2i only show pixels with precipitation > 1 mm h^{-1} in that hour.’

- *Lines 345-346, 349, 356, 358: Six different proxies for convective intensity are used in a small section: convective precipitation area, convective 20-dBZ echo-top height, area with column max reflectivity >= 45DBZ, max 30-dBZ echo-top height, max 40-dBZ echo-top height, mean convective 20-DBZ echo-top height. Why are all these different proxies are being used – do the underlying results differ? I’d find it easier to read if the convective intensity results were all discussed in the frame of one proxy.*

Reply:

By using multiple variables, we just wanted to confirm that our results are robust. In addition, we hoped to separate the strongest convective activity (area with column max reflectivity ≥ 45DBZ and max 40-dBZ echo-top height) from the mean convective activity (convective 20-dBZ echo-top height). Since the original sentences are confusing, we have made some changes in Lines 363 – 364, 374 – 383, and 387 – 393, and only used convective 20-dBZ echo-top height as the proxy for mean convective intensity. Table 1 (Line 404 in the revised main manuscript) and Table S5 (Line 89 in the revised supplement) have been updated accordingly.

- *Lines 363-370: While Section 3.2 is a good application of the climatology product, it isn't "a detailed examination of the 3D evolutions of MCS/IDC events."*

Reply:

No, it isn't. Section 3.2 is just an example of the potential applications of the data product, as we mentioned in Line 400 in the revised main manuscript. The data product can be useful in a variety of other studies, although we only show some direct results from the data product in this study. In fact, although Section 3.1 also shows some results related to MCS and IDC, it is more intended to be used to verify our data product, to ensure the MCS and IDC climatological characteristics consistent with our algorithm definitions and general knowledge. Therefore, we summarize the potential applications of the data product in Lines 395 – 400 in the revised main manuscript. Lines 400 – 402 is used to connect with Section 3.2.

- *Line 391-393: Instead of using "stratiform" as the name for all precipitation not associated with MCSs or IDCs, I suggest the phrase "non-convective". "Stratiform" is confusing as there is stratiform rain within both MCSs and IDCs.*

Reply:

Thank you for your suggestions. We have changed “stratiform” in Section 3.2 and Section 4 to “non-convective” (NC) accordingly, as well as figures and tables in the revised main manuscript and supplement. Besides, we have added another sentence in Lines 426 – 428 in the revised main manuscript discussing the limitation of NC precipitation, possibly containing some convective-associated rain. We think adding this sentence can make the definition more accurate, although we also discussed the limitation in Section 3.2.3 and Section 4.

- *Lines 451, 460, 466: Discussion of Figure S9 happens before that of Figure S8.*

Reply:

Thank you for your suggestions. Figures S6 (the old Figure S8) and S7 (the old Figure S9) first appeared in Line 493 with the correct order. In this sentence, we wanted to keep precipitation amounts and fractions together (because precipitation fractions are calculated from precipitation amounts), so we put S6 before S7. We understand that we first discussed Figure S7 in detail to make the paragraph easy and fluent. However, we had a summarized sentence at the beginning of the paragraph and intended to discuss these figures together. Therefore, we want to keep the current figure order.

- *Lines 565-567: Can the authors elaborate how each dataset is incorporated into the CCF/PF and CCS criteria listed in Section 2.2?*

Reply:

As defined in Lines 238 – 243 and 249 in the revised main manuscript, CCF is a continuous updraft/convective area with precipitation > 0 mm h^{-1}, PF is a continuous updraft/convective/precipitating-stratiform area with precipitation > 1 mm h^{-1}, and CCS is generally a continuous area with T_b < 241 K (exceptions and details are discussed in Lines 248 – 257 in the revised main manuscript). As mentioned above, all the precipitation values are from Stage-IV, not related to Gridrad reflectivity at all in this study. Gridrad only provides reflectivity Z_H, and satellite infrared T_b dataset only provides T_b. Therefore, we can understand which datasets are used based on their definitions. CCS is mainly based on the satellite T_b dataset. We use "mainly" is because, as demonstrated in Lines 254 – 257 in the revised main manuscript, CCSs sharing the same coherent precipitation feature (different from PF) are connected, and the coherent precipitation feature is defined based on reflectivity. PF, firstly, is related to Stage IV precipitation dataset, as it requires precipitation > 1 mm h^{-1}. Secondly, updraft/convective/precipitating-stratiform categories are from the SL3D algorithm (Lines 229 – 232 in the revised main manuscript), and SL3D is based on Gridrad reflectivity and ERA5 melting-level heights (Lines 232 – 233 in the revised main manuscript). Therefore, PF is defined based on Stage IV, Gridrad, and ERA5 datasets. CCF is similar to PF, since it is also related to SL3D categories and precipitation. Because all these datasets are at the same grids, we are able to handle them simultaneously, such as finding continuous areas satisfying specific criteria, e.g. CCS, CCF, and PF. After finding out CCS/CCF/PFs, we can calculate their characteristics, such as area, major axis length, rain rate, aspect ratio, etc.

- *Line 613: Instead of individual NEXRAD radar data, could the Multi-Radar Multi-*

Sensor radar dataset be used? (https://www.nssl.noaa.gov/projects/mrms/)

Reply:

Just to be clear, the GridRad radar dataset used in our study is a mosaic of all the NEXRAD radar data east of the Rocky Mountains, but not "individual radar data." Based on the parameter "3D Mosaic Levels" shown on https://mrms.nssl.noaa.gov/qvs/product_viewer/, the Multi-Radar Multi-Sensor radar dataset can be used by the SL3D and FLEXTRKR algorithms after re-gridding. The Multi-Radar Multi-Sensor radar dataset has a resolution of 1 km and 2 minutes, covering 33 vertical levels from 0.5 km to 19 km, which is better than the Gridrad 3.1 dataset used in our study. In addition, the Multi-Radar Multi-Sensor data also contains rotation, which can be used for supercell identification.

- *Line 633: Section 3.2.2 –> Section 2.2.2*

Reply:

Thanks. We have corrected it. Please see Line 694 in the revised main manuscript

- *Section 4.4: I appreciate the authors' testing of the MCS and IDC definition criteria and discussion of that criteria's impact on classified precipitation. I would recommend the authors urge caution of future researchers using this dataset to examine transport or large-scale circulation impacts without conducting their own, similar analysis.*

Reply:

Thank you for your suggestions. We have added a relevant sentence in Lines 744 – 749 in the revised main manuscript. The sentence is as follows.

‘Lastly, although our sensitivity test in Section 4.4 shows that precipitation characteristics are similar between two different sets of MCS/IDC definition criteria, we still recommend users conduct further sensitivity tests and examine the impact of different definition criteria on the results if the data product is applied to other studies, such as the effects of MCS and IDC events on atmospheric circulation, environmental conditions associated with the initiation and evolution of MCS and IDC events, and MCS/IDC associated weather hazards.’

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